Survivable Virtual Network Redesign and Embedding in Cloud Data Center Networks

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ABSTRACT

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Today, the cloud computing paradigm enables multiple virtualized services to co-exist on the same physical machine and share the same physical resources, hardware, as well as energy consumption expenses. To allow cloud customers migrate their services on to the cloud side, the Infrastructure Provider (InP) or cloud data centre operator provisions to its tenants virtual networks (VNs) to host their services. Virtual Networks can be thought of as segmenting the physical network and its resources, and such VN requests (or tenants) need to be mapped onto the substrate network and provisioned with sufficient physical resources as per the users' requirements. With this emerging computing paradigm, cloud customers may demand to have highly reliable services for the hosted applications; however, failures often happen unexpectedly in data-centers, interrupting critical cloud services. Consequently, VN or cloud services are provisioned with redundant resources to achieve the demanded level of service reliability. To maintain a profitable operation of their network and resources, and thus achieve increased long term revenues, cloud network operators often rely on optimizing the mapping of reliable cloud services. Such problem is referred to as in the literature as "Survivable Virtual Network Embedding (SVNE) " problem. In this thesis, the survivable VN embedding problem is studied and a novel cost-efficient Survivable Virtual Network Redesign algorithm is carefully designed, presented, and evaluated. Subsequently, we distinguish between the communication services provided by the cloud provider and study the problem of survivable embedding of multicast services; we formally model the problem, and present two algorithms to reactively maintain multicast trees in cloud data centers upon failures.

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Abbreviations

BG - Backup Group

DFS - Distribyted File-Systems

DVBMT - Delay- and Delay-Variation Bounded Multicast Tree

FDP - Failure Dependent Protection

FIP - Failure Independent Protection

HPC - High Performance Computing

IaaS - Infrastructure as a Service

InP - Infrastructure Provider

MVN - Multicast Virtual Network

NP-hard - Non-deterministic Polynomial-time hard

PaaS - Platform as a Service

QoS - Quality of Service

SaaS - Software as a Service

SDN - Software Define Network

SLA - Service Level Agreement

SMVN - Survivable Multicast Virtual Network

SMVNE - Survivable Multicast Virtual Network Embedding

SP - Service Provider

SVN - Survivable Virtual Network

VDC - Virtual Data Center

VL - Virtual Link

VM - Virtual Machine

VN - Virtual Network

VNE - Virtual Network Embedding

WG - Working Group

Chapter 1

Introduction

1.1 Background and Motivation

The Internet has made significant impact on our society, business models and our daily lives. As a new paradigm for the future Internet, cloud computing has drawn the attention of the general public in recent years. In simple terms, cloud computing is capable to create a virtual environment which allows both software and hardware to be shared by multiple-users via the Internet. With cloud computing, businesses are no longer required to incur investment on purchasing hardware and software licenses in order to deploy their services and applications. Moreover, human expenses can also be reduced since the operating and maintaining cost will be shifted to the cloud side [1].

Today, there are two main players in the cloud computing market; namely, the Service Provider (SP) and the Infrastructure Provider (InP). The former allows cloud users access to the cloud service via the Internet; whereas, the latter manages infrastructures and leases physical resources to SP [2]. According to the type of services, cloud service scenarios can be classified into three main types: Infrastructure as a Service (IaaS), in which the InPs split their resources and outsource

them to the SPs; for instance Amazon EC2 and Microsoft Azure are the applications that would provide such service. Platform as a Service (PaaS), it offers a framework which systems users can build on, such as Google Apps Engine [2]. Last but not least, Software as a service (SaaS); instead of purchasing applications running them locally, SaaS allows a software to be shared among users via the Internet; an example is GRIDS Lab Aneka[3]. In this thesis, a role of InP is assumed, and IaaS services, precisely Virtual Network (VN) service, are served to SPs based on their demands.

The InP provides an environment that allows Virtual Machines(VM) coexist on the same physical machine. Through a VMs management software "Hypervisor", the InP is able to create, run and allocate resources for VMs. By sharing infrastructures, the operating cost and hardware investment can be greatly reduced. VMs demand a minimum level of hardware specifications, typically in terms of CPU capacity, memory, disk space, etc. In order to host multiple VMs in one server, the server has to have sufficient physical resources. We address the VM placement action as *"Virtual Machine Embedding"*. In addition, cloud customers may migrate their network services to the cloud, thus Virtual Networks(VNs) need to be embedded with more requirements on bandwidth, delay and so on. Hence, the placement of VN becomes critical as good mapping solutions may cost less and result in better service admissibility in a data center. Accordingly, it is important for cloud vendors to optimize the placement of services to improve their revenue. The optimal placement of cloud services, referred as "Virtual Network Embedding (VNE)", is known to be -Hard [4].

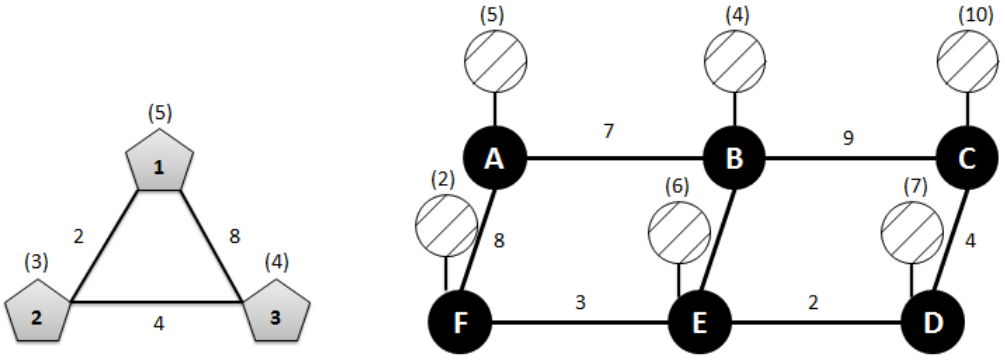
Now, cloud users may deploy certain critical services on the resources they leased, but the hosting servers may break down for a variety of reasons. When they do ,VNs would get disconnected and the services would be disrupted. Hence, it is very important for cloud vendors to provide certain degree of reliability to their hosted VNs in the datacenter. In fact, most of the major cloud sevice provider gaurantee their customers a certain level of QoS (Quality of Service), donoted as

"Service Level Agreement (SLA)"[5]. For example, Microsoft Azure promises its users 99.9% availability of their virtualized services. To obtain such highly reliable service level, certain level of resource redundancy is required. The problem of embedding a virtualized service with reliability is referred as *"Survivable Virtual Network Embedding (SVNE)"*. There are two common failure scenarios in a cloud datacenter: Substrate node failure and substrate link failure. In both cases, redundancy needs to be provided in order to restore the failed services. Similar to working resources, the redundant resources also need to be mapped onto the substrate network, either before or after a failure; we call former *"proactive protection"*, as it reserves resources to be ready for for future failures; and we refer the latter *"reactive restoration"*, since it finds alternative mapping solutions to restore the VN services after a failure. Indeed, the mapping of redundant resources would complicate the problem.

There are many SVNE solutions proposed by recent research papers; depending on the failures considered, some work focus on the failure of physical links[6–9], whereas others tackle the problem of node failures[10–17]; In this thesis, only facility node (servers for example) failures are considered, the reasons are two folds: On one hand, link failures have been addressed in plenty of literatures, and the techniques introduced can be reused in the light of network virtualization; On the other hand, node failures effect the virtualized services running on the failed server directly, thus triggering VM migration to re-place those VMs and the corresponding virtual links must be re-mapped to resume the service. This is a variation of VNE problem, thus it is also considered to be NP-hard. Moreover, some work have been done to solve the SVNE problem in case of facility node failures in the substrate network. In [10, 16, 18–22] node mapping and link mapping methods are developed for embedding a reliable-virtual-network, the resource sharing techniques are explored to reduce the cost for embedding redundant resources. However, in those work, redesigning survivable virtual network has never received enough attention; though in [11] [12], backup resources are augmented only when the overall availability does not meet the requirement, nonetheless cost efficient

is never considered for SVN redesign. Therefore, a technique is needed to design VN requests, taking sharing of resources into account, and output a survivable VN that can be embedded with least cost. In the first part of the thesis, a cost-efficient-oriented survivable virtual network redesign algorithm is proposed, which designs a VN request at virtual level, considering the future resource sharing in the embedding phase. In the second part of this thesis, we address the problem of Multicast Virtual Network (MVN) failures, and a novel reactive protection method is developed to protect the embeded MVNs from node failures.

1.1.1 Problem Definitions



(a) Non-Survivable Virual Network (b) Substrate Network

FIGURE 1.1: Virtual Network Embedding Problem

The Substrate Network : We represent the substrate network as an undirected graph denoted by $G^s = (N,L)$, where N is the set of substrate facility nodes, and L is the set of substrate links. Facility nodes are connected to the network via network nodes (routers/switches). Each substrate facility node $n \in N$ is associated with a finite computing capacity, denoted by c_n. Similarly, each substrate link $l \in L$ has a finite bandwidth capacity, denoted by d_l. Figure 1.1(b) illustrates a substrate network with 6 facility nodes, each with a CPU capacity varying from 2-10 units (represented by the number in parenthesis above each facility node). Similarly, bandwidth on the substrate links interconnecting the network nodes

exhibit a range from 2 to 9 units of bandwidth on each (represented by the number in parenthesis above each substrate link).

The Virtual Network (VN) : A Virtual network represents a client's request to deploy an application in a cloud data center. It consists of a set of virtual nodes (virtual machines), interconnected with virtual links. The virtual links correspond to the communication requirements between the virtual nodes in a given VN request. We denote a VN as a graph $G^v = (V,E)$, where V represents the set of virtual nodes, each with a CPU demand of c_v, and e is the set of virtual links, each with a bandwidth demand of d_e. Figure 1.1(a) shows an example of a VN request with 3 virtual nodes and links, in addition to their associated CPU and bandwidth demands, respectively.

Given the VN request, the VNE problem aims to map this request onto the substrate network while providing enough resource as demanded. On one hand, each substrate element has independent capacity; on the other hand, each VN request has specific resource requirement[23]. Hence, the problem is to find a minimal cost solution for each VN request. The formal definition of virtual network embedding is described as follows:

Problem Definition 1. *Given a substrate network $G^s = (N, L)$, and a VN request $G^v = (V,E)$. Find the optimal embedding solution of $G^v = (V,E)$, such that cost of resources spent in the substrate network is minimized, while guaranteeing the capacity on the substrate network elements are not violated.*

1.1.2 Reasoning and Optimizations

Many research work has been done to solve the VNE problem presented above. As this problem is proven to be $NP-hard$[4] , much research focuses on developing heuristic and meta-heuristic methods and solutions [23]. With these VNE techniques, the mapping of VN requests should be able to obtain low-cost solutions, and thus yield higher VN requests admission. Consequently, the long term revenue

is increased for InP, and the rental cost for VN customers can be lowered.

Today, most cloud vendors guarantee their users with high level of service availability; for instance, services that are hosted on Amazon EC2 are promised to have 99.95 % availability; users can get 10% - 30% of their service credits back, if the reliability level of their virtual services are violated. To achieve such high level of service survivability, resource redundancy to virtualized services need to be deployed at provisioning time or post-failure. On one hand, InPs are required to deliver highly reliable VNs, thus redundancy must be deployed; on the other hand, without a proper embedding technique, such redundancy may not be cost-efficient [24]. Such problem is known as "Survivable Virtual Network Embedding". As SVNE problem can be divided into primary resource embedding and backup resource embedding, and the former alone is a $NP-hard$ problem (virtual network embedding problem), thus survivable virtual network embedding problem is even harder to solve.

Numerous research work have attemptted to address the SVNE problem. Similar to the VNE problem, most of the work relax it by solving the embedding in more than one step. Moreover, mathmetical models [10–12, 16, 18–22] proposed but most of them are either not scalable or non-linear. Consequently, heuristics[10, 12, 16, 18, 20] are introduced and acceptable solutions can be achieved.

In this thesis, we make two main contributions on SVNE problem, and are summarized as the following:

- A cost-efficient SVN redesign algorithm is proposed to solve the survivable VN redesign problem, and a mathmetical model is presented to embed a given SVN assuming single facility node failures.
- We consider multicast cloud services and in particular present embedding and maintenance techniques when such services are hosted by a cloud data center.

1.2 Thesis Organization

The rest of this thesis is organized as follows. In Chapter 2, related background knowledge are introduced; specifically, the type of failures in the cloud datacenter, and corresponding protection methods. Also, each processing stage in SVNE is discussed in this Chapter. The characterization of VNs are discussed at the end of this Chapter. Chapter 3 studied the survivable VN redesign taking the sharing techniques into account, a novel design method is proposed and compared against conventional redesign schemes. Multicast virtual network is being considered in Chapter 4, two multicast-tree maintance algorithms are designed to reactively restore multicast VNs from node failures, while ensuring the delay constraints are satisfied. Finally, conclusion and future work are presented in Chapter 5.

Chapter 2

Preliminaries and Related Work

2.1 Failure Senarios and Protection Methods

Fault-tolerance is a major concern of datacenter operators[25]. To protect virtualized services from failures, failure senarios must be studied as well as the commonly deloyed countermeasures. In this subsection, the related work and recent researches are surveyed.

2.1.1 Type of Failures

Both substrate links and substrate nodes may fail, and all virtualized services that are running on top of them would be interupted. If a physical server fails, all VMs that are being hosted on it will be shut down. Figure.2.1 illustrates how a facility node (server) failure will affect the Virtual Machine (V_1) running on top of it. Similarly, the disconnection of a physical link may suspend all virtual links that traverse through it. As shown in Fig.2.1, the physical link failure disconnects the communication between VM V_5 and V_6. Therefore, we classify the substrate failures as "Link Failure" and "Node Failure", where the latter can be further subdivided as "Network Node Failure" and "Facility Node Failure"[18]. "Network Nodes" usually refer to networking devices such as routers, switches, whereas

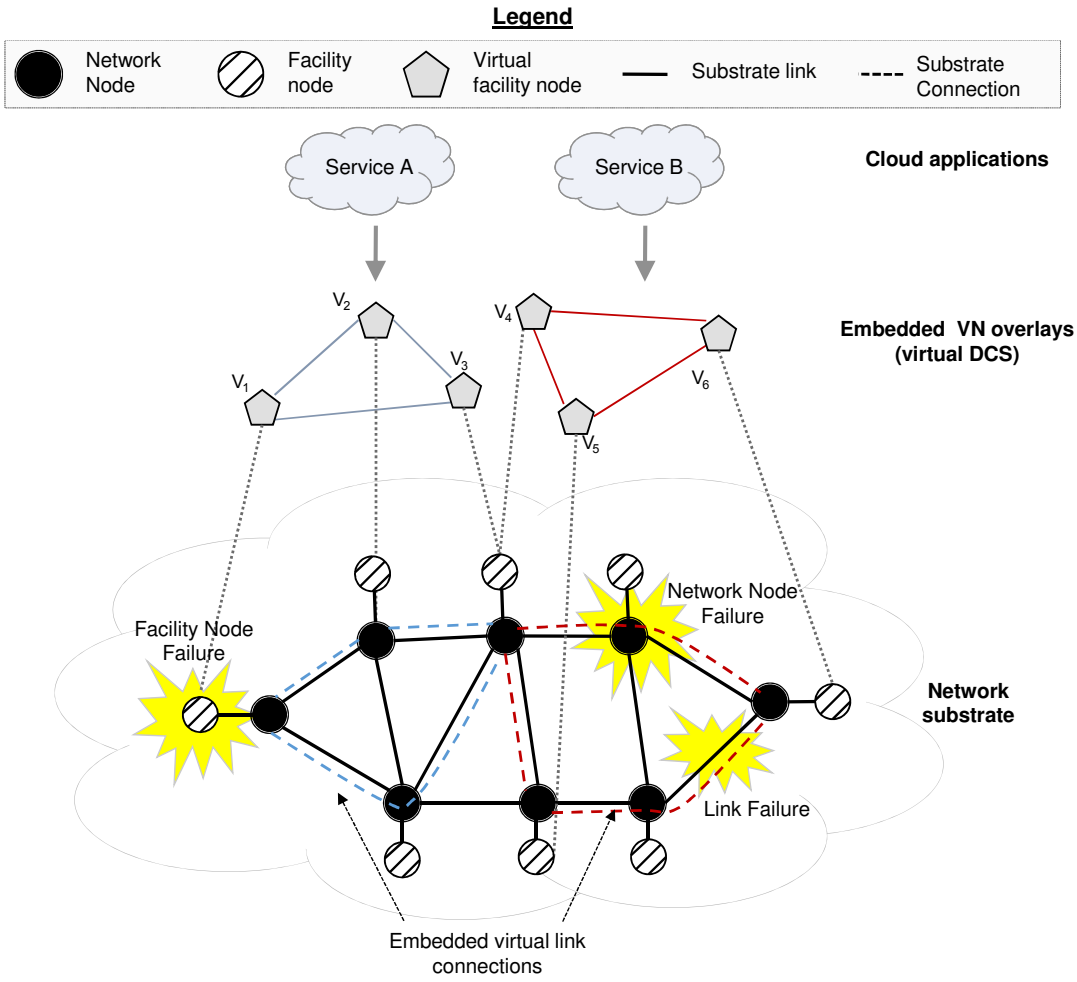


FIGURE 2.1: Failure in the Substrate Network

"Facility Nodes" refer to servers that host virtual machines. In Fig.2.1, a failure of a network node would terminate all the comunications which traverse through.

In terms of the scale of failures, there are "Regional Failure"[26], which effect multiple substrate elements, including nodes and links, at a time; and "Signle Failure", which means only one substrate element outage, it can be either signle server break down or single link disconnection. In this thesis, only a single facility node failure is assumed.

2.1.2 Protection Methods

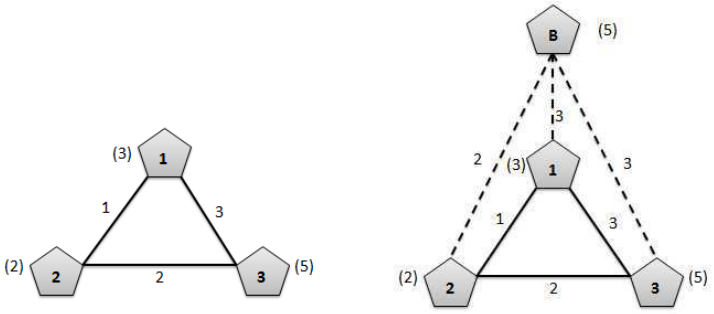
There are two main types of failure countermeasures, namely *Protection* and *Restoration*[27]. Protection reserves backup resources proactively, the redundant

backup resources are always assigned before actual failure. These resources would keep inactive until failure happens. On the other hand, restoration protects VNs in a reactive manner. It is only activate after failure happens, and it is called on demand to search for alternative mapping solution for the failed element(s).
In reactive approach, there is no redundancy provided, therefore, the embedding cost of VNs that are running reactive restoration is definitely less than it of VNs assigned with redundancy, hence it may allow substrate network to admit more VN requests. However, upon failures, reactive approach does not gaurantee 100% recovery of disrupted VNs, as it may not be able to find a feasible solution; whereas proactively protected VNs can always be reconnected.

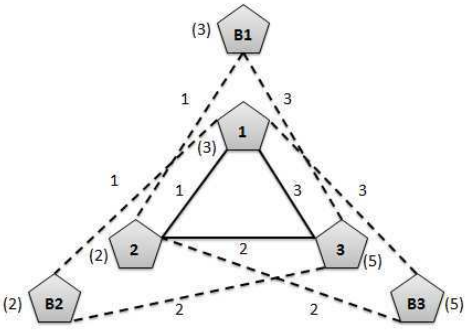
In terms of post-failure recovery capability, there are Failure Dependent Protection (FDP)[28, 29] and Failure Independent Protection (FIP)[10, 19–22]. In FIP, each primary node will be assigned a specific backup node, such that upon failure occurence, the primary can only be migrated to that backup host. In comparison, FDP allows working hosts to have different backup hosts in different failure scenarios, and sometimes even working nodes are allowed to migrate [14]. In this thesis, only FIP methods are considered.

2.2 Virtual Network Redesign and Embedding

In a typical Survivable Virtual Network Embedding solution, two design stages are performed, namely "reliable virtual network redesign" and "survivable virtual network embedding". In the redesign stage, a given Virtual Network would be augmented with redundant computational and bandwidth resources, such that any facility node failure can be tolerated. The resulting graph is called "Survivable Virtual Network", and sometimes it is referred to "Survivable Virtual Infrastructure"[16]. In the embedding stage, the reliable-virtual-network from the previous stage would be mapped onto the substrate network. While embedding, it is important to make sure that the resources are shared and total cost is minimized[18].



(a) Non-Survivable Virual Network (b) 1-Redundant Survivable Virual Network



(c) K-Redundant Survivable Virual Network

FIGURE 2.2: Survivable Virual Network Redesign Schemes

2.2.1 Related Work on Virtual Network Redesign and Embedding

Many work in the literature has been devoted towards understanding and characterizing failure in cloud data center networks [24], [30]. From these studies, we can conclude that failure in data center networks can happen due to single or multiple network components failures (facility nodes, links, switches/routers), and the incurred financial losses are real. This means that the cloud provider must invest additional resources to mitigate substrate network failures, and fulfil the promises of reliability and availability to the hosted tenants's applications and services. In [30], the authors focus on characterizing servers failure rate. The authors analyzed these failure characteristics using a real data center over the period of 14 months, and concluded that hard-disks are the most dominant reason behind server failures, and that 8% of all servers in a data center are expected to fail within a year. Further, the authors have also looked at successive failure rates, meaning

the probability that a failed server would fail again after repair, and it was found that successive failure rates are quite high. For a 100 servers data center where 4 machines has failed more than once in 14 months; it was found that 20% of all repeat failures happen within a day of the first failure; while 50% happen within two weeks. Indeed, the estimated repair cost for a typical data center with more than 100,000 servers is estimated in millions of dollars; not to mention the incurred penalty cost due to affected services disruption.

In this regard, survivability against facility node failure is of paramount importance, particularly in the case of critical services that don't tolerate failure. Indeed, this problem has attracted significant attention from the literature; here we can distinguish between single facility node failure [16], [18], [14], [15], and multiple facility nodes failure [17], [13], [10]. In the case of single facility node failure, the authors of [18] introduce a two-step approach to fully restore a VN from any single facility node failure. Mainly, their approach consists of augmenting the VN request with a 1-redundant or k-redundant backup nodes (where k represent the number of critical nodes). The resultant SVN is then mapped onto the substrate network by placing virtual nodes in a given VN on distinct substrate nodes, while aiming to minimize the overall embedding cost. For this purpose, the authors introduce two backup-sharing techniques to minimize the incurred backup-bandwidth cost, namely cross-sharing and back-up sharing. The same problem is tackled in [16], here the authors consider the SVN to be given, and their aim is to map the SVN onto the substrate network while minimizing the amount of idle backup bandwidth. The virtual nodes in a given VN maybe be mapped on the same substrate nodes, as long as their corresponding backup nodes are mapped on distinct nodes; this guarantees survivability against any single facility node failure. To embed the SVN onto the substrate network, two embedding heuristics are presented: A disjoint and a coordinated virtual node and virtual link mapping. For the disjoint embedding approach, a set of feasible node mapping solutions is first enumerated, then this set is passed on to an ILP model that picks the node mapping solution with the lowest reserved backup bandwidth, while the coordinated embedding

adopts a link packing approach. Further, in [14], the authors present a novel approach for redesigning an SVN, denoted as Enhanced VN (EVN), and distinguish between failure-dependent and failure-independent EVN. The failure-independent EVN is similar to the 1-redundant SVN, while the failure-dependent EVN aims at minimizing the amount of idle backup resources by relaxing the constraint that only failed nodes will migrate. Instead, for each different failure-event, virtual nodes (primaries and backups) within a given VN will be re-arranged (migrated) differently to resume a working VN. Note that such approach incurs a considerable amount of migration overhead that can potentially cause a longer down-time. Moreover, in [15] the authors also adopt the 1-redundant SVN scheme to create an Auxiliary Protection Graph (APG). The APG is next embedded onto the substrate network using a tabu-search meta-heuristic with cross-sharing and backup-sharing to minimize the backup footprints.

As for survivability against multiple facility node failure [17], [13], [10], the VN is augmented with the minimum number of backup nodes needed to guarantee a reliability degree r under a given probability of failure p. Further, in [17] and [10], the authors employ sharing across VNs in order to circumvent the inconvenience of idle resources. As for [13], the authors employ survivability at the inter-data center level, where a local protection approach is introduced to eliminate backup bandwidth over wide-area network.

Equal effort has been devoted towards inaugurating effective protection schemes against substrate link failures [6], [22], [7], [21]. Here protection schemes can be mainly categorized as link-based and path-based protection. Further, few work in the literature tackled the case of correlated failure [31], [32], that is the case of single "regional" failure that brings down multiple substrate nodes and links at the same time. Substrate nodes and links that fail together are also referred to as "shared risk group". Here risk groups are considered to be given and protection schemes are tailored for the case of a single risk group (regional) failure. A thorough taxonomy of the various failure scenarios and existing protection methods can be found in [33].

2.2.2 Virtual Network Redesign Solutions and limitations

Two redesign topologies are commonly deployed in the literature, namely 1-Redundant and K-Redundant.

A. 1-Redundant scheme[18]

In 1-Redundant scheme, one backup virtual machine is added to the original virtual network, connecting all primary virtual nodes via backup virtual links. When any of these primary virtual node fails, it migrates the redundant virtual machine through VM migration, and continue communicating with other virtual nodes using the backup virtual links. Figure 2.2(a) shows an example of a VN request, which is consist of 3 VMs interconnected by virtual links. In Fig. 2.2(b), the given VN is redesigned using the 1-Redundant method, the virtual node B is the redundant virtual machine, and it is connecting virtual node 1, virtual node 2 and virtual node 3 via virtual backup link $\{B, 1\}$, $\{B, 2\}$ and $\{B, 3\}$ respectively. Assume a failure occured on virtual node 1, backup virtual node B will then take over the role of virtual node 1, and establish connections with node 2 and 3 through link $\{B, 2\}$ and link $\{B, 3\}$; as B, in this example, has to re-connect the service assuming any primary node can fail and thus it must be able to replace the failed VM, clearly node B has to be provisioned with the maximal amount of computational resources among all the primary VMs; in this example backup node B has to reserve 5 units of CPU. Similarly, the amount of backup bandwidth which is required to be reserved on backup links also need to be calculated such that, when backup node is replacing the disconnected VM, the backup virtual links will have sufficient bandwidth to establish network connections with the neighbors of the disconnected VM. For example, when failure occures and bring down primary node 1, and B will be activated to replace node 1. To resume the communications between B to 2 and B to 3, virtual backup link $\{B, 2\}$ and link $\{B, 3\}$ must also have enough reserved bandwidth to replace primary link $\{1, 2\}$ and link $\{1, 3\}$ respectively. Hence, we temperorarily allocate virtual backup link $\{B, 2\}$ a

bandwidth amount of 1 and link $\{B, 3\}$ 3 units of bandwidth. However, in the case of node 3 failure, link $\{B, 2\}$ must have 2 units of bandwidth to recover the connection between node 2 and 1. Therefore, due to the fact that $\{B, 2\}$ will be activated when either node 1 or 3 fails, we assign this link a bandwidth demand of 2, which is the maximal among the bandwidth demand in both cases.

B. K-Redundant scheme[18]

In K-Redundant scheme, K (K equals to the number of critical nodes) in number of backup virtual machines which are added to the original virtual network; here, unlike the 1-Redundant scheme, in which a backup node connects to all primary virtual nodes, each backup node in K-Redundant only connects to the neighbors of the primary node it protects. In other words, each primary node is assigned a backup VM, and this backup VM also has virtual links connecting all its neighbors. Figure 2.2(c) shows an example of a K-Redundant design, where the given VN in Fig. 2.2(a) is provisioned with 3 backup nodes. $B1$, $B2$ and $B3$; they are assigned to replace VM 1, VM 2 and VM 3 respectively. As each backup node protects one primary VM only, the computational resource which needs to be reserved is equal to the CPU requirement of the corresponding primary VM, rather than the max of the CPU demand of all VMs as in the 1-Redundant. For example, in 2.2(c), backup node B_1 only needs to reserve 3 units of CPU, as it only protects node 1. Moreover, since backup nodes do not require to connect to all VMs, it is more flexible in the embedding phase. However, since more VMs are used in this solution, the amount of reserved CPU units will always be higher than 1-Redundant solution.

C. Current Redesign scheme Limitations

So far, research work that address the SNVE problem considering single node failure always emphasise on the SVN mapping solutions, and pay less attention on

the survivable redesign phrase of VN requests. In fact, the SVN design is an important factor that could decide the cost of a VN request. However, most existing literature simply apply either the 1-Redundant or the K-Redundant scheme.[16]. No research, however, has a clear SVN redesign method, that is able to specify the exact number (n, $1 \leq n \leq K$) of backup nodes of a given VN should have and how are they connecting to the original VN in a cost-efficient way. In this thesis, an SVN redesign algorithm is introduced in Chapter 3, in order to address this issue.

2.2.3 Resource Sharing techniques

After provisioning VN requests with redundant resources at the VN level, the obtained SVN will be required to be embedded onto the substrate network. However, as redundant node(s) and link(s) are added to the VN, they may consume large amount of physical resources. As a consequence, the entire SVN may be rejected by the cloud operator, due to insufficient bandwidth and computational resource. Hence, it is very important to explore the opportunities of sharing backup resources, as a mean to increase the network availability. In fact, recent research[34] shows the data transfer and exchange between VMs count for 80 % of the total traffic in a data center. Thus, by sharing the bandwidth capacity between VMs, we may reduce the traffic congestion within a data center, and eventually boost the VN requests admission. In this subsection, two bandwidth sharing techniques are introduced.

A. Backup Sharing[18]

To explore bandwidth sharing, we first identify a working-group, denotes as $WG(v)$ and a backup-group $BG(v)$ for each VM $v \in N_v$. A working-group $WG(v)$ contains virtual links that are connecting VM v itself and its neighbors. For instance, in Figure 2.3, $l_{\{v1,v2\}}$ and $l_{\{v2,v4\}}$ are the working-group of virtual node $v2$. A backup-group $BG(v)$ represents the set of virtual backup links that are going to

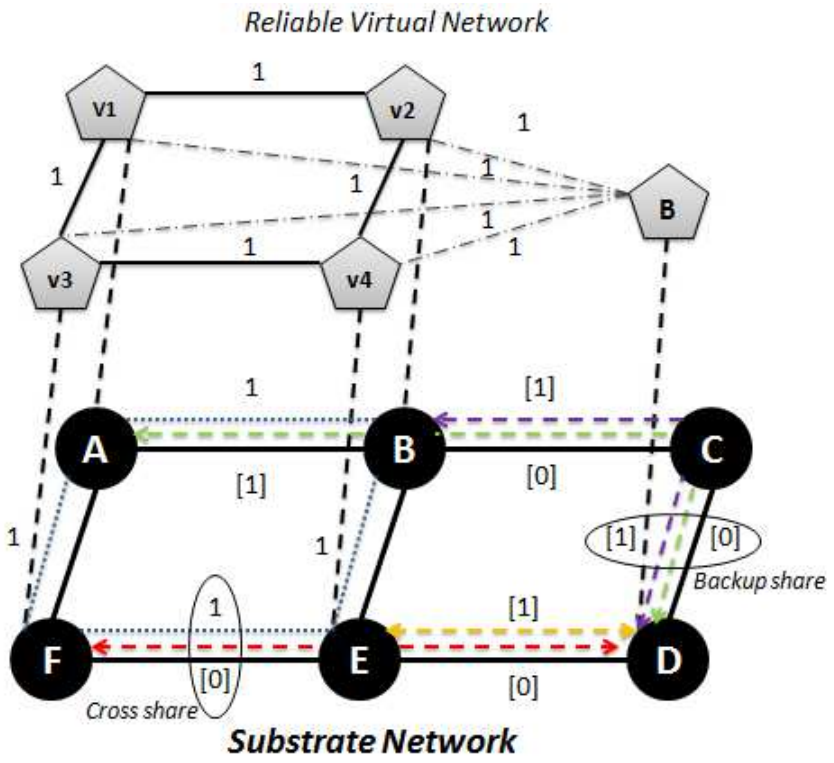


FIGURE 2.3: Resource Sharing techniques in SVN embedding phrase

be activiated after the failure of node v. They are usually connecting v's backup VM and v's neighbors [18]. In Fig. 2.3, the backup-group of VM $v4$ has link $l_{\{v2,B\}}$ and $l_{\{v3,B\}}$. Upon the failure of $v4$, it migrates to VM B and continues communicating with $v2$ and $v3$ via $l_{\{v2,B\}}$ and $l_{\{v3,B\}}$.

Given the backup-group of each virtual node, it is obvious that links in different backup-groups will not be activiated at the same time, as we only consider single node failure. Hence, if the mapping of the virtual links in different backup-groups have common substrate links, the bandwidth resource reserved on that specific physical link can be shared, and only the maximal amount needs be allocated. In Figure 2.3, $l_{\{v1,B\}}$ is in $BG(v2)$ and $BG(v3)$, whereas $l_{\{v1,B\}}$ can be in the backup-group of $v1$ and $v4$. Therefore, those two virtual links will never be activated simultaneously, thus upon the link mapping, $l_{\{v1,B\}}$ and $l_{\{v2,B\}}$ pass through two common substrate links $l_{\{D,C\}}$ and $l_{\{C,B\}}$, on which the reserved bandwidth can be shared. Therefore, we allocate only 1 unit of backup bandwidth on substrate links $l_{\{D,C\}}$ and $l_{\{C,B\}}$, whereas without sharing 2 units must be reserved on them.

We denote such type of sharing "backup share"[18].

B. Cross Sharing[18]

Upon the failure of a facility node, the VM(s) running on top of this node will fail as well, and the communications between this VM and other VMs in the same virtual network are disconnected. As a result, there will be some bandwidth released from those disconnected communications which then can be reused by the backup virtual links, only if the disconnected virtual primary links are in $WG(v)$ and the backup virtual links are in $BG(v)$. For instance, in Figure 2.3, $l_{\{v3,v4\}}$ and $l_{\{v3,B\}}$ are in $WG(v4)$ and $BG(v4)$ respectively, so the failure of $v4$ will disconnect $l_{\{v3,v4\}}$, which is mapped on substrate link $l_{\{E,F\}}$; the amount of bandwidth reserved on it will be released, and since $l_{\{v3,B\}}$ will be activated after the failure, the released 1 unit of bandwidth on substrate link $l_{\{E,F\}}$ can be reused by $l_{\{v3,B\}}$, therefore, there is no need to provision backup on $l_{\{E,F\}}$. We classify such bandwidth sharing stragegy as "cross share"[18].

C. Current Resource Sharing Methods Limitations

In existing SVNE solutions, resources sharing normally happens in the embedding phase, and is encouraged throughout the whole process, in both node mapping and link mapping. To achieve optimal solution for the embedding problem, one must add both cross share and backup share as constraints to reduce the mapping cost. The mapping of both primary and backup resources would be decided with the objective of maximizing shared resources. This attempt puts the SVN embedding into an awkward position, as the SVN intends to be embedded in a way that the shared resources are maximized; on the other hand, the resources can only be shared once the mapping solution are given. This fact slows down the execution of the SVNE solutions. Therefore, the challenge is to find a time-efficient search technique that utilizes resources sharing as much as possible. Hence, a prognostic

SVN redesign technique "ProRed" is proposed in this thesis, the highlight of this technique is its ability to consider the resource sharing while augmenting backup resources to the original VN, as if the redundant resources in the output SVN can "predict" sharing at the virtual level. Consquently, upon the embedding phase, the sharing does not need to be involved, and solutions can be found rapidly.

2.3 Multicast Virtual Network

One-to-many communication is quite common in multiple applications and services hosted in cloud data center networks [35–41]. For instance, High Performance Computing[1] (HPC) applications often need to distribute a large amount of data from storage to all compute nodes [39]. Web-search services are another example of multicast services that consist of redirecting incoming search-queries to a set of indexing servers [44]. Further, bandwidth-hungry Distributed File-Systems (DFS) are common data center applications [37], [45], [46]. DFS divides files into fixed-size chunks to be replicated and stored in different servers for reliability [35], [37]. Moreover, multicasting can be employed for the distribution of executable binaries among participating servers in map reduce-like cooperative computation systems [35], [36].

Services with a one-to-many communication mode can be easily treated as unicast by replicating the transmission to each receiver, or as broadcast by flooding the data throughout the network [47]. However, if the multicast of data is occurring in high volumes (e.g. HPC applications), then replacing these multiple unicast messages by a single multicast message can incur great benefits in terms of reducing the computation efforts at the source node, greatly shrinking bandwidth consumption in the network, and subsequently increasing the application's throughput and enhancing its response time. Similarly avoiding the use of broadcasting can alleviate unnecessary processing to detect and reject irrelevant traffic from nodes

[1]HPC applications are conventionally employed in distributed parallel computers such as supercomputers and grid-computing. However, the emergence of cloud computing has triggered significant attention around the possibilities of migrating HPCs to the cloud [42, 43].

outside the multicast group. Hence, for network operators that host multicast services with heavy traffic, it is imperative to have efficient multicast support in their data center networks.

IP Multicast [48] is the traditional implementation of multicast in the Internet. However, this former suffers from many limitations which have inhibited its ubiquitous use. These limitations are mainly concerns of security, scalability, and flow control [49]; many of which have been alleviated and tackled in data center networks owing to the emergence of Software Defined Networks (SDNs) [49]. SDN provides a vantage point to network and applications information, allowing the detection and handle of diverse service classes with distinct QoS requirements (i.e. delay-sensitive multicast services). Further, it enables the support of multicast in commodity-switches that lack built-in support. This emerging networking paradigm has surpassed the mere potential to enable multicast in data center networks, rendering a fertile ground to innovate and enhance its adoption.

To this extent, multicast in data center networks has become a prominent research topic [35, 37, 40, 41, 49–51], with particular attention to the resource allocation problem of MVNs [40, 41, 50, 51]. The former consists of allocating physical resources to the Virtual Machines (VMs) running a tenant's service, and routing the traffic flow between them via substrate paths. In the case of a multicast service, this embedding problem differs from the classical (unicast) VNE problem in many aspects; mainly, a multicast VN comprises two types of virtual nodes (machines): the multicast source node and a set of multicast recipient nodes (terminals). The traffic flow routing now consists of building a multicast distribution tree between the multicast source and terminals in order to avoid redundant traffic. Also, multicast services that involve real-time communication entail stringent QoS requirements, such as end-delay and delay-variation constraints. Another QoS requirement that both unicast and multicast VNs share is a demand for reliability guarantees; that is a reassurance that the hosted service will remain up and running despite any network component failure. Failure in the physical infrastructure is common due to a multitude of reasons [52] that can affect one or many network component. In fact, it can either attain a facility node (servers), a network node

(e.g. router/switch), or a substrate link.

Although the problem of survivable unicast VNs has been widely discussed [33], the impact of failure on multicast services differs in several aspects, which ultimately inhibit the applicability of existing unicast protection schemes. Indeed, in this case, restoring a failed service component is not solely restricted to finding a backup that matches the failed component's resource demands, but also to connect this backup to the rest of the multicast service while satisfying its QoS requirements, and maintaining a low cost distribution tree. Therefore, this work is dedicated towards studying the problem of reliable MVNs in failure-prone data center networks, and propose a novel post-failure restoration scheme with tree maintenance. Our work is different from the relevant literature [40], since our proposed protection scheme capable of restoring MVNs against any single facility node or substrate link failure. Further, our tree maintenance component guarantees that the restored solution maintains a low cost tree that respects the delay constraints of the restored MVN services. Our numerical results prove that our suggested approach outperforms existing protection schemes in terms of achievable long-term revenue.

In Chapter 4, an effort has been put on embedded multicast virtual networks considering the case of single node failure.

Chapter 3

Survivable Virtual Network Redesign and Embedding

3.1 Introduction

Network virtualization is a key enabler of the multi-tenancy concept [25], where multiple network architectures and services can run on top of the same physical infrastructure. With network virtualization, the problem of allocating resources to the various tenants emerges as a challenging problem. This problem is formally known as the Virtual Network Embedding problem (VNE), which is proven to be NP-Hard [4]; therefore, numerous efforts have been devoted towards inaugurating effective heuristics for solving it [19, 20, 53–55]. The main weakness in these suggested approaches, in addition to the lack of a guarantee on the quality of the obtained solution, is that they assume that the physical infrastructure is available at all times, which renders most of the work in the area of VNE inapplicable in scenarios where network component failures can occur. Failures in the physical infrastructure are common due to a multitude of reasons [56]. In fact, the year 2013 has witnessed multiple cloud outages[57]; one of which got hold of the famous Amazon's EC2 cloud, causing 5 million dollars in revenue loss for a single hour of

offline time. With millions of dollars at stake, attention converged towards solving the Survivable Virtual Network Embedding problem (SVNE) [6, 7, 14–18, 31]. Given that the SVNE problem is a variation of the VNE problem, it is also NP-Hard. Hence, most of the relevant literature relax the problem by targeting one network component failure type: facility node failures, network node failures, or link failures, as illustrated in Figure 2.1. Some further simplify the problem by considering that a single network component can fail at any given point in time.

In this Chapter, we consider the case of single facility node failures. When a facility node fails, the hosted virtual node(s) needs to migrate to a backup facility node, as well as its associated connections to other virtual nodes belonging to the same virtual network (VN). One way of achieving this failure recovery is by redesigning the VN request into a Survivable VN (SVN), and then mapping the resultant SVN onto the physical network. This redesign consists of augmenting the original VN with backup nodes. Each backup node is in charge of protecting one or many primary nodes. Hence, backup virtual links must be established between each backup node and the neighbors of the primary nodes it protects. Upon the failure of a facility node which hosts a virtual node v, v will migrate to its associated backup node, which will then resume the communication with v's neighbors. The augmented backup virtual nodes and links need to be provisioned with sufficient computing and bandwidth capacity to recover from any facility node failure.

The survivable redesign technique encloses multiple challenges. Chief among these challenges is deciding how many backup nodes to use and how to allocate these backup nodes to the primary nodes in each VN such that we minimize the backup footprints in the substrate network. This problem is of paramount importance since these provisioned resources will remain idle until failures occur. Hence, over-provisioning can greatly impact the network's ability to admit future requests. Indeed, the cost-efficient survivable redesign problem against single facility node failures has recurred multiple times in the literature [16], [18], [14], [15]. However, in all of the previous contributions, the number of backup nodes is fixed to either

1 or k, k being the number of critical nodes in a given VN. In addition, to circumvent the inconvenience of idle resources, these latter introduce various backup resource sharing opportunities which can be exploited in the substrate network upon mapping the resultant SVN. In this Chapter, we argue that fixing the number of backup nodes to either 1 or k could yield infeasible or even costly mapping solutions. We provide several motivational examples to support our proclamation. Moreover, we observe that all of the aforementioned redesign techniques are agnostic to the backup resource sharing in the substrate network, where this responsibility is delegated to the adopted mapping algorithm. This is problematic, since given that the SVNE is NP-Hard[4], adding more constraints for backup resource sharing will surely yield a more complex model. Hence, the existing literature solve this problem by relaxing the SVNE algorithm [6, 7, 14–18, 31]. For instance, by solving the virtual node mapping and virtual link mapping disjointly [6], [16], [7], [17], [14], [15] or by performing the primary and backup mapping in a sequential fashion [6], [31], [18], [14]. Multiple other decomposition schemes can be applied; however, it is these very same relaxation techniques that sacrifice the quality of the obtained solution. This results in costly embedding solutions that are incapable of exploiting backup resource sharing in the substrate network, and lead to a substantial amount of backup idle resources that limit the cloud provider's long term revenue.

In light of the above, we introduce Pro-Red; a novel prognostic redesign approach that explores the space between 1 and k and promotes backup resource sharing at the VN level. Hence, it alleviates this concern from the embedding algorithm and achieves cost-efficient SVNs using abridged mapping techniques. Pro-Red adopts a unique approach for the redesign; not only does it determine the augmented number of backup nodes and their connections to the primary nodes, but also their actual positioning in the VN such that it minimizes the provisioned cost at the substrate level. Hence, its prognostic property lays in its ability to foretell the backup resource sharing at the VN level, prior to the embedding phase. Our numerical results prove that our suggested approach yields significant gain in terms of increasing the substrate network's admission rate, decreasing the amount of idle

bandwidth in the substrate network, and boosting the overall revenue of the cloud provider.

In this Chapter, we focus on the case of single facility node failure. Our work is different since mainly we prove that while existing techniques tend to fix the number of back-up nodes to either 1 or k, in this Chapter we present firm motivational examples that prove that in many cases the 1 or k redundant schemes can yield infeasible or costly mapping solutions. Hence, we introduce a novel redesign technique that is capable of exploring the space between 1 and k. Further, while all of the existing work employs backup-sharing during the embedding phase, we swerve from this conventional approach and take the backup-sharing to the VN level by designing SVN with inherit back-sharing properties. This allows us to embed the SVN as a VN without the complication of backup-sharing concerns that surely yield a more complex mapping.

The rest of this Chapter is organized as follows: Section 2.2.1 is dedicated for highlighting related work in the literature. In Section 3.2, we formally present the SVN redesign problem for single facility node failure. Section 3.3 presents firm motivational examples that prove the misfits of conventional redesign techniques. In Section 3.4, we introduce the theocratical foundation of Pro-Red, and then present its step-by-step procedural details. Section 3.5 introduces our SVN embedding model that complements the features of Pro-Red. Section 3.6 is dedicated for the numerical results. We conclude this Chapter in Section 3.7.

3.2 Problem Definition

1. **The Substrate Network :** We represent the substrate network as an undirected graph denoted by $G^s = (N,L)$, where N is the set of substrate facility nodes, and L is the set of substrate links. Facility nodes are connected to the network via network nodes (routers/switches). Each substrate facility node n

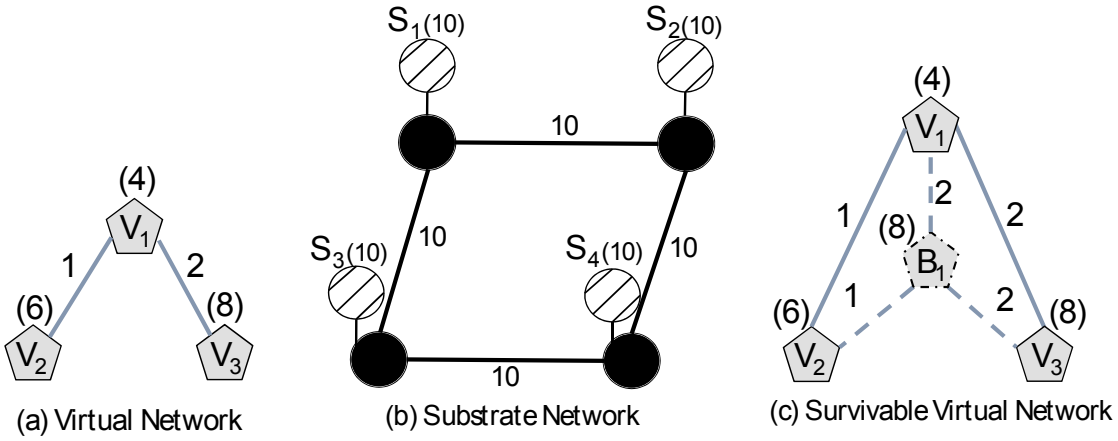


FIGURE 3.1: Substrate Network and Virtual Network Representation

$\in N$ is associated with a finite computing capacity, denoted by c_n. Similarly, each substrate link $l \in L$ has a finite bandwidth capacity, denoted by d_l. Figure 3.1 illustrates a substrate network with 4 facility nodes, each with a CPU capacity of 10 units (represented by the number in parenthesis above each facility node). Similarly, we observe that the substrate links interconnecting the network nodes exhibit 10 units of bandwidth capacity each (represented by the number in parenthesis above each substrate link).

2. **The Virtual Network (VN) :** A Virtual network represents a client's request to deploy an application in a cloud data center. It consists of a set of virtual nodes (virtual machines), interconnected with virtual links. The virtual links correspond to the communication requirements between the virtual nodes in a given VN request. We denote a VN as a virtual graph $G^v = (V,E)$, where V represents the set of virtual nodes, each with a CPU demand of c_v, and e is the set of virtual links, each with a bandwidth demand of d_e. Figure 3.1 shows an example of a VN request with 3 virtual nodes and links, in addition to their associated CPU and bandwidth demands, respectively.

3. **Problem Definition 1:** Given the VN request, the SVNE problem aims to map this request onto the substrate network while providing survivability against single facility node failures. This can be done by redesigning the VN request into an SVN, which consists of augmenting the VN with backup nodes and provisioning enough bandwidth and CPU resources to recover from any

facility node failure. The problem of designing reliable VNs encloses two major concerns: First, deciding how many backup nodes are needed to protect a given VN, and second, determining which backup node will be in charge of protecting which set of critical nodes. These two concerns highly depend on the substrate network capacity. On one hand, provisioning a high number of backup nodes and links greatly decreases the substrate network's admission rate, since these resources will remain idle until failure occurs. On the other hand, limiting the number of backup nodes to a pre-determined constant may yield infeasible mapping solutions. Hence, finding the optimal design of reliable VNs consists of finding the tradeoff between the amount of backup resources provisioned and the efficient utilization of the substrate network. The SVN redesign problem can thus be formulated as follows:

Problem Definition 2. *Given a substrate network $G^s = (N, L)$, and a VN request G^v = (V,E), Find the optimal redesign d of the given VN request G^v into a reliable VN (SVN), such that the amount of backup idle resources in the substrate network is minimized, while guaranteeing survivability against single facility node failure.*

One way to solve the problem is by enumerating all possible designs $d \in D$, where each d can contain between 1 to k backup nodes. For any given i ($2 \leq i \leq k$), there could exist multiple designs d. These designs are represented by the different ways the V virtual nodes are divided into i clusters, where each cluster is protected by a single backup node. This is similar to the various ways n distinct objects can be distributed into m different bins with k_1 objects in the first bin, k_2 in the second, etc. and $k_1 + k_2 + ...k_m = n$. This indeed is obtained by applying the multinomial theorem where $\sum_{k_1+k_2+...+k_m=n} \binom{n}{k_1+k_2+...+k_m} = m^n$. Therefore, for V virtual nodes and i backup nodes, there are $|V|^i$ different mapping designs. Once the set of all possible designs d is enumerated, it can be fed to an ILP model to determine the optimal design d that achieves the lowest amount of backup idle resources in the substrate network. It is important to note that in order for the model to determine the optimal design, it requires to solve the SVNE for each

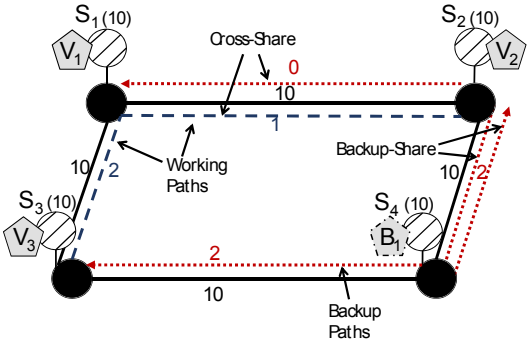
design d; this renders the problem NP-Hard.

In this regard, we reformulate the problem to seek a redesign approach that promotes backup sharing in the substrate network, hence it is inheritably capable of minimizing the backup footprints. In section 3.4, we introduce a heuristic-based redesign approach that renders such prognostic SVNs.

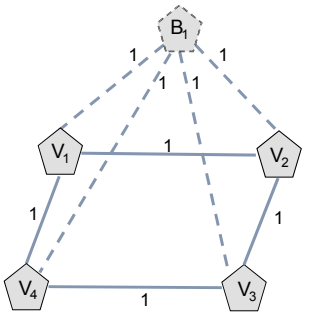
3.3 The SVN Redesign Problem

3.3.1 Limitations of Conventional VN Redesign Techniques

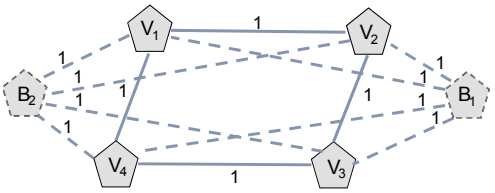
One of the most commonly adopted redesign techniques for recovery against single node failure are formally known as the 1-redundant and k-redundant schemes. In the case of the 1-redundant scheme, the VN request is augmented with a single backup node that needs to be connected to the neighbors of each critical node via backup virtual links. Next, the resultant SVN is embedded onto the substrate network while forcing the primary and backup nodes in a given SVN to occupy distinct substrate nodes. This ensures that a single substrate node failure will not affect more than one virtual node in the same VN request. Figure 3.2(c) illustrates the case where the VN request presented in Figure 3.2(a) is augmented with a single backup node b_1, as per the 1-redundant scheme. The backup node must be provisioned with the maximum CPU demand of all the critical nodes, so it can assume any single facility node failure. Hence 8 units of CPU is reserved on backup node b_1. Moreover, for each backup virtual link connecting b_1 to any critical node v, it is sufficient to reserve the maximum bandwidth demand on v's adjacent links, since backup link (b_1,v) will only be activated upon the failure of one of v's neighbors. For example, the backup link (b_1,v_1) will only be activated in the case where virtual node v_2 or v_3 fails. In the case where v_2 fails, 1 unit of bandwidth is required to resume the communication on backup link (b_1,v_1). Similarly, in the case where v_3 fails, it will also migrate to b_1 and communicate



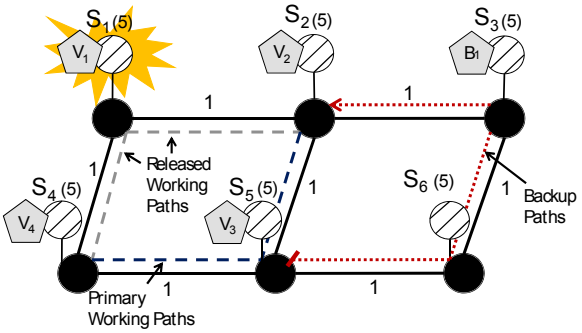
(a) Backup Resource Sharing



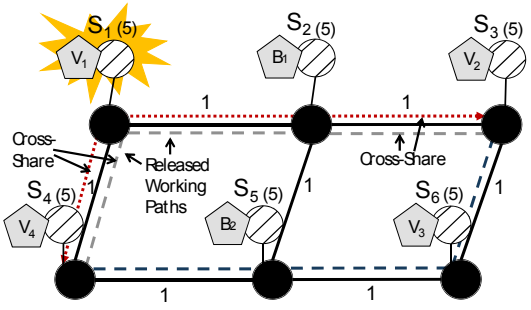
(b) 1-Redundant SVN



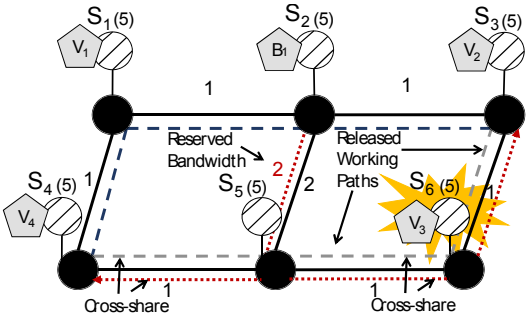
(c) 2-Redundant SVN



(d) 1-Redundant SVN Embedding Solution (1)



(e) 2-Redundant SVN Embedding



(f) 1-Redundant SVN Embedding Solution (2)

FIGURE 3.2: Designing and Embedding Reliable VNs

with v_1 with 2 units of bandwidth. Given that at any point in time either v_2 or v_3 would fail, it is sufficient to reserve 2 units of bandwidth on the link connecting b_1 to v_1. The set of backup links that are activated simultaneously upon the failure of a virtual node v are denoted as the Backup-Group of v ($BG(v)$) [18]. For instance, the $BG(v_1)$ contains backup links (b_1,v_2) and (b_1,v_3). Similarly, the backup group

of $BG(v_2)$ and $BG(v_2)$ is (b_1,v_1).

Now, for the k-redundant scheme, the VN is augmented with k backup nodes, where k represents the number of primary critical nodes. In this case, each backup virtual node protects a single primary node, and hence it only connects to its neighbors via backup virtual links. Each backup node along with its associated backup links will be provisioned with the same amount of resources as the primary node it protects and its adjacent links, respectively.

When a facility node fails, only the affected node will be disconnected from the substrate network. However, its adjacent network node and substrate links will remain active and capable of routing traffic. Thus, upon the failure of a facility node that hosts a virtual node v, the bandwidth on the original working paths that connect v to its neighbors in the substrate network will be released, and hence becomes available. This released bandwidth can thus be reused by the corresponding backup paths of v's backup node. Such type of sharing is known as $cross - sharing$ [18] between working and backup paths. Each virtual node v is associated with a working-group ($WG(v)$) that contains the set of v's working paths. For instance, the $WG(v_1)$ contains (v_1,v_2) and (v_1,v_3). Hence, the $BG(v_1)$ can reuse the bandwidth of the $WG(v_1)$ upon v_1's failure through cross-sharing. Moreover, given that a single node might fail at any point in time, the backup paths belonging to different backup groups can share their bandwidth in the substrate network. Such type of sharing is referred to as $backup - sharing$ [18]. Figure 3.2(a) shows a mapping solution for the 1-redundant SVN presented in Figure 3.2(c) over the substrate network in Figure 3.2(b). We observe that for backup link (b_1,v_3), 4 units of bandwidth needs to be reserved, since the substrate links that route this backup path do not overlap with any other appropriate backup or working paths. However, backup paths (b_1,v_1) and (b_2,v_2) overlap over substrate link $\{s_2,s_4\}$; and given that these backup paths belong to distinct backup groups, only 2 units of bandwidth need to be reserved on substrate link $\{s_2,s_4\}$, rather than 3 due to backup-sharing. Moreover, backup path (b_1,v_1) further overlaps with working path (v_1,v_2) on substrate link $\{s_1,s_2\}$; hence 0 units of bandwidth needs to be reserved on this substrate link via cross-sharing.

The problem with the 1-redundant and k-redundant schemes is that by forcing the number of backup nodes to be either 1 of k, we may end-up with infeasible or costly mapping solutions. This is due to the fact that the substrate might not have enough bandwidth capacity to route the traffic between 1 backup node to the neighbors of all critical nodes, in the case of the 1-redundant scheme. Whereas, in the case of the k-redundant scheme, a substantial amount of CPU resources remain idle until a failure occurs, since k-redundant requires as many backup nodes as primary critical nodes, not to mention the large number of backup virtual links needed to associate each backup node with its appropriate primary critical node. This motivates the need for a cost-efficient redesign technique that is capable of exploring the space between 1 and k, and finding the balance between the amount of provisioned CPU and bandwidth to yield feasible and cost-efficient embedding solutions.

3.3.2 Illustrative Example

To further illustrate the inconvenience of the conventional redesign techniques, consider the case of a 4 nodes VN in Figure 3.2, where each virtual node is considered to be critical. Using the 1-redundant scheme, we augment this VN with a single backup node, connected to the neighbors of all critical nodes via backup virtual links, as illustrated in Figure 3.2(b). Now, consider a substrate network with 6 facility nodes interconnected via substrate links, each with a bandwidth capacity of 1 unit, as shown in Figure 3.2(d). Given the 1-redundant SVN, there exist no feasible mapping solutions on the aforementioned substrate network. For instance, consider embedding the SVN using the mapping solution illustrated in Figure 3.2(d). When the substrate node s_1 fails, the virtual node v_1 migrates to b_1 which needs to communicate with virtual nodes v_2 and v_4. b_1 is capable of reaching virtual node v_2 through path $\{s_3 \rightarrow s_2\}$. However, the substrate network's capacity, with the current embedding solution inhibits b_1 from reaching node v_4, since the working path of $\{v_3\text{-}v_4\}$ remains operational, occupying the 1-unit of

bandwidth on the substrate link $\{s_4\text{-}s_5\}$. This renders the embedding solution illustrated in Figure 3.2(d) infeasible. By examining all possible mapping solutions of the 1-redundant SVN on the given substrate network, we find that they are all infeasible. This is because the 1-redundant scheme connects a single backup node to the neighbors of all critical nodes. Hence b_1's bandwidth demand along with the given substrate network capacity, inhibits b_1 from protecting this VN against any single node failures.

On the other hand, consider the case where the aforementioned VN is augmented with 2 backup nodes b_1 and b_2, as shown in Figure 3.2(c). b_1 assumes the failure of critical nodes v_1 and v_2, and b_2 replaces v_3 and v_4 in case any of them failed. Upon embedding the resultant SVN, we notice that this reliable design does indeed yield a feasible solution and requires 0 units of reserved bandwidth due to cross-sharing, as illustrated in Figure 3.2(e). For example, consider the case where the facility node s_1 fails; subsequently, v_1 will migrate to b_1, and that latter needs to resume v_1's communication with v_2 and v_4. The failure of virtual node v_1 leads to the release of the active bandwidth on working paths $\{s_1\text{-}s_2\}$ and $\{s_1\text{-}s_4\}$ connecting virtual node v_1 to v_2 and v_4, respectively. The released bandwidth will be reused by b_1 to reach v_2 and v_4 through cross-sharing. By employing cross-sharing for all other virtual node failures in the given VN, we can conclude that indeed the 2-redundant SVN requires 0 unit of reserved bandwidth.

Further, consider the same substrate network, where link $\{s_2 \rightarrow s_5\}$ has a capacity of 2 units, as illustrated in Figure 3.2(f). In this case, we can indeed find a feasible embedding solution for the 1-redundant SVN with a provisioned bandwidth cost of 2 units, whereas the 2-redundant scheme still requires 0 units of provisioned bandwidth.

These motivational examples prove our proclamation that by forcing the number of backup nodes to be either 1 or k, we might end up with infeasible or costly mapping solutions. Whereas when we augment the VN with i $(1 \leq i \leq k)$ backup nodes ($i = 2$ in the above example), we achieve a balance between the amount of backup bandwidth and CPU that needs to be reserved. In fact, this balance yields a feasible solution, when the 1-redundant and k-redundant fail to find one.

This motivates the need for a redesign approach that is capable of finding that balance, rather than being fixed to either 1 or k backup nodes. By exploring the space in the range between 1 and k, we can obtain lower-cost mapping solutions, and increase the network's admissibility. This is one of Pro-Red's unique capabilities. Another advantage of Pro-Red is that it redesigns the VN in a way to promote the backup bandwidth sharing at the substrate network. In the next section we present Pro-Red's theoretical foundation that enables it to fulfil these two promises.

3.4 Prognostic Redesign Approach (Pro-Red) :

3.4.1 Theoretical Foundation

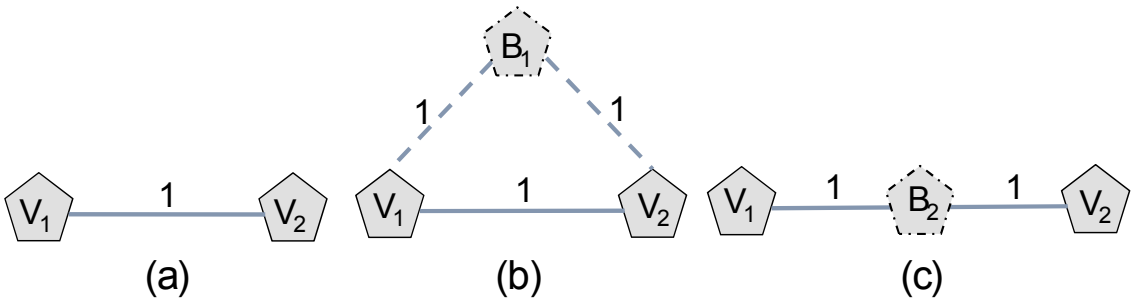


FIGURE 3.3: Theoretical Foundation

In this section, we present the theoretical foundation on which Pro-Red's redesign technique is established. We begin our explanation with a motivational example: Consider a 2 nodes VN illustrated in Figure 3.3(a). Augmenting the VN with a single backup node, using the 1-redundant scheme, requires 2 units of reserved bandwidth (as shown in Figure 3.3(b)). By employing an effective embedding approach, this estimated bandwidth cost could be minimized at the substrate network level via cross-sharing and backup-sharing. Observe, however, that by placing this backup node along the path connecting v_1 and v_2, the resulting SVN will require 0 additional units of bandwidth once embedded into the substrate network. This is due to the fact that by placing the backup node in between its associated primary nodes, we force the primary path that routes the traffic

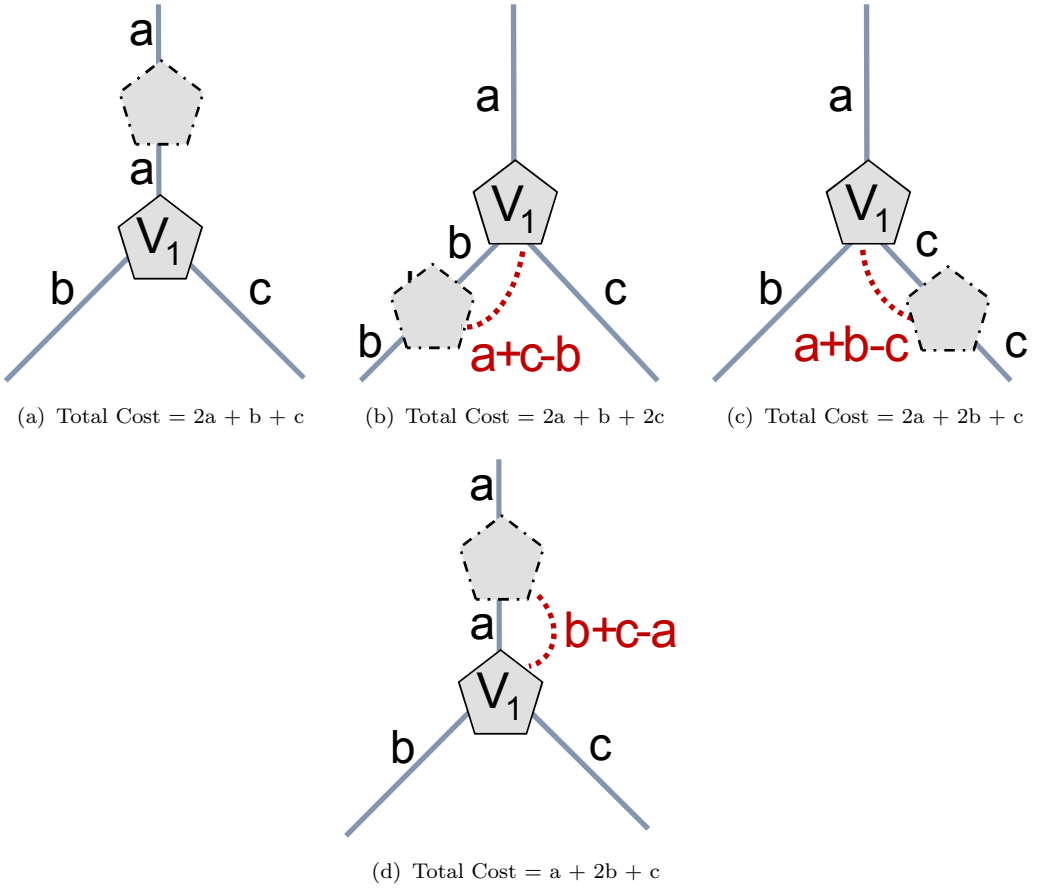
between v_1 and v_2 in the substrate network to pass through b_1 [1]. Subsequently, if either one of these primary nodes fail, the backup node will cross-share (reuse) the released primary bandwidth. It should be noted here that this redesign approach is indeed prognostic to backup resource sharing, as it is able to predict (promote) the cross-sharing (bandwidth reuse) at the VN level. Indeed, throughout our numerical results, we show that Pro-Red achieves considerable gains in terms of reducing the total bandwidth cost against the conventional redesign techniques, and greatly decreasing the network's blocking ratio.

We build on this motivational example to formulate a novel redesign technique that determines the location of backup nodes in the VN, such that cross-sharing and backup-sharing can be fully exploited in the substrate network. Placing the backup node between every two virtual nodes is definitely costly in terms of idle CPU resources. Hence, we resort to clustering a subset of virtual nodes into distinct sets, where nodes in a particular set are covered by a single backup node. In each set, the backup node is positioned such that the maximum amount of backup resource sharing is guaranteed upon the embedding. This clustering technique can thus create a balance between the amount of provisioned backup nodes and links. To create a set, we begin by selecting the virtual node with the highest degree. This allows a larger number of primary virtual nodes to be clustered within a single set, which can substantially decrease the amount of reserved CPU resources. Once the starting node is identified, we place the backup node on the adjacent link with the highest bandwidth demand, which guarantees the most backup resource sharing. To support this analysis, consider the following example illustrated in Figure 3.4. Let v_1 be the node with the highest nodal degree 3. Its adjacent links have a bandwidth demand of a, b and c respectively. We assume (without loss of generality) :

$$a > b + c > b > c \tag{3.1}$$

In order to protect V_1, we need to place a backup node on one of its adjacent links. In this case, we have 3 different scenarios, we can either place the backup node on

[1] Note that once a backup node is placed between v_1 and v_2, the associated working path connecting v_1 and v_2 in the substrate network will be routed differently.



(a) Total Cost = 2a + b + c (b) Total Cost = 2a + b + 2c (c) Total Cost = 2a + 2b + c

(d) Total Cost = a + 2b + c

FIGURE 3.4: Designing Reliable VNs

the link with bandwidth demand a, b, or c. These different scenarios are illustrated in Figure 3.4(a), 3.4(b), and 3.4(c), respectively. Notice that in the case where the backup node is placed on the link with the highest bandwidth demand a (shown in Figure 3.4(a)), 0 units of reserved bandwidth is needed. In fact, by placing the backup node on this former link we can always achieve the lowest total cost, since upon failure the backup node is able to reach all of v_1's neighbors by fully reusing the released bandwidth through cross-sharing. Whereas, by placing the backup node on the link with bandwidth demand b (shown in Figure 3.4(b)) additional bandwidth needs to be reserved in order to reach v_1's neighbors. In fact, since $b < a$, the backup node can never reach v_1's neighbor at link a without reserving an additional (a - b) units of bandwidth. The same applies to reach v_1's neighbor at link c, hence an overall (a + c - b) units of bandwidth needs to be reserved. This renders a total cost of ($2a$ + b + $2c$), which is obviously more expensive that the redesign solution presented in Figure 3.4(a). Note that in the case where $a \leq (b$

+ c), and a is the link with the highest bandwidth demand; to place the backup node on link a, a total of (b + c - a) must be reserved, as illustrated in Figure 3.4(d). However, this solution still renders the lowest total bandwidth cost.

3.4.2 Pro-Red Algorithm :

Algorithm 1 Pro-Red: Prognostic Redesign Heuristic

1: **Given** $V(U, E)$ */*Virtual Network Topology*/*
2: */*Set cover flag for nodes and links to false*/*
3: **for** ($u \in U$) **do**
4: $u.covered$ = false;
5: **end for**
6: $C = \{\ \}$; */*Initialize the list of covered nodes*/*
7: **while** ($—C— ¡ U$) **do**
8: $\hat{C} = \{U\}$ - C;
9: **Step 1: Find Starting Node**
10: $v_1 = GetNodeWithHighestNodeDegree(\hat{C})$;
11: $L = GetAllAdjacentLinks(v_1, \hat{C})$;
12: **Step 2: Find Starting Link**
13: $e = GetHighestBW(L)$;
14: $v_2 = GetTheOtherNode(v_1, e)$;
15: **Step 3: Create a new Set**
16: $s = CreateSet(v_1, v_2, e)$;
17: $C = C \cup \{s\}$;
18: **end while**

In this section, we present the SVN redesign heuristic that is founded on the theories and observations presented in Section 3.4.1. The objective of this algorithm is to assign a backup node for each critical node in the given VN topology; we refer to a critical node that is assigned to a backup node as *covered* (or protected). Initially, all the virtual nodes in the VN topology are considered as *uncovered*; hence, we initialize the virtual nodes with a cover flag set to false. Next, we define two new sets C and $\hat{C}$ that are updated at the end of every iteration with the list of covered and uncovered nodes, respectively. The process terminates when C contains all the critical nodes in the VN request. At each iteration, the algorithm creates a single set. We define a set as an ensemble of critical nodes protected by a single backup node. To create a set, we first need to identify a starting point, from which a set will begin and grow. Based on the previous observations presented

in Section 3.4.1, the starting point is defined by node v_1 with the highest nodal degree in the list of uncovered nodes $\hat{C}$, and its adjacent link e with the highest bandwidth demand. Next, the algorithm invokes the *CreateSet* function that returns a set s which contains the critical nodes covered by the newly discovered set.

In Algorithm 2, we highlight the procedural details of the *CreateSet* function. It begins by creating a new backup node b to be placed between the edge nodes (v_1, v_2) of link e. To exploit cross-sharing, link e will be replaced by two backup virtual links $\hat{e_1}$ and $\hat{e_2}$ that position backup node b in between nodes v_1 and v_2. This would force the primary virtual link connecting nodes v_1 and v_2 to be routed through b. Hence, if any one of them failed, the released bandwidth on links $\hat{e_1}$ and $\hat{e_2}$ can be reused by backup node b. Initially, the CPU demand of b is set to the maximum CPU demand of critical nodes v_1 and v_2 (line 6). Also, the bandwidth demand on link $\hat{e_1}$ is set to the sum of the bandwidth demands of v_1's adjacent links, subtracted by the bandwidth demand of link e (line 4), since that latter will be released and cross-shared (reused) upon failure of node v_1. The same applies when assigning the bandwidth demand on link $\hat{e_2}$ (line 5). Subsequently, nodes v_1 and v_2 are now protected (covered) by backup node b. Once this set is established, we need to grow it in order to cover the highest number of adjacent nodes possible without incurring too much additional backup bandwidth. First, we need to include all the adjacent leaf nodes in the set, otherwise leaf nodes will be left uncovered, or would require a dedicated backup node, which is seemingly not cost efficient. To cover leaf nodes, we need to adjust the bandwidth demand on links $\hat{e_1}$ and $\hat{e_2}$, appropriately, with enough bandwidth to assume the failure of any leaf node, as well as the CPU demand of backup node b. Finally, the algorithm will also attempt to cover non-leaf neighbors nodes of v_1 and v_2 using backup-sharing. Meaning, without reserving any additional bandwidth on backup virtual links $\hat{e_1}$ and $\hat{e_2}$. Given a non-leaf neighbor node v' of v_1, if the sum of the bandwidth demand on n''s adjacent links, including link (v',v_1) is smaller than the reserved bandwidth on link $\hat{e_1}$, and excluding link (v',v_1) is smaller than the bandwidth demand on link (v',v_1); further, if (v',v_1) is the link with the highest

Algorithm 2 CreateSet(virtual_node v_1, virtual_node v_2 virtual_link e)

1: $s = \{\}$;
2: **Step 4: Create a new backup node** b
3: $\hat{e_1}$ = new virtual_link(v_1,b);
4: $\hat{e_2}$ = new virtual_link(v_2,b);
5: $setCPU(b,\max(v_1,v_2))$;
6: $d_{\hat{e_1}} = d_{\hat{e_2}} = d_e$;
7: **if** (Sum($GetAdjacentLinksBandwidth(v_1)$) $\geq 2d_e$) **then**
8: $d_{\hat{e_1}}$ = Sum($GetAdjacentLinksBandwidth(v_1)$) - d_e;
9: **end if**
10: **if** (Sum($GetAdjacentLinksBandwidth(v_2)$) $\geq 2d_e$) **then**
11: $d_{\hat{e_2}}$ = Sum($GetAdjacentLinksBandwidth(v_2)$) - d_e;
12: **end if**
13: $v_1.covered = v_2.covered$ = true;
14: $l.covered$ = true;
15: $s = s \cup \{v_1,v_2\}$;
16: **Step 5: Protect Adjacent Leaf Nodes**
17: $T = v_1.getAdjacentLeafNodes()$
18: **while** ($!T.isEmpty$) **do**
19: $t = T$.next();
20: $t.covered$ = true;
21: $s = s \cup \{$t$\}$;
22: $setBW(\hat{e_1},\max(d_{\hat{e_1}},d_{(v_1,t)}))$;
23: $setCPU(b,\max(b,t))$;
24: **end while**
25: Repeat the same while loop for Adjacent leaf nodes of v_2
26: **Step 6: Protect Adjacent non-leaf Nodes**
27: $R.addAll(getAdjacentNonLeafNode(v1))$;
28: $R.addAll(getAdjacentNonLeafNode(v2))$;
29: **while** ($v_1.hasAdjacentNonLeafNodes()$) **do**
30: $r = R$.next();
31: **if** (($2d_{(v_1,r)} \geq$ Sum($GetAdjacentLinksBW(r)$))&&
32: ($d_{\hat{e_1}} \geq d_{(v_1,r)}$ && ($r.hasAdjacentLeafNodes()$ = null)) **then**
33: $r.covered$ = true;
34: $s = s \cup r$;
35: $setCPU(b,\max(b,t))$;
36: **end if**
37: **end while**
38: Repeat at line 21 for v_2
39: **return** s;

bandwidth demand among v''s adjacent links, then v' could be included in v_1's set and subsequently protected by backup node b without incurring any additional backup bandwidth via backup-sharing. Finally, the algorithm returns the set of nodes that are covered by the newly created set s. The *CreateSet* function has a complexity of O(n), which renders the complexity of Pro-Red's redesign heuristic to be O(n^2), since we call the *CreateSet* function for each uncovered node in the VN request.

To further illustrate the enactment of Pro-Red's redesign algorithm, consider the VN topology presented in Figure 3.5(a). The algorithm begins by identifying a starting node and link, which in this case are node v_7 with link $\{v_4,v_7\}$, since they correspond to the node with the highest degree, and its adjacent link with the highest bandwidth demand. Next, a set is created by placing a backup node b_1 on link $\{v_4,v_7\}$, as shown in Figure 3.5(b). This implies that nodes v_4 and v_7 are now protected by backup node b_1. Since the sum of the adjacent links to v_4 (excluding link $\{v_4,b_1\}$) is smaller than the bandwidth on link $\{v_4,b_1\}$, 0 units of bandwidth is required to protect node v_4. When v_4 fails, the bandwidth on the substrate paths that are routing virtual links $\{v_4,b_1\}$, $(b_1,v_7\})$, $\{v_4,v_3\})$ and $\{v_4,v_5\})$ will be released. Now, v_4 will migrate to b_1 and that latter needs to resume v_4's communication with v_3, v_5 and v_7; b_1 will thus reuse 8 units of released bandwidth on the path connecting b_1 to v_7 to reach v_7. Similarly, b_1 will reuse 2 units of released bandwidth on $\{v_4,b_1\}$ and $\{v_4,v_3\})$ to reach v_3, and 3 units on $\{v_4,b_1\}$ and $\{v_4,v_7\})$ to reach v_7.

Now to protect virtual nodes v_7, we observe that the sum of its adjacent links is 12, which implies that 3 additional units of bandwidth must be reserved on link $\{v_7,b_1\}$ in order to protect node v_7. This is because when v_7 fails it migrates to b_1, that latter now needs to go through the path connecting b_1 to v_7 and then cross-share the released bandwidth on the paths connecting v_7 to v_6, v_8 and v_9. Now, given that only 8 units of bandwidth is released on $\{v_7,b_1\}$; hence, 3 additional units must be reserved to fully protect v_7.

Next, the set is grown by adding the adjacent leaf nodes of v_4 and v_7. The only

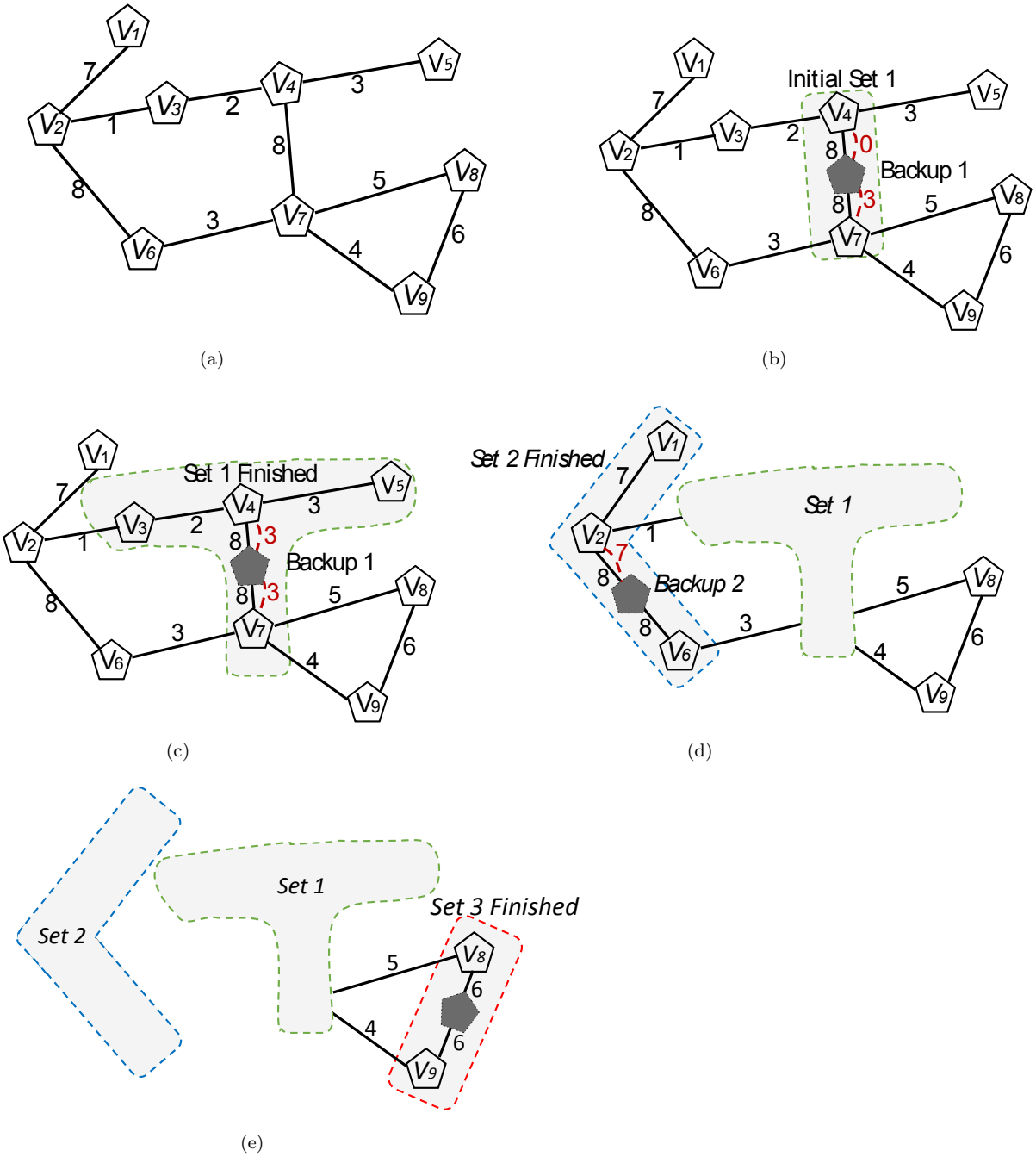


FIGURE 3.5: Step-by-Step SVN Redesign Algorithm.

leaf node found is v_5 which will be added to the set, and subsequently incurs 3 additional units of bandwidth to be reserved on link $\{v_4,b_1\}$. Finally, the potential of adding non-leaf nodes is explored. Indeed, we find that only node v_3 can be added to the set with no additional bandwidth, as shown in Figure 3.5(c). When no additional nodes can be further added to the set, the set becomes saturated.

Subsequently, the *CreateSet* function returns set s_1 with backup node b_1 protecting virtual nodes v_3, v_4, v_5, and v_7, which leaves 5 critical nodes in the given VN uncovered. Hence, a new set is initiated starting with node v_2, since it represents the next uncovered node with the highest nodal degree. The same process repeats, and returns set s_2 with backup node b_2 protecting virtual nodes v_1, v_2, and v_6, as shown in Figure 3.5(d). Finally, set s_3 is created with backup node b_3 covering nodes v_8 and v_9, illustrated in Figure 3.5(e). Once all critical nodes are protected, the algorithm terminates. At the end, we obtain 3 sets with 3 backup nodes protecting 9 critical nodes with only 12 units of reserved bandwidth.

It is important to note that if we were to employ the 1-redundant scheme, then a single backup node b needs to connect to each virtual node; hence a total of 9 backup links are needed. This means that potentially 47 units (sum of all bandwidth demand in the given VN) of bandwidth needs to be reserved to connect b to the virtual nodes. Here, the actual amount of reserved backup bandwidth in the substrate network depends on the quality of the adopted SVNE approach. It can indeed be substantially reduced with a highly-efficient embedding approach that exploits cross-sharing and back-sharing; or it can get aggravated if the backup node was poorly placed far from the primary virtual nodes, requiring multiple hops to reach them. Versus in the case of ProRed, placing the backup nodes along the paths connecting the primary nodes guarantees the predicted cross-sharing that the resultant SVN will enjoy once embedded onto the substrate network.

3.5 The SVN Embedding

Upon obtaining the redesigned VN, the next step is to embed this latter onto the substrate network. Since the SVNE problem is NP-Hard, we adopt a disjoint mapping approach, where we preform the node mapping first and then the link mapping. For the node mapping, we use the VMP algorithm in [16] to find a set of M feasible node mapping solutions. Note both the primary and backup

node placement is performed jointly. For the link mapping, we formulate an ILP model that will select the lowest cost mapping solution $m \in M$, and determine its corresponding link mapping solution. Given our prognostic redesign, our ILP model assumes as input the backup resource sharing identified during the redesign phase. Our link mapping model is thus formulated as follows:

- Parameters:

$G^s(N, L)$: substrate network with N nodes and L links.
$G^v(V, E)$: virtual network with V virtual nodes and E virtual links.
$\hat{E}$: the set of backup virtual links $\hat{e} \in \hat{E}$.
M : the set of all node mapping solutions $m \in M$.
S : the list of constructed sets $s \in S$.

$$\delta_{n,n}^{m} = \begin{cases} 1, & \text{if } v \text{ is mapped onto substrate node } n \text{ in } m, \\ 0, & \text{otherwise.} \end{cases}$$

$$\sigma_{\hat{e}}^{s} = \begin{cases} 1, & \text{if backup link } \hat{e} \text{ belongs to set } s, \\ 0, & \text{otherwise.} \end{cases}$$

$\gamma_{\hat{e}}$: the amount of bandwidth to be reserved on $\hat{e}$.

- Decision Variables:

$$x_m = \begin{cases} 1, & \text{if node mapping solution } m \text{ is chosen,} \\ 0, & \text{otherwise.} \end{cases}$$

$$y_{i,j}^{e,m} = \begin{cases} 1, & \text{if } e \text{ is mapped on substrate link } (i,j) \text{ in } m, \\ 0, & \text{otherwise.} \end{cases}$$

$$y_{i,j}^{\hat{e},m} = \begin{cases} 1, & \text{if } \hat{e} \text{ is mapped on substrate link } (i,j) \text{ in } m, \\ 0, & \text{otherwise.} \end{cases}$$

$t_{i,j}$: the primary traffic mapped on substrate link (i, j).
$\hat{t}_{i,j}$: the backup traffic reserved on substrate link (i, j).

- Mathematical Model:

$$Min \sum_{(i,j)\in L} (t_{i,j} + \hat{t}_{i,j})$$

Subject to

$$\sum_{m\in M} x_m = 1 \tag{3.2}$$

$$y_{i,j}^{e,m} \leq x_m \quad \forall e \in E, m \in M, (i,j) \in L. \tag{3.3}$$

$$t_{i,j} = \sum_{m\in M} \sum_{e\in E} y_{i,j}^{e,m} d_e \quad \forall (i,j) \in L. \tag{3.4}$$

$$y_{i,j}^{\hat{e},m} \leq x_m \quad \forall \hat{e} \in \hat{E}, m \in M, (i,j) \in L. \tag{3.5}$$

$$\hat{t}_{i,j} \geq [\sum_{m\in M} \sum_{\hat{e}:\sigma_{\hat{e}}^s=1} y_{i,j}^{\hat{e},m} \gamma_{\hat{e}} \ \ \forall s \in S] \quad \forall (i,j) \in L. \tag{3.6}$$

$$t_{i,j} + \hat{t}_{i,j} \leq d_l \quad \forall l : (i,j) \in L. \tag{3.7}$$

$$x_m,\ y_{i,j}^{e,m},\ y_{i,j}^{\hat{e},m} \in [0,1] \quad \forall m \in M, e \in E, \hat{e} \in \hat{E}, (i,j) \in L. \tag{3.8}$$

$$t_{i,j},\ \hat{t}_{i,j} \geq 0 \quad \forall (i,j) \in L. \tag{3.9}$$

We aim at minimizing the overall bandwidth cost for the given SVN mapping solution. This encourages the model to select a node mapping solution where the nodes are not too widely spread. Hence, we set the model's objective function to minimize the sum of primary and backup traffic on the substrate links. Two flow conservation constraints are needed to route the primary and backup virtual links. The details of these constraints have been omitted due to space limitation. Constraint (3.2) forces the model to select a single node mapping solution. Constraint (3.3) indicates that a primary link mapping solution will only be constructed for

the chosen node mapping solution. Constraint (3.4) measures the primary traffic routed on every physical link in the substrate network. Constraint (3.5) indicates that a backup link mapping solution will only be constructed for the chosen node mapping solution. Constraint (3.6) measures the backup link traffic routed on every physical link in the substrate network. Notice that for every given link, the amount of backup bandwidth reserved is the max of the sum of backup bandwidth provisioned within each given set. This is because our approach enables backup sharing among the backup virtual links belonging to distinct sets, since these latter will not be activated at the same time. Constraint (3.7) ensures that the sum of the primary and backup bandwidth routed on each substrate link does not violate its capacity.

3.6 Numerical Results

We evaluate the performance of Pro-Red against the 1-redundant and k-redundant schemes for various metrics: Blocking Ratio, Average Cost, Revenue and Execution Time. We adopt two different substrate network topologies to conduct this evaluation. The substrate networks used for our simulation are FatTree (K=4) [25], in addition to a randomly generated network [58] R, with 36 nodes and 48 links. In both these substrate networks, we set the CPU capacity of each host node to 48 units, and the bandwidth capacity on the substrate links is set to 750 units. We perform the redesign and mapping of VNs in an online fashion, upon the arrival of each request. Hence, we assume that the VNs arrival and departure follow a Poisson distribution. The VN requests are randomly generated, where the size of each VN can range between 2 to 8 virtual nodes. Each virtual node can be connected to any other virtual node in the VN request with a probability of 50%. The CPU demand of the virtual nodes is set to be in the range [1:5], and the bandwidth demand on the virtual links is in the range [10:50]. To conduct the comparison with 1-redundant and k-redundant, we employ the same embedding

approach presented in section 3.5; however, we replace Constraint (3.6) with Constraint (10) that performs cross-sharing and backup-sharing [18]:

$$\sum_{m \in M} \sum_{\hat{e}:\in BG(v)} y_{i,j}^{\hat{e},m} \; d_{e:\{v,d(\hat{e})\}} \; - \sum_{m \in M} \sum_{e:\in WG(u)} y_{i,j}^{e,m} \; d_{\hat{e}} \leq \hat{t_{i,j}} \quad \forall \; (i,j) \in E, \; v \in V \quad (10)$$

In all test cases, the results are averaged over 5 runs.

1. **Blocking Ratio :** The first metric we evaluate is the blocking ratio. We vary the load of the poisson process between 4 to 16 and run Pro-Red, 1-redundant and k-redundant over the same distribution and generated VN list. The results are shown in Figure 3.6(a) and 3.6(b). We observe that for FatTree (K = 4), Pro-Red achieves a lower blocking ratio over 1 and k-redundant. This gain is mainly attributed to Pro-Red's ability to explore the space between 1 and k. Since FatTree connects each host node to the substrate network with a single substrate link, this architecture puts 1-redundant at a great disadvantage, as the backup node is forced to go through a single substrate link in order to reach the neighbors of all the critical nodes in a given VN. Indeed, we observe that Pro-Red achieves 51% lower blocking ratio over 1-redundant when the load on the substrate network is equal to 8. Similarly, we observe that Pro-Red achieves 40% lower blocking ratio over k-redundant when the load is equal to 6. Though k-redundant does not concentrate the backup bandwidth load on a single substrate link, its redesign technique requires as many backup nodes as the number of critical nodes in a VN request, which renders a substantial amount of CPU and bandwidth demand to associate each backup node with its corresponding primary virtual node. Whereas Pro-Red maintains a balance between the number of allocated backup nodes and links, thus its blocking ratio prevails over its peers. Given that the FatTree topology does not allow Pro-Red to employ its prognostic redesign technique, we further compare these 3 redesign techniques over a randomly generated topology to evaluate the advantage of this property. We observe that Pro-Red achieves encouraging gain in terms

of decreasing the blocking ratio. We find that as we increase the load to 16, 1-redundant and k-redundant's blocking ratio becomes at least 50%, while Pro-Red's blocking ratio remains below 20%. In this case, Pro-Red achieves a 60% gain. The rich interconnection of the random network topology enables Pro-Red from exercising its prognostic redesign technique, i.e. finding node mapping solutions that are capable of placing the backup node in between its associated primary virtual nodes. Hence, Pro-Red is capable of greatly decreasing the incurred bandwidth cost for each VN, and subsequently increasing the network's admissibility.

2. **Average Cost :** For a given VN, the cost is measured using the objective function of the SVN embedding model presented in Section 3.5, which represents the sum of the primary and backup bandwidth cost incurred by this VN in the substrate network. For each of the aforementioned techniques, we average the cost of the admitted VNs as we vary the load. First, we compare the average cost obtained by Pro-Red against 1 and k-redundant using FatTree. Again, we observe that in addition to Pro-Red's lower blocking ratio, it can also achieve a lower average cost. This greatly motivates the inconvenience of fixing the number of backup nodes to either 1 or k. Further, as we compare the average cost over the randomly generated topology, we observe that Pro-Red's unique redesign technique enables it to greatly decrease the average cost over the substrate network. While the gain over 1-redundant is between 8 and 17%; however compared to k-redundant, Pro-Red achieves a constant gain of 30%. Pro-Red's prognostic redesign technique for backup resource sharing enables it to achieve this gain, while 1-redundant and k-redundant falls short due to their agnostic approach.

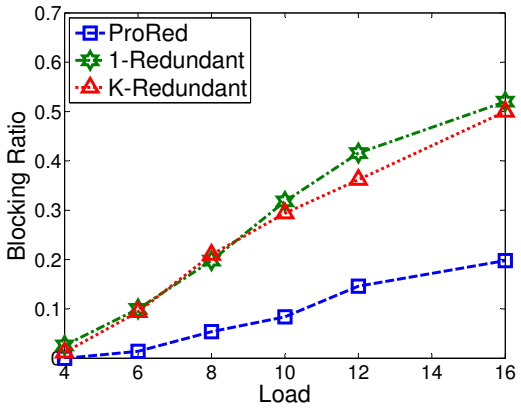
3. **Revenue :** Revenue is an important metric that highly complements the blocking ratio metric. A low blocking ratio does not necessarily implicate a high revenue. This is because the concerned model may only be capable of admitting small-size VNs with low CPU demands. When in fact, large size VNs with substantial CPU requirements are more profitable to the cloud provider. In this regard, we measure the revenue obtained using Pro-Red, versus the

1-redundant and k-redundant schemes. Given that the aim of the metric is to evaluate each of the aforementioned techniques's ability to admit large and profitable VNs, we measure the revenue of each admitted VN in function of its overall CPU demands and size using the following equation: Revenue = $\sum_{v \in V} c_v + \pi_v$ —V—. We observe that for the FatTree network presented in Figure 3.6(e), Pro-Red achieves encouraging results, with a 59% gain over 1-redundant and 31% gain over k-redundant for a load of 12. Similarly, Figure 3.6(f) presents the obtained results over the random network. We observe that as we increase the load, Pro-Red's revenue gain increases. In fact, for a load of 16, Pro-Red achieves 40% revenue gain over both 1 and k-redundant. This gain is mainly attributed to ProRed's unique redesign properties, which significantly reduce the average cost, and hence leverage the efficient utilization of the substrate network. Subsequently, ProRed is capable of admitting larger and more profitable VNs in comparison with the 1 and k-redundant schemes.

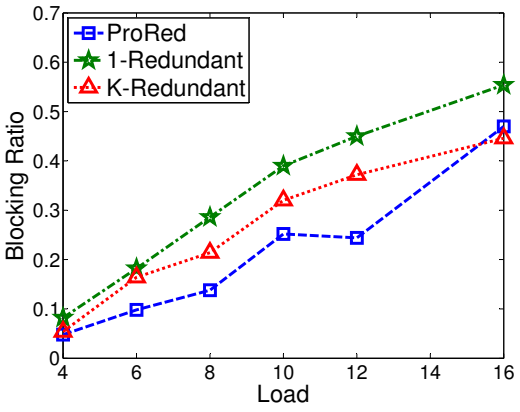
4. **Execution Time :** Finally, we measure the runtime of embedding a single SVN by varying its size between 2 to 8 virtual nodes, and we compare the execution time of the 3 redesign techniques over the FatTree network (illustrated in Figure 3.6(g)). We observe that the runtime of 1 and k redundant follows a step increase as we vary the size of the SVN. This is due to its cross-sharing and backup-sharing (Constraint 10) that measures the allocated bandwidth on each substrate link for each primary virtual node during the embedding phase. The size of this constraint grows more complex as the number of virtual nodes in the SVN increases. However, our prognostic redesign technique alleviates this load from the embedding algorithm, which is reflected in the linear execution time achieved by Pro-Red. Pro-Red returns the sets of backup nodes and their associated backup links, as well as the amount of required backup resources to be reserved, while promoting backup resource sharing. Hence, all of these information will serve as an input to the model, rather than being explored at the embedding phase. This alleviated load is reflected in the runtime gain that Pro-Red achieves.

3.7 Conclusion

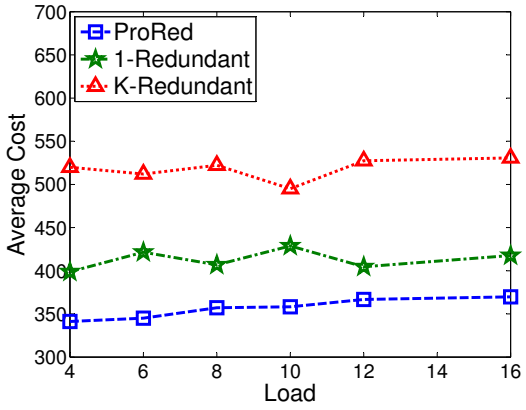
In this Chapter, we presented Pro-Red a novel prognostic redesign technique for survivable virtual networks against single facility node failures. Pro-Red swerves from the dogmatic redesign techniques that fix the number of backup nodes to either 1 or k. Further it is equipped with a unique property that enables it to design SVNs that can highly promote backup resource sharing once embedded in the substrate network. This property lays in positioning of the backup nodes in the SVN such that backup-sharing and cross-sharing can be fully exploited. We compared Pro-Red against 1-redundant and k-redundant schemes, and we show that it achieves significant gains in terms of decreasing the blocking ratio, achieving lower average cost and substantially higher revenue, in considerably lower execution times.



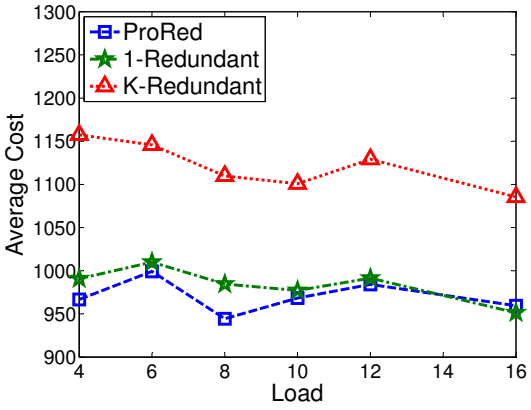
(a) Blocking Ratio - R



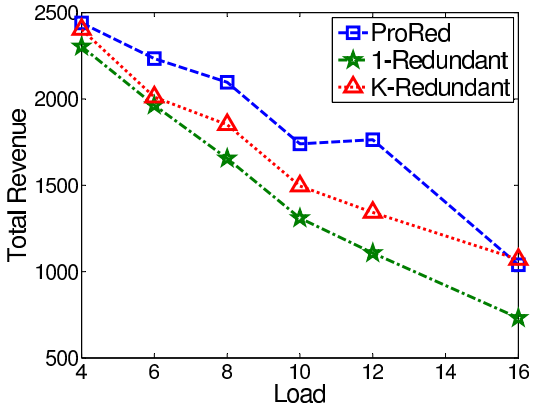
(b) Blocking Ratio - FatTree



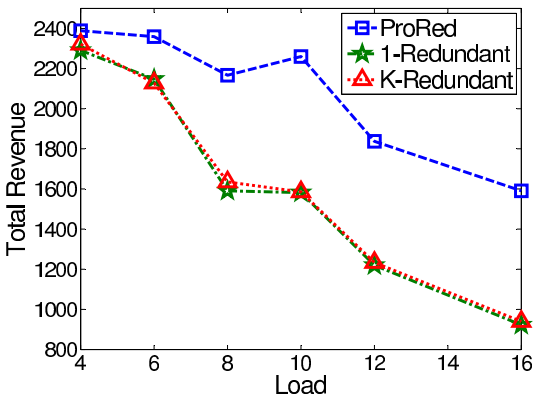
(c) Average Cost - R



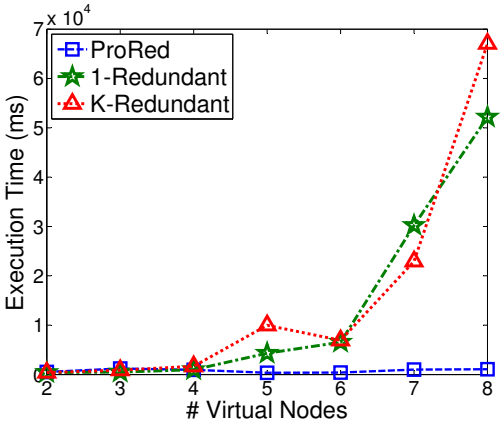
(d) Average Cost - FatTree



(e) Revenue - FatTree



(f) Revenue- R



(g) Execution Time - FatTree

FIGURE 3.6: Comparison between Pro-Red, 1-Redundant and K-Redundant Scheme.

Chapter 4

Post-Failure Restoration for Multicast Services in Data Center Networks

4.1 Introduction

Most of the existing work on either the VNE or the SVNE does not characterize the mode of communication among virtual machines belonging to the virtualized service. In fact, characterizing the mode of communications in the VNs will benefit the optimization of VN embedding. There are different types of VN requests depending on the type of applications running on. Namely, One-to-one Communication VN(unicast), One-to-many Communication VN(multicast) and all-to-all Communication VN(broadcast). VNs in different categories have different ways of transmitting data. For instance, in a unicast VN, the a sender only sends files to a signle receiver; whereas in multicast VN, a sender distributes the same copy of file to a group of receiver[59]. Hence, in unicast VNs, each communication must be delicated a set of physical paths with sufficient bandwidth capacity; however, the routing of communications in multicast VNs may share bandwidth, as all receiver will obtain the exact same file from the sender.

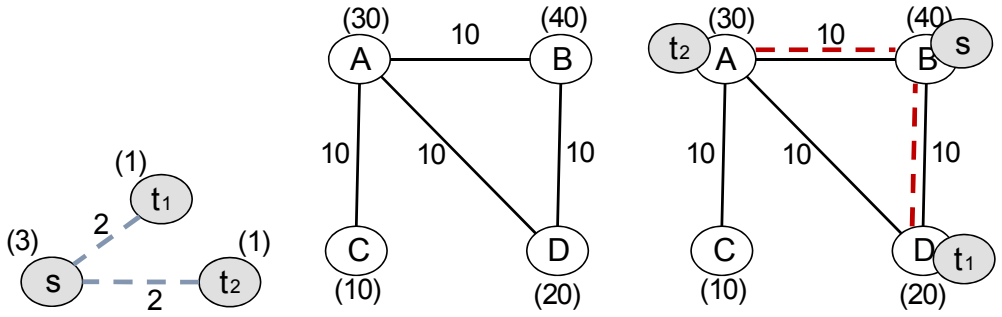
Therefore, embedding a multicast VN using a unicast VN mapping algorithm will not encourage the bandwidth sharing in MVN(Multicast Virtual Network) communications, thus not cost-efficient. Moreover, different types of VNs may have specific requirements other than just physical resource capacity. For example, MVNs that are running online gaming platform require the same data sent by source node, to be delivered to all terminals within a sepcific delay range, and the delay variation of all terminals must respect a pre-defined threshold.

The rest of this Chapter is organized as follows: Section 4.2 is dedicated for formally defining the MVN restoration problem and studying the impact of failure on embedded MVNs in data center networks. In Section 4.3, we propose a path-convergence for restoring source node failure. Section 4.4 presents our hop-to-hop algorithm to restore a MVN against any terminal node failure. Section 4.5 is dedicated for the numerical evaluation. We conclude this Chapter in Section 4.6.

4.2 Network Model and Problem Description

4.2.1 Network Model

In this section, we formally define the MVN Restoration problem by describing the network environment and the various components involved. Next, we study the impact of failure on this service class.



(a) MVN (b) Substrate (c) MVNE

FIGURE 4.1: Network Model

1. **The Substrate Network:** We represent the substrate network as an undirected graph, denoted by $G^s = (N,E)$, where N is the set of substrate nodes, and E is the set of substrate links. Each substrate node $n \in N$ is associated with a finite computing capacity, denoted by c_n. Similarly, each substrate link $e \in E$ has a finite bandwidth capacity, denoted by b_e. Figure 4.1(b) illustrates a substrate network with 4 substrate nodes and links. The resource capacity of the substrate nodes and links is represented by the number next to each node or link, respectively.

2. **The MVN Request:** A MVN represents a client's request to deploy an application with a one-to-many communication mode in a cloud data center. It consists of a single source node s, and a set of terminal nodes T. The source node is connected to all terminal nodes via virtual links. The set of all virtual links is denoted by E'. Every virtual link $e' \in E'$ requires a specific amount of bandwidth, denoted by b'. For the sake of simplicity, we assume that the bandwidth demand between the source and each terminal node is the same. In addition, each virtual node is usually associated with computation demands, denoted by d_v. We note that one of the most important properties for multicast VNs is delay; particularly for applications that involve real-time communication. Here, it is important that the source node reaches all terminals within an acceptable delay, denoted by γ. Moreover, the delay variation between all terminal nodes in a given VN must also respect a given threshold δ, in order to ensure correctness and synchronization among all terminal nodes. Without the delay-variation constraint, some terminal nodes might fall behind in the multicast session, which can potentially degrade the QoS of the hosted application. For instance, consider the case of a distributed database system that is constantly updated with new information. A large delay-variation between the terminal nodes that host the databases, will lead to unfairness, inconsistencies and possibly lead to incorrect computations [60]. A multicast VN is thus denoted by $G^v = (s, T, b', \gamma, \delta)$.

   We define the transmission delay between the source and a terminal node $t \in$

T to be the sum of the delays experienced at every edge (e.g. queueing delay, propagation delay, transmission delay, and processing delay) along the path from the host of the source to that of the terminal t. Hence, if we denote the delay at edge $e \in E$ as $\hat{d}_e$, then the delay between the source s and a terminal t is equal to $\sum_{e \in P_{(s,t)}} \hat{d}_e$; where $P_{(s,t)}$ represents the physical path between the host of s and t respectively. The transmission delays of the edges in the substrate network can be measured using SDN with OpenFlow network monitoring systems (e.g. OpenNetMon [61]). However, for simplicity, we assume throughout this Chapter that the transmission delay is uniform across all substrate links, and hence it reduces to the count of hops along the path between the source and any terminal node.

Figure 4.1(a) represents a multicast VN with two terminal nodes, t_1 and t_2. The resource demands of each virtual node is denoted by the number in parenthesis on each node; and that of the substrate links by the digits placed on each link. We assume that the end-delay requirement of this VN is set to 2 hops, while the differential delay requirement is set to 0.

3. **A Multicast VNE (MVNE) Solution** A MVNE solution indicates the mapping of a VN request onto the substrate network that respects the the virtual nodes and links's resource demands, and satisfies the QoS requirements, mainly end-delay and differential-delay constraints. The MVNE problem can be logically divided into two subproblems: Virtual Node Mapping (VNM) (source and terminal nodes), and Virtual Link Mapping (VLM). That latter consists of a multicast tree m rooted at the source of the VN request and spans all the terminal nodes. Figure 4.1(c) illustrates a MVNE solution of the given MVN over the 4-nodes substrate network.

Given a cost function ϕ_m, finding the optimal MVNE for a given MVN can be formulated as follows:

$$Min \sum_{m \in M} \phi_m$$

Subject To

$$m \in M \tag{4.1}$$

Here, ϕ_m is a function of substrate link utilization, and m represents a feasible mapping $m = (m_N, m_E) \in M$ of the VN request. Note that a mapping m holds the solution for the two subproblems:

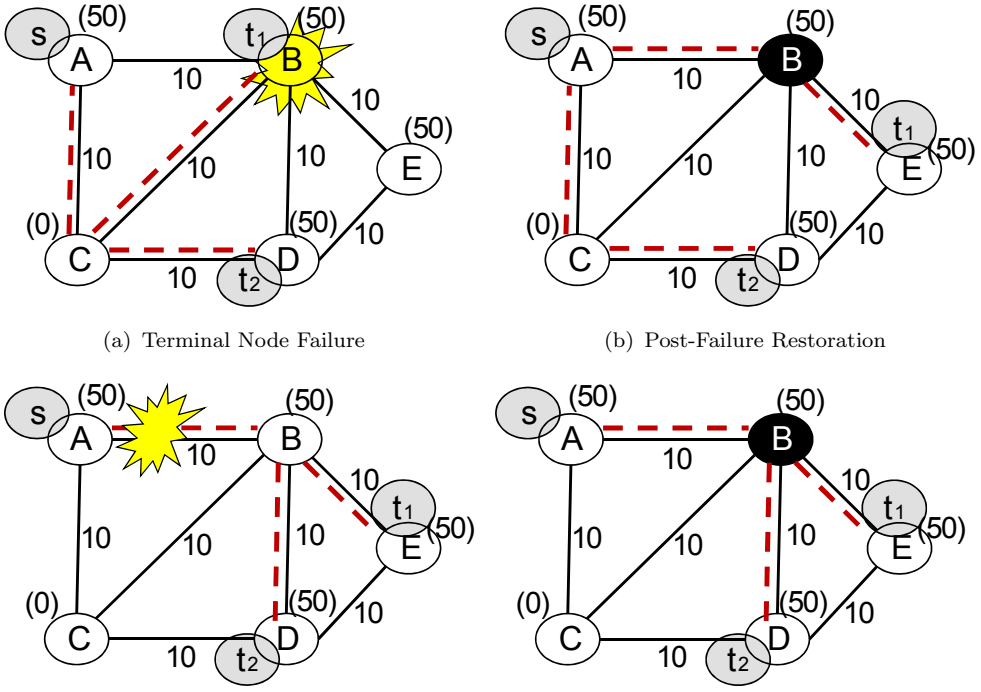
(1) Virtual Node Mapping (VNM): m_N: $(s, T) \longrightarrow N$

(2) Virtual Link Mapping (VLM): m_E: $E' \longrightarrow P$; P represents the set of paths that form the multicast tree.

In [62], the problem of embedding MVN is investigated in data center networks. Due to its NP-Hard nature (as shown in **??**), the authors proposed a novel 3-Step approach for solving this mapping problem[62]. Throughout this Chapter, we assume that the MVNE solutions are given (using our 3-Step Embedding technique), and our work is mainly focused on understanding the impact of failure on this service class, and proposing a tailored restoration technique that can mitigate against any network component failure.

4.2.2 Understanding the impact of failure on MVNs

To understand the impact of failures on MVNs, we look at how a failure affects each component of a multicast service; that is source node, terminals nodes and the links that compose the distribution tree. As we have previously mentioned, failures in data center networks can either affect a substrate facility node, a substrate link, or a network node. In this Chapter, we only consider the case of a facility node or a substrate link failure. Here, it is important to note that when a facility node fails, only the affected node(s) will be disconnected from the substrate network. However, its adjacent network node (router/switch) and substrate links will remain active and capable of routing traffic. One way to protect a multicast VN against a facility node failure is by augmenting the latter with backup nodes, and then embed the resultant graph onto the substrate network while provisioning



(a) Terminal Node Failure

(b) Post-Failure Restoration

(c) Tree Link Failure

(d) Tree Maintenance

FIGURE 4.2: Impact of a Substrate Node or Physical Link Failure

enough backup resources. As for the failure of substrate links, this can be mitigated by constructing an edge-disjoint backup tree. Such a scheme is commonly known as proactive protection, since the backup nodes and links are instated prior to any failure. While this offers a certain degree of reliability, it is also fairly costly since the provisioned resources for these backup nodes and links remain idle until failures occur. An alternative approach could be to restore the affected resource(s) upon failures. Such a "reactive approach" is more cost-efficient as it eliminates idle resources in the network, but it may fail to find backups for the failed resource(s) due to scarcity in the network at the moment when the failure occurred.

When a failure affects a substrate node hosting a terminal VM, the restoration scheme necessitates finding a backup that can host the failed VM with sufficient resources. In addition, when the failed terminal belongs to a delay-sensitive MVN, the path used to connect the backup to the rest of the multicast tree must also maintain the MVN's QoS requirements; that is it must be within the end-delay constraint, and satisfies the differential-delay with the remaining working terminals. Figure 4.2(a) illustrates the case of a terminal node failure. Here, the failure

of substrate node C brought down terminal t_1 of the 2-terminals MVN illustrated in Figure 4.1(a). Given the substrate network's capacity, E is the only substrate node that has enough resources to host t_1. Now to connect t_1's new host to the rest of the MVN, the path used to reach E must be within the end-delay constraint of 2, and satisfies the differential delay to the rest of the working terminals; the working terminal in this case is t_1. Hence, we need to connect E to the remaining working tree with exactly 2 hops given the differential-delay constraint of 0 for the MVN in question. Subsequently, the only feasible restoration solution in this case is to connect E to the multicast tree via the substrate path $\{A\text{-}B\text{-}E\}$, as illustrated in Figure 4.2(b). On the other hand, when a failure affects a substrate node hosting the source of a MVN, it mandates a look-up for a backup node that can host the failed source, as well as a multicast tree reconstruction that spans all existing terminals and respects the QoS requirements. Finally, in the event of a substrate link failure, this latter will detach an entire subtree, thereby disconnecting one or many terminal nodes connected via this subtree to the multicast source. Figure 4.2(c) illustrates the case where substrate link $\{A - B\}$ fails, thereby detaching the subtree rooted at B, disconnecting terminals t_1 and t_2.

When restoring a MVN, it is not solely sufficient to find the backup node that maintains the service's QoS, but it is also important to consider the cost of the resultant tree. It is in the network provider's best interest to minimize the embedding cost of the hosted services in the aim of maximizing both his/her revenue, as well as the network's admissibility. For instance, after restoring terminal t_1 post-failure of its original host B, the resultant tree shown in Figure 4.2(b) is more costly than the pre-failure multicast tree of the given MVN. An alternative solution (illustrated in Figure 4.2(d)) could be to re-route the traffic to t_2 via substrate path $\{A - B - D\}$, thereby maintaining the MVN's QoS requirements while achieving a lowest-cost tree. In the light of the above, we can conclude a key observation: Multicast VN restoration demands both a service repair to restore the failed element, as well as a multicast tree maintenance to reconstruct the lowest-cost tree that maintains the requested QoS.

4.2.3 The MVN Restoration Problem

4.2.3.1 Problem Formulation

In this section, we mathematically formulate the MVN Restoration Problem. Given the initial MVN embedding solution and the failed node, we attempt to find a new server for the failed node and re-connect the multicast tree with lowest cost. Our proposed MVN restoration model achieves the following two objectives:

- **MVN Repair :** which consists of restoring the failed service component, be it failure of the source node or any terminal node in the multicast tree.
- **Tree Maintenance :** which ensures that the MVN repair does not violate the requested QoS, and yields a lowest-cost tree.

Our model assumes as input a substrate network, and a set of MVNE solutions for the hosted multicast services. When a failure occurs, the restoration model is invoked for each affected MVN in the aim to repair the affected service components, and restore a low-cost delay-bounded multicast tree. Hence, our objective function is presented in Equation 4.2.

$$Minimize \sum_{(i,j)\in E} t'_{i,j} \tag{4.2}$$

Here, $t'_{i,j}$ represents the set of substrate links that composes the restored multicast tree. First we begin by repairing the failed terminal node using Equation 4.3.

$$\sum_{n'\in N'} y^{v}_{\widetilde{n},n'} = 1 \quad \forall v \in T,\ \widetilde{n} \in \widetilde{N} \tag{4.3}$$

$\widetilde{N}$ represents the set of failed substrate nodes, $N' = N - \widetilde{N}$ represents the set of active substrate nodes, and $y^{v}_{\widetilde{n},n'}$ is a variable that denotes the relocation of failed

terminals. $y^{v}_{\widetilde{n},n'}$ is a boolean variable that indicates whether terminal node v that was hosted on a failed substrate node $\widetilde{n} \in \widetilde{N}$ has relocated to an active substrate node $n' \in N'$. This constraint is used to ensure the embedding of the failed source node or failed terminal node(s).

$x^{0}_{v,n}$ is a boolean input that denotes the pre-failure node mapping solution of the affected MVN. We identify the set of post-failure active virtual nodes by those who were embedded on an unaffected substrate node $n \in N'$. Subsequently, a new node mapping solution will be obtained that we represent with the following decision variable $x^{1}_{v,n'}$.

New Node Mapping Solution :

$$x^{1}_{v,n'} = y^{v}_{n,n'} + x^{0}_{v,n'}.(1 - m_v) \quad \forall v \in \{s, T\},\ n \in N,\ n' \in N' \tag{4.4}$$

$$\sum_{n' \in N'} x^{1}_{v,n'} = 1 \quad \forall v \in \{s, T\} \tag{4.5}$$

$$\sum_{v \in \{s,T\}} x^{1}_{v,n'} \leq 1 \quad \forall n' \in N' \tag{4.6}$$

Equation 4.4 is used to indicate the new node mapping solution. Note how $y^{v}_{n,n'}$ loops over all $n \in N$ in order to fetch the new node mapping solution for failed virtual nodes, whereas maintaining the initial embedding solution (in the case of no migration) is restricted to the virtual nodes hosted on active substrate nodes. Further, observe that the new node mapping solution ensures that every virtual node in a particular MVN request is mapped on a distinct substrate node in order to reduce the impact of failures via Equations 4.5 and 4.6. Further, it is imperative to ensure that the new node mapping solution respects the substrate network's capacity constraints. Hence, we develop the following substrate nodes capacity constraints.

Substrate Nodes Capacity Constraints :

$$c'_n = c_n + (\sum_{v\in\{s,T\}} \sum_{n'\in N'} y^v_{n,n'}.d_v) \quad \forall n \in N' \tag{4.7}$$

$$\sum_{v\in\{s,T\}} x^1_{v,n}.d_v \leq c'_n \quad \forall n \in N' \tag{4.8}$$

Here, it is important to release the resources provisioned for a particular virtual node in case this latter has migrated, as presented in Equation 4.7. To complement the node mapping solution, a link mapping solution must be constructed to route the traffic between the relocated terminals and the multicast source.

Multicast Tree Reconstruction :

$$\sum_{j:(i,j)\in E} q^v_{i,j} - \sum_{j:(j,i)\in E} q^v_{j,i} = x^1_{v,i} - x^1_{s,i} \; \forall i \in N', \; v \in T \tag{4.9}$$

$$\sum_{i\in S} \sum_{j\in S} \sum_{v\in T} q'^v_{i,j} \leq |S| - 1 \quad \forall S \subset N', 2 \leq |S| \leq N' \tag{4.10}$$

Equations 4.9 represents the flow conservation constraint to reconstruct the multicast tree, whereas constraint 4.10 ensures that the constructed tree is cycle-free (subtour elimination constraint). Next comes the multicast tree maintenance constraint to guarantee that the newly constructed multicast tree satisfies the end-delay constraint via Equation 4.11, as well as the delay-variation constraint represented in Equations 4.11-4.14, where θ_{min} and θ_{max} represent the minimum and maximum delay experienced in the constructed multicast tree, respectively.

Multicast Tree Maintenance

$$\sum_{(i,j)\in E} q'^v_{i,j} \leq \gamma \quad \forall v \in \{T\} \tag{4.11}$$

$$\sum_{(i,j)\in E} q'^{v}_{i,j} \geq \theta_{min} \quad \forall v \in \{T\} \tag{4.12}$$

$$\sum_{(i,j)\in E} q'^{v}_{i,j} \leq \theta_{max} \quad \forall v \in \{T\} \tag{4.13}$$

$$\theta_{max} - \theta_{min} \leq \delta \quad \forall v \in \{T\} \tag{4.14}$$

Finally, the newly constructed tree must also respect the substrate link's capacity constraints as presented below. Note if two terminals share the same substrate link (i, j) towards the source, the bandwidth requested for the given MVN is provisioned once over (i, j) since intermediate nodes in multicast trees copy-and-forward the traffic towards the leafs.

Substrate Link Capacity Constraints

$$z_{i,j} \geq q'^{v}_{i,j} \quad \forall v \in T, (i,j) \in E \tag{4.15}$$

$$z_{i,j} b' - t_{i,j} \leq t'_{i,j} \quad \forall (i,j) \in E \tag{4.16}$$

$$t'_{(i,j)} \leq b_e \quad \forall e : (i,j) \in E \tag{4.17}$$

4.2.3.2 Complexity Analysis

Given a substrate network $G = (N, E)$ and a set of hosted MVNs denoted by M, the MVN Restoration problem can be formally defined as follows:

Problem Definition 3. *When a failure affects any MVN $m \in M$, find an optimal restoration solution for m that maintains the MVN's end-to-end delay γ and delay-variation constraint δ with the remaining working terminals, while achieving the lowest-cost multicast tree.*

The MVN Restoration problem is NP-Hard, since when failure occurs, the problem becomes that of finding a Delay- and Delay-Variation Bounded Multicast Tree (DVBMT)[63]. In the case of a source or a terminal node failure, the goal of the DVBMT is to find the delay-constrained lowest cost tree that reconnects the new backup node and the rest of the MVN service components (active virtual nodes). Given the NP-Complete nature of this problem, in the next section we propose two alternative techniques for restoring MVNs against single facility node failure. Here, we separate the failure of terminal node from that of a source node, since a terminal node failure only requires reconnecting the backup of the failed terminal to the rest of the multicast tree, whereas a source node failure entails reconstructing the entire multicast tree from the newly found source. The details of the proposed algorithms are elucidated in the following sections. We leave for future work the quest to mitigate against substrate links failure.

4.3 Path-Convergence Method for finding a backup source

In this section, we propose an alternative approach for finding a backup node upon the failure of the primary source. Our suggested approach consists of a receiver-driven path-convergence lookup. The search begins from each terminal node onwards; where at iteration k, all nodes at k hops from any terminal are explored. The search persists until all the terminals converge to a single node that satisfies the source's resource demands, or until the maximum number of hops is reached, which is equal to the end-delay threshold γ.

Algorithm 3 FindBackupSource Algorithm(G^s,G^v,M)

1: **Step 1: Explores k hop neighbors**
2: $k = 1$; /*Initialize hop count to 1*/
3: $C = \{\}$; /* Initialize candidate solutions list*/
4: **for** $(t \in T)$ **do**
5: $\quad S_t = t$;
6: **end for**
7: **while** $((C \neq \emptyset)$ —— $(k \leq \gamma))$ **do**
8: $\quad$ **for each** $(t \in T)$ **do**
9: $\quad\quad S' =$ exploreAllNeighbors(S_t);
10: $\quad\quad$ **for each** $(w \in S')$ **do**
11: $\quad\quad\quad$ **if** (!hasSufficientBW($P_{(t,w)}$)) **then**
12: $\quad\quad\quad\quad S'$.remove(w);
13: $\quad\quad\quad$ **else**
14: $\quad\quad\quad\quad$ **if** (isCandidateNode(w)) **then**
15: $\quad\quad\quad\quad\quad C_t = C_t \cup w$
16: $\quad\quad\quad\quad$ **end if**
17: $\quad\quad\quad$ **end if**
18: $\quad\quad$ **end for**
19: $\quad\quad S_t = S'$;
20: $\quad$ **end for**
21: $\quad C = \cap_{k-\delta}^{k} C_t$;
22: $\quad k$++;
23: **end while**
24: **Return** getLowestCostSolution(C);

The procedural details of the proposed method are illustrated in Algorithm 3. It begins by initializing the hop count k to 1 and creating $|T|$ lookup sets to store the new nodes explored by each terminal $t \in T$. At the beginning, each set will contain one distinct terminal node, since the search will begin from each terminal node until they all converge to a single feasible substrate node. Next, while k is less than the end-delay threshold δ, each terminal t will explore all neighbors at k hops from t's host. The substrate path used to reach any neighbor w is validated against the bandwidth demand of the MVN. If the path's capacity is below the requested bandwidth, then the node will not be aggregated to the corresponding lookup set as it will yield an infeasible link embedding solution. Similarly, a validation process is initiated at each newly-explored neighbor w to ensure that this latter satisfies the resource demands of the source. If valid, then w will be added to the candidate solutions set C_t explored by the corresponding terminal t. Once

all terminals are done exploring their neighbors at the k^{th} hop, the set of all nodes found between [k-δ,k] hops by each terminal are compared to find a single common nodes. The aforementioned range guarantees that the set of paths used to reach the backup source satisfies both end-delay and differential-delay constraints. If multiple common nodes where found, the algorithm returns the one that yields the lowest cost tree. The complexity of our proposed approach is O(γ.$|T|$.$|N|$).

4.4 Hop-to-Hop Terminal Finding Algorithm

In the event of a terminal node failure, a hop-to-hop terminal finding algorithm is triggered from the source and a set of "assisting" terminal nodes. Assisting terminals are those that can contribute to the backup terminal lookup. Not all terminal nodes can contribute to the search, particularly those that lie on the bounds of a tree with a height equivalent to the end-delay threshold. Since in this case any neighboring node will violate the end-delay constraint. The need for foragers is to be able to find a backup for the failed terminal and connect it to the rest of the multicast group while reusing most of the existing tree. However, in the case of delay-sensitive applications, assisting terminals alone might fail to find a backup; hence the need to include the source node in the backup terminal search.

The terminal backup finding algorithm begins by finding the acceptable range R; R being the minimum and maximum acceptable delay of the path connecting the backup terminal to the rest of the working tree. This latter will be used to determine the "assisting terminals" set, as well as terminate the search on any path that exceeds R's upper bound. Algorithm 4 illustrates the procedure to compute the acceptable range. Given θ_{min} and θ_{max} as the minimum and maximum delay in the remaining working tree, the newly found path that will connect the backup to the multicast group must remain in the range between θ_{min} and θ_{max} in order to not violate the end-delay and differential-delay constraints of the overall tree. However, it could be that the working tree does not exhaust the delay thresholds,

hence if θ_{max} is less than the differential-delay constraint δ, then the path to the terminal backup must not exceed $(\theta_{min} + \delta)$, unless its value is larger than the end-delay constraint γ, then R's upper bound becomes γ. Whereas in the case where θ_{max} is greater than the δ, then $R = [\theta_{max} - \delta, \theta_{max} + \delta)]$; unless the upper bound violates γ, then R's upper bound would be restricted to the value of γ.

Algorithm 4 GetAcceptableRange(G^v,M,$\hat{T}$)

```
1: let R denote the acceptable range
2: let θ_min and θ_max denote the min and max end-delay in the remaining working
   tree
3: if (δ ≥ θ_max) then
4:     R.setLowerBound(1);
5:     if (θ_min + δ ≥ γ) then
6:         R.setUpperBound(γ);
7:     else
8:         R.setUpperBound(θ_min + δ);
9:     end if
10: end if
11: if (δ ¡ θ_max) then
12:     R.setLowerBound(θ_max − δ);
13:     if ((θ_max + δ) ≥ γ) then
14:         R.setUpperBound(γ);
15:     else
16:         R.setUpperBound(θ_max + δ);
17:     end if
18: end if
19: Return R;
```

Algorithm 5 illustrates the Hop-to-Hop backup terminal finding algorithm. It begins by initializing the weight on the substrate links to 0 in case they belong to the multicast tree, and 1 otherwise. This weight distribution encourages the selection of a terminal backup path that reuses the current multicast tree, hence renders a low cost tree. Now given R, the set of assisting terminal nodes is identified as any terminal node whose path to its immediate neighbors does not violate R's upper bound; in addition of course to the source node. Next, a candidate solutions set C is initialized, where each time an assisting node finds a candidate substrate node within the acceptable range R, it computes the cost of the path followed to reach this node; which is the sum of the weights on the substrate links used. Then, the node is stored with its appropriate cost in C. Note that if this latter has already

Algorithm 5 FindTerminalBackup Algorithm(G^s,G^v,M,$\hat{T}$)

R = GetAcceptableRange(G^v,M,$\hat{T}$);
$k = 1$;
Step 1: Initialize weight on substrate link
for each ($e \in E$) **do**
    if ($e \subset M_E$) **then**
        e.weight = 0;
    else
        e.weight = 1;
    end if
end for
Step 2: Identify the set of assisting terminal nodes
$S_s = \{\}$;
$Q = s$;
for each ($t \in T$) **do**
    if ($—P_{s,t}— + 1 \leq R$.upperBound()) **then**
        $S_t = t$;
        $Q = Q \cup t$;
    end if
end for
Step 3: Begin Hop-to-Hop look-up
while (($C \neq \emptyset$) —— ($k \leq R$.upperBound())) **do**
    for (**each** $v \in Q$) **do**
        S' = exploreAllNeighbors(S_v);
        for each ($w \in S'$) **do**
            if ($—P_{(v,w)}— \subset R$) **then**
                w.cost = $\sum_{e \in P_{(v,w)}} e$.weight;
                $C_v = C_v \cup w$;
            end if
        end for
        $S_v = S'$;
    end for
    $C = \cup_{v=1}^{|Q|} C_v$;
    k++;
end while
Return getLowestCostSolution(C);

been found, and the computed cost is lower than the one stored in C, then the corresponding node's cost is simply updated. The Hop-to-Hop lookup consists of having each assisting terminal node explore its immediate neighbors iteratively until a solution is found. When all foragers are done looking at all their neighbors at the k^{th} hop, the set C is checked to see if any solution is found at hop k. If more than one solution is found, the algorithm returns the one with the lowest cost. The hop-to-hop lookup terminates when a solution is found, or until all the lookup paths have exceeded R's upper bound. If we denote R's upper bound by K, then the complexity of our proposed algorithm is O($K.|T|.|N|$).

4.5 Numerical Results

We evaluate the performance of our algorithms against the model for various metrics: Blocking Ratio, Restoration Ratio, Total Revenue and Execution Time. We adopt two different substrate network topologies to conduct this evaluation. The substrate networks used for our simulation are FatTree (K=4) [25], as it is a commonly deployed datacenter network. We set the CPU capacity of each host node to 64 units, and the bandwidth capacity on the substrate links is set to 5000 units. We perform the mapping of MVNs using the same approach as in [59] in an online fashion, upon the arrival of each request. Hence, we assume that the VNs arrival and departure follow a Poisson distribution. The VN requests are randomly generated, where the size of each VN can range between 2 to 12 terminal nodes. The CPU demand of the virtual nodes is set to be in the range [1:8], and the bandwidth demand on the virtual links is in the range [10:100]. To conduct the simulation of failures, we let one substrate node to fail periodically, and recovery before next failure takes place. If the failed substrate node has VMs running on it, those VMs will be disconnected from their MVNs. To restore those failed MVNs, our algorithms and model are called after each failure. A comparison is presented in this section using metrics like Blocking Ratio, Restoration Ratio, Total Revenue and Execution Time. All results we collected are averaged over multiple runs.

Blocking Ratio: Blocking Ratio measures the number of failed MVN embedding attempt over a total of 50 incoming MVN requests. In this Chapter, although both Algorithms and model use the same embedding method initially, the restoration process would yeild different re-mapping solutions after failures, thus resulting different re-embedding cost. This metric is used to test the ability to achieve low-cost tree after failures. As shown in Figure 4.3(a), the overall trend of blocking ratio is raising as the Poisson Load increases. Clearly our algorithms almost achieved the same results as the model. This is due to the algorithms' ability to reuse the old links and explore sharing, hence, most of the time it is able to achieve optimal or suboptimal solution. At Load 4, 8 and 10, it is estimated that our algorithms have 5% higher blocking rate, this is because algorithms were not able to find the lowest cost solutions in some failure cases, consquently, the available rsources were tight compared to them of our model. Hence when new MVN requests came, some were rejected due to the lack of resources.

Restoration Ratio: We measure the percetage of successful recovery after failures using Restoration Ratio. As we obesrve, the number of failure in one run is usually between 50 120. At load 4 and 6, both Algorithm and model could restore 100% of the failed MVNs. However, as load increases, we can observe the restoration ratios for both Algorithm and model are decreasing. That's because the amount of available resources is limitted when the load is high. Overall, our Algorithm is able to obtain the same level(above 98.5 %) of restoration ratio as the model.

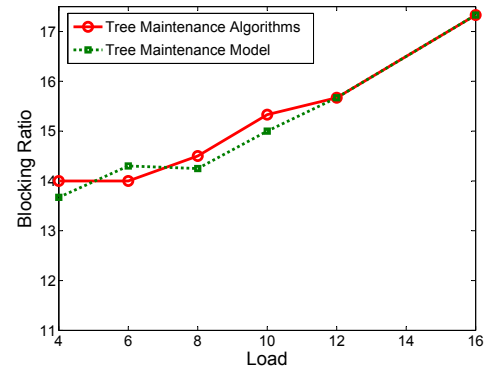
Execution Time: As both methods we proposed are reactive approaches, the execution time is a crucial metric to show how fast a method can restore a failure. If the execution of a method is too high, the disconnection time of MVN becomes significant and put SLA at risk. In Figure 4.3(c), we can observe a dramatic performance difference between our algorithms and model; the execution time of algoritms ranges from 3 ms to 10 ms, whereas the model normally takes 420 ms to 470 ms for one run, which is at most 140 times slower than the algrithms. This

is due to the efficient searching techniques of our algorihms.

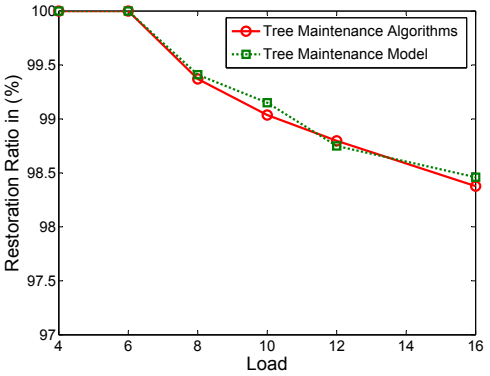
Total Revenue: In this Chapter, we also measure the total revenue to show benefit they gain for the InP. We assume the revenue of one MVN depends on its total resource requirement. The revenue of a MVN can be gained only if this MVN is successfully embedded. However, if the failure of a MVN can't be restored, 25% of its revenue will be sustracted as a penalty. Figure 4.3(d) shows the total revenue of both algorithms and model. At load 4, model was able to obtain approximately 8% higher total revenue as it has less blocking than algorithms. For the rest of the loads, Algorithms and model achieves close results. Hence, overall, we conclude that the Algorithms not only is able to achieve close performance as the model in terms of the revenue gain, but it is much more efficient in terms of execution.

4.6 Conclusion

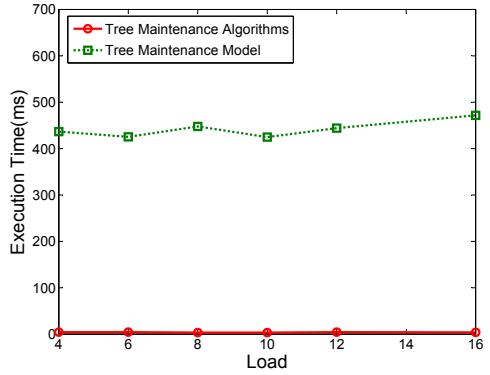
In this Chapter, Multicast Network in data centers is discussed and the failure scenarios are analysed. The Survivablility of Multicast Virtual Network problem is then investigated and formally defined. To address this problem, we presented a mathametical model, which can be used to find recovery solutions in case any node failures in a reactive manner. In addition, two alternative techniques, namely "Path-Covergence source node finding" and "Hop-to-Hop terminal finding", are introduced to solve the source node failure and terminals failure respectively. We compared our model with algorithms, the results show that our Algorithms are able to run much more efficient while maintaning close performance.



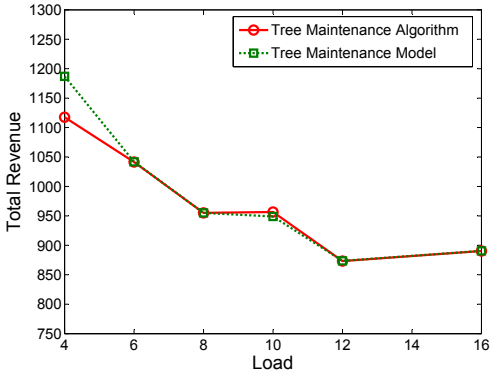
(a) Blocking Ratio



(b) Restoration Ratio



(c) Execution Time in (ms)



(d) Total Revenue

FIGURE 4.3: Muticast VN Maintenance Approaches Comparision Test Results

Chapter 5

Conclusion and Future Work

5.1 Conclusion

This dissertation has explored several aspects of the survivalbility of virtual network in cloud data center. Two main issues, namely the survivable VN redesign and embedding problem, and multicast VN maintenance problem, are addressed in Chapter 3 and Chapter 4 respectively.

In Chapter 3, the optimization problem of the survivable virtual network redesign and embedding problem is dicussed and formally defined. The weakness of current survivable design schemes and resource sharing techniques are illustrated via some illustrative examples. To overcome this drawback, our prognostic VN redesign algorithm is developed, along with its theoretical foundations. With the introduced SVN embedding model in this Chapter, we compared our algorithm with the 1-Redundant and the K-Redundant schemes, and results show our algorithm outperform current redesign solutions inn terms of cost, addmission, execution time and revenue.

In Chapter 4, Multicast Network in data centers is discussed and the failure scenarios are analysed. The Survivability of Multicast Virtual Network problem is then investigated and formally defined. To address this problem, we presented a

mathematical model, which can be deployed to reactively find recovery solutions in case of both source node failure or termial node failure. In addition, two alternative techniques, namely "Path-Covergence source node finding" and "Hop-to-Hop terminal finding", are introduced to solve the source node failure and terminals failure respectively. We compared our model with our Algorithms, the results show that our Algorithms are able to run much more efficient while maintaning close performance.

5.2 Contributions

The contributions of this thesis are summarized as follows:

- Develped a Survivable Virtual Network Redesign Algorithm that determines the survivable design of a VN considering sharing techniques.

- Presented a Survivable Virtual Network embedding model that optimizes the embedding solution of a given SVN and a node mapping solution.

- Compared our redesign algorithm against the existing redesign schemes, 1-Redundant and K-Redundant. The results show our method is able to achieve higher admission and revenue; meantime keeps the embedding cost and execution time in a lower level.

- Introduced a mathmetical model to reactively maintain a multicast VN tree in cloud data centers.

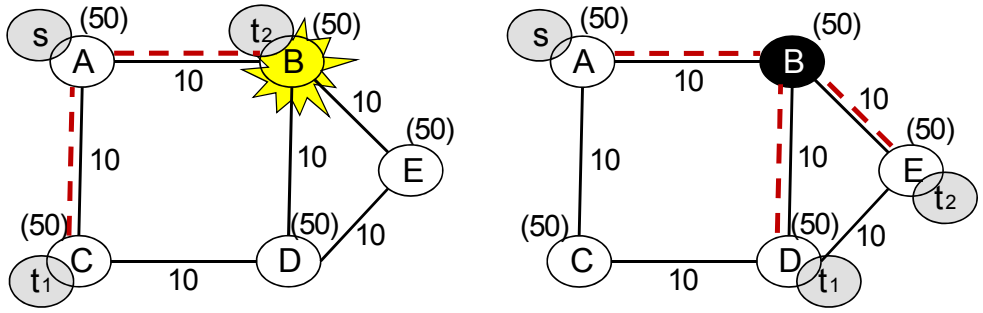
- Developed two novel algorithms as an alternative approach to do multicast tree maintenance. Through the test results, our algorithms have proven to have much less execution time but close performance compared to the model.

5.3 Future Work

In our future study of survivability of VN, it would be interesting to cover failure of elements into our problem for the future work. Thus far, research on VN/SVN embedding are either seen virtual nodes as VMs, which have computation and storage resource demands, or consider the virtual topology as "Virtual Data Center(VDC)", which consist of VMs and network elements. To the best of our knowledge, both assumptions share the same principle and can be protected from failures using the same method. In "Virtual Data Center(VDC)", VMs and network elements are differentiated and embedded on physical servers. Similarly, in conventional VN, even though there are only VMs, but though NFV (Network Functions Virtualization), network elements can be virtualized on top of VMs. With that being said, the separation of network elements and facility elements provides InPs a better view of resources demand variation, and to achieve better optimization of VNE. Therefore, for our future work, we would like to consider the survivable redesign and embedding of "Virtual Data Center(VDC)".

Regarding the work of multicast VN maintenance, we figured the drawback of our approach, is that we can not gaurantee the restoration for all failure cases, especially when the capacity state of the network elements is limited. In fact, this is also a common weakness of the reactive restoration. Hence, in our future work, we aim at finding a technique that would improve the chance of successful restoration. As we investigated on the unsuccessful restoration cases, we found that by enabling the migration of one or more working terminal node(s), the multicast tree can be recovered. The following example is used to demonstrates our statement:

Recall our 2-terminals MVN (presented in Figure 4.1(a)) hosted in a 5-nodes substrate network as shown in Figure 5.1(a). The failure of terminal node t_2 kicks off a reactive look-up for a valid backup node that can assume the role of t_2 and restore the affected service. Given that the MVN in question has an end-delay requirement of 2, then t_2 can migrate to substrate nodes D or E while satisfying the



(a) No Feasible Restoration

(b) Migration-Aware Restoration

FIGURE 5.1: Advantage of Terminal Nodes Migration

end-delay constraint. However, with the additional differential-delay constraint of 0, there are no possible ways to restore t_2 while maintaining the requested QoS. One possible solution for this problem could be to re-embed the failed MVN from scratch. Such an approach is seemingly unpleasant as it disrupts the entire service. A more promising solution is to encourage migrating some parts of the working MVN to widen the search space. Figure 5.1 highlights this advantage. Clearly, by migrating the working terminal t_1 to substrate node D, it is now possible to migrate the failed terminal t_2 onto substrate node E and reconstruct a multicast tree that interconnects both terminals to the source while satisfying both end-delay and differential-delay requirements.

With the motivation of improving our algorithm, in the future work, we intend to re-design our approach considering migrations of working terminals, we name such approach "Migration-Aware Tree Maintenance". We believe this new approach is able to achieve better results in terms of restoration and total revenue.

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