Network Virtualization for Disaster Resilience of Cloud Services

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ABSTRACT

Today’s businesses and consumer applications are becoming increasingly dependent on cloud solutions, making them vulnerable to service outages that can result in a loss of communication or access to business-critical services and data. Are we really prepared for such failure scenarios? Given that failures can occur on both the network and data center sides, is it possible to have efficient end-to-end recovery? The answer is mostly negative due to the separate operation of these domains. This article offers a solution to this problem based on network virtualization, and discusses the necessary architecture and algorithm details. It also answers the question of whether it is better to provide resilience in the virtual or physical layer from a cost effectiveness and failure coverage perspective.

INTRODUCTION

The way people communicate and do business today is changing. Beyond calling people, we send messages or emails. We upload pictures and videos or post about what we are doing. These services are generally provided by servers located in large data centers. Previously, many companies had various servers located in different locations, but now they outsource their IT services to cloud providers or locate them in private clouds within their company network. As a result, today’s communication infrastructures consist not only of communication networks but also storage and compute elements located in big data centers that constitute cloud infrastructures. Even the communication networks themselves will depend on clouds in the near future. Software defined networking (SDN) and network virtualization technologies enable network functions virtualization, where the basic idea is to locate the network elements’ intelligence in the cloud and enable the use of standardized proprietary hardware within the networks.

In a nutshell, the networks need the cloud to function, and the clouds need the network for information exchange and especially to reach the end customers. Such interdependence requires conscious coordination between the network and cloud domains. However, these domains are currently often operated by separate entities, making coordinated failure coverage and end-to-end optimization largely impossible. However, to provide sufficient quality of service (QoS) and reliability to customers, services need to be optimized in an end-to-end fashion. Reliability plays a crucial role in the decision to adopt cloud services by businesses and is their primary concern according to a survey conducted of over 3700 companies worldwide [1]. Performance ranks third in the list of concerns and has about the same significance as the second, security. Performance concerns are understandable since service degradation and outages can be mission-critical or even fatal. Outages do happen: in the past two years, there have been many outages, some lasting for hours or days, even occurring in the networks and data centers of governments, cities, airline systems, big cloud, and network providers, affecting many businesses and millions of users [2]. Besides local causes of outages caused by power outages, fiber cuts, server or router failures, and so on, some outages can affect a large area and have an even larger impact on businesses and society (e.g., in natural disasters). Cloud providers, affecting many businesses and millions of users [2]. Besides local causes of outages caused by power outages, fiber cuts, server or router failures, and so on, some outages can affect a large area and have an even larger impact on businesses and society (e.g., in natural disasters). Combined, outages and outage recovery in the cloud spans the entire cloud domain. This article discusses the necessary architecture and algorithm details. It also answers the question of whether it is better to provide resilience in the virtual or physical layer from a cost effectiveness and failure coverage perspective.
unique layer-specific address space, protocol stack, routing, and QoS definitions. Virtual networks mimic the whole functionality of a physical network, and on top of that offer more flexibility in network design due to an overview of different physical network and cloud domains.

In this article, we propose resilient network virtualization as an approach to disaster recovery, and first describe the network virtualization architecture enabling end-to-end resilience for cloud services. Then we answer the questions of how to design resilient virtual networks and at which layer to apply resilience. We consider different alternatives and compare them in terms of their cost and failure coverage to provide a handy framework to future network providers when deciding on their resilience design. This article extends our previous works [8, 10] by introducing the architectural details and hybrid resilience models, and providing an overview of cost and failure coverage comparison.

**NETWORK VIRTUALIZATION ARCHITECTURE**

In a network virtualization environment, new business roles are expected to emerge [3, 4]. In our architecture, we define three main business roles, as shown in Fig. 1. The physical infrastructure provider (PIP) is the owner of the physical infrastructure, which can consist of fixed or mobile networks (layer 1, 2, or 3) and IT resources like compute and storage, or any combination of them. The physical infrastructure can be composed of multiple PIP domains. The choice of technology in the communication network is not limited; it can be wavelength-division multiplexing (WDM), Ethernet, IP, and so on. A PIP can fully control and monitor its resources, where it can use a generalized multiprotocol label switching (GMPLS) control plane or an SDN-based approach like OpenFlow (OF). A data center PIP is expected to have its own data center network with various interconnected servers. The interface between the data center and WAN depends on the technologies used on both sides. For example, if MPLS is used in the data center, one can easily connect it to the GMPLS WAN with, say, hierarchical label-switched paths (LSPs) or LSP stitching. If OF is used in the data center, the OF controller can communicate with other OF controllers and with GMPLS. For non-MPLS IP virtual private networks (VPNs) and IP overlays not based on VPN like virtual extensible LAN (VXLAN) in the data center, the connection can go over an autonomous system border router (ASBR) and a data center gateway (GW). In the case of an ASBR, there are different options like back-to-back virtual routing and forwarding (VRF), and External Border Gateway Protocol (EBGP) redistribution of labeled VPN-IP routes between neighboring autonomous systems (ASs) without and with multipath EBGP redistribution of labeled VPN-IP routes between source and destination ASs, listed in increasing scalability and decreasing security order [5]. For GW solutions, network overlay stitching can be applied using a data center–WAN GW performing, for example, VRF termination or translation between the virtual network IDs on the data center side and VPN labels on the WAN side [5].

The resources of the PIPs are virtualized and appropriately advertised to the virtual network operators (VNOs). These resources can be virtu-

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**Figure 1.** Network virtualization architecture showing an example scenario including a service provider (SP), a virtual network operator (VNO) network, and the physical infrastructure of one or more physical infrastructure providers (PIPs) connected via user network interfaces (UNIs) and external network–network interfaces (E-NNIs).
al network links and nodes as well as virtual machines inside servers. A VNO selects the resources it requires and requests the setup of a virtual network with these resources from the PIP(s). Once the virtual network is established, the VNO has full control over it using its own control and management plane. Combined control of virtualized network and IT resources is enabled, enabling an end-to-end design and recovery for cloud services, regardless of whether they belong to various PIPs or heterogeneous networks. The last business role is the service provider (SP), who requests cloud or connectivity service from the VNO.

The literature [3, 4] usually defines an additional role, the central broker between many PIPs and VNOs, which we assume to be included in the VNO role since it does not provide an additional effect on the resilience analysis.

**Resilient Virtual Network Design: Problem Statement**

The aforementioned network virtualization architecture leads to the question of how to design virtual networks for end-to-end-resilient cloud services. Virtual networks are generally similar to overlay networks and VPNs, but there are some differences. In network virtualization, there is a complete isolated network slice as opposed to mere traffic isolation as in VPNs and just node virtualization in the case of overlay networks, which allows the VNOs to operate their service-tailored networks.

Moreover, the design proposals from the VPN or overlay network literature cannot be applied directly. As shown in Fig. 2, in a virtual network environment, the virtual network is mapped on a physical infrastructure, and service requests are routed within the virtual network. Figure 2a shows the case of overlay networks, where the virtual network is already given and the mapping is known. This type of literature addresses how to route the services in a resilient way [6]. For survivable VPNs or virtual network embedding [7], the virtual network is given and should be embedded onto the physical infrastructure in a survivable way, as shown in Fig. 2b. However, a VNO, which needs to design a virtual network to serve its customers, does not have a priori knowledge of a cost-optimal topology. Since a VNO needs to pay a certain fee for renting the virtual resources, it tries to design a virtual network that best fits the requirements of the service requests at a lowest possible cost using input from its customers and the SPs, and knowledge about the advertised resources of different PIPs, as shown in Fig. 2c. A PIP’s aim is to serve as many customers, VNOs, as possible, hence efficiently using its physical resources. In order to achieve this, a PIP can favor advertisement of certain virtual resources to a VNO. As a result, we propose the use of a variety of customized virtual network planning and optimization algorithms for a VNO, which can be selected and used according to its needs in order to design resilient virtual networks.

These algorithms can rely on integer linear programs or heuristics. Optimization objectives include minimum cost virtual network design, minimum latency of the service requests [8], and fulfillment of specific QoS requirements while keeping cost in an acceptable range. Special protection mechanisms like shared protection can create win-win situations [9]. It lowers the virtual network setup cost for VNOs by sharing redundant virtual resources among different services. For PIPs, it increases the physical resource usage efficiency and hence enables more customers to be served.

The general structure of these algorithms is described in the following. The algorithm takes as input:

- Advertised network resources from the PIP(s) modeled as an undirected physical network graph
- Available data center resources with their network connection nodes
- Set of virtual link and node candidates given as a multigraph connecting all service source nodes with each other and with all possible data center locations

**Figure 2.** The differentiation between network virtualization, overlay networks, and survivable VPNs: a) in overlay networks, the virtual network and its mapping onto the physical substrate are given as input to the problem and the services need to be routed under survivability constraints; b) for survivable VPNs and virtual network embedding, the virtual network topology is given again and needs to be embedded into the physical infrastructure in a survivable way; c) in network virtualization, however, the virtual network topology is generally unknown a priori. Therefore, it is not taken as input, but has to be determined according to the available physical resources and incoming service requests, which need to be routed in this virtual network.
One question when designing resilient virtual networks is at which layer resilience mechanisms should be applied. There are three basic alternatives: providing resilience in the virtual layer by the PIPs (PIP-Resilience), in the physical layer by the PIPs (PIP-Resilience), or a combination of both. Resilience in a certain layer has its advantages and drawbacks. The decision metric can vary depending on the priorities of a network provider; these can be, for example, virtual network setup cost, failure coverage, service latency, recovery time, and network utilization. We focus on the first two because there is a trade-off between the price one needs to pay and the offered protection level. Moreover, cost is not the only but usually the main driver for decision making in businesses.

**Resilience Design Alternatives**

The resilience design alternatives we address in this section are shown in Fig. 3. In each option, one primary and one DR data center site is used for each service. Network resilience, using 1:1 protection, is also provided for the paths leading to those sites. The figure uses a single service as an example to describe the models; however, multiple services are normally routed using multihop routing within the same virtual network, and each service can be routed to any two geographically disjoint data centers. Note that the protection level can be increased by using a higher number of DR sites and a higher level of network resilience, accordingly.

In **PIP-Resilience**, both the network and cloud resilience are delegated to the PIP(s). Each service is routed to a single data center site using a single path within the virtual network as shown with a bold line in Fig. 3a. Since the information about the services is not available at the PIP level, resilience is provided at the virtual link level by using a 1:1 protection mapping for them in the physical layer. For anycast services, cloud resilience is the responsibility of the cloud provider owning the primary data center site. In case of a failure, it redirects the traffic to the DR site in the physical layer. This approach is based on the literature on resilient anycast routing [10]; that is, the services are routed to any two sites, which operate as primary and protec-
tion sites and fulfill the service requirements, with one difference being that the optimization objective is the cost of the virtual network. This recovery action is transparent to the VNO.

If a VNO wants to provision resilience in the virtual layer, it can do so by routing each service to two disjoint data center locations, where the working and protection paths leading to these locations need to be physically disjoint. The same is valid for the unicast case, where the destination nodes of the two paths are identical. This model is called VNO-Resilience and is shown in Fig. 3b. In this case, it is sufficient to have a single path mapping for the virtual links. Moreover, cloud resilience is not limited to a single cloud provider, and the VNO can select any two geographically disjoint data center locations from any provider best suit the needs of the cloud service requests.

The mathematical formulation of PIP-Resilience and VNO-Resilience models can be found in [8]. The hybrid models are based on the VNO-Resilience model. The main idea behind the usage of the hybrid models is making use of the flexibility of the VNOs in choosing the data center sites and delegating network resilience to the PIPs, which already possess this knowledge and have access to all physical network information. This is a realistic use case for business roles possessing data center resources but no network resources and no network resilience knowledge. Moreover, another big advantage of hybrid models from an operational point of view is the avoidance of unnecessary data center switching due to network failures, which can happen more frequently than complete data center failures.

In the first hybrid model, hybrid all paths protected (HAP), the virtual links used in the paths leading to both the primary and DR sites are resilient, as shown in Fig. 3c. The difference of this model with VNO-Resilience is that there is no longer any need for diversity constraints for the network resources, since network resilience is delegated to the PIP(s).

In HAP, the additional protection against joint data center and backup path failures compared to VNO-Resilience might increase the virtual network price. If failures of the primary data center and the protection path are assumed to be independent, it is sufficient to use unprotected virtual links for the protection path as shown in Fig. 3d, which is called hybrid primary path protected (HPP).

<table>
<thead>
<tr>
<th>Failure type</th>
<th>VNO</th>
<th>PIP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Failure detection</td>
<td>Recovery</td>
</tr>
<tr>
<td>Transport link failure</td>
<td>Implicit detection</td>
<td>Yes</td>
</tr>
<tr>
<td>Router/switch/ server failure</td>
<td>Implicit detection</td>
<td>Yes</td>
</tr>
<tr>
<td>Virtual link failure</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Internal virtual machine failure</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Complete virtual machine failure</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Hypervisor (management of VMs) failure</td>
<td>Implicit detection</td>
<td>Yes</td>
</tr>
<tr>
<td>Control plane (CP) failure</td>
<td>Its own CP</td>
<td>Its own CP</td>
</tr>
<tr>
<td>Complete data center failure</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Sub-network failure</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
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Table 1. Possible failures in a virtual network environment, layers they are detectable, and layers that are responsible for the recovery.
PIP. Still, normally it is the responsibility of a VNO to restart its virtual machines and take the necessary recovery actions.

In case of a hypervisor failure, which is similar to a physical link/node failure, both roles can detect the failure and recover from it; however, to solve the cause of the problem is the responsibility of the PIP. In the case of a control plane failure, each layer can detect the problems within its own control plane and react to them only. However, since in that case the data plane continues to work and hence a fast recovery is not required, we do not go into more detail on this problem.

Finally, protection against complete data center failures or subnetwork failures, or disaster recovery, can be provided by both business roles. In both of these failure types, where a part of a physical domain or a complete domain is affected, PIPs might have a disadvantage compared to VNOs, who have an overview of different PIP domains. For example, if a PIP only possesses a single data center or the complete PIP domain goes down, it has no chance of offering any recovery for the failed services. However, a VNO can make use of the other available network and cloud domains, and can even have a solid disaster recovery strategy by selecting its resources in advance from disjoint physical domains or availability regions. Availability regions are ideally predetermined such that a failure in one region does not affect the other regions.

In conclusion, recovery against physical failures can be provided by both business roles, where problems occurring within the virtual layer can only be detected and reacted to by the VNOs. Therefore, for physical failure protection, one can choose to provide resilience in the physical or virtual layer, or a combination of both. A recovery strategy in the virtual layer requires reserving redundant virtual resources in advance or requesting them in case of failure depending on the level of protection required, increasing the cost and level of necessary network management knowledge at the VNO. A PIP layer can cope better with physical failures but is restricted in terms of accessing the resources of other domains. Since it is not trivial to decide on the layer to provision resilience, this issue is discussed further in the next section.

**What Level of Resilience Should Be Used? At Which Layer Should It Be Applied?**

Resilience provisioning increases the overall network cost; however, it also increases the service quality and customer satisfaction. Therefore, there is a trade-off between cost and the level of protection or failure coverage an operator should provide.

**Cost vs. Failure Coverage**

First, we give some insight on how the virtual network cost changes with increased protection levels to help future operators in their decision on a feasible level of resilience provisioning. Figure 4 shows a virtual network setup cost comparison for different levels of protection with PIP-Resilience and VNO-Resilience. Protection against single link/node failures and subnetwork failures is realized by using two link/node or subnetwork disjoint paths for the routing of services or the mapping of virtual links, respectively. In a subnetwork failure, all the links and nodes in that subnetwork are assumed to fail. For protection against double link failures, three link disjoint paths are utilized. The number of service nodes signifies the different source node locations of the services, where services with different destinations do not necessarily use the same routing. In our analysis, we define the setup cost of a virtual network as the summation of virtual link, node, and vir-
Figure 5. Virtual network cost comparison of the resilience design alternatives. The cost is defined as (virtual link cost, virtual node cost, virtual machine cost), where the setup and capacity-dependent costs of each individual resource type are equal. L is the physical length of a virtual link in kilometers, and using this option states that the cost of a virtual link is dependent on its length. A is the average shortest path length in the physical topology, and x is a positive scalar and is in the same order as A if specified as $x \sim A$.

The cost components consist of certain fixed cost values signifying the cost of setting up this virtual element and a capacity-dependent cost value per unit capacity requested on the virtual element. For this example, the cost factors are chosen such that fixed cost components are higher than the capacity-dependent cost components, and link cost is the dominant cost factor: the setup used and capacity-dependent values for the link/node cost are 200/4 and 20/4, respectively. The reason for this is the assumption that the initial setup of a virtual element can be more costly than increasing its capacity incrementally. Due to the use of fixed cost values, the relative cost behavior is mainly unaffected by the number of service nodes. Further cost analysis with varying cost values is provided in the next section using the more general case of anycast services.

Under the given assumptions, it is shown that PIP-Resilience results in a lower cost value than VNO-Resilience for all considered failure types due to the high link setup cost and higher number of virtual links required in the VNO-Resilience model. The most interesting result is that providing resilience against single link, node, or subnetwork failures has almost the same cost to an operator. In a subnetwork failure, it is assumed that all the links and nodes in a certain availability region fail simultaneously due to, for example, a disaster [11]. Thus, an intelligent virtual network design enables disaster resilience at the same cost as single link failure protection. Moreover, if protection against double link failures is requested (i.e., protection against simultaneous failure of two independent links), the cost increase compared to single link failure protection is significantly lower with PIP-Resilience than with VNO-Resilience. Finally, failures occurring in the virtual layer can only be detected and recovered from in the virtual layer. Moreover, if protection against virtual link and node failures is already provisioned in the virtual layer, it is more cost efficient to request a non-resilient network from the PIP(s) since single physical link and node protection is implicitly provided in the virtual layer.

Cost Comparison of Resilience Design Alternatives

Since it is rather difficult to estimate future cost values, the effect of varying cost parameters is analyzed to build a framework for the resilience layer decision. The cost trade-off for a VNO occurs due to the choice between renting cheaper non-resilient virtual elements but requiring a larger number of them due to redundancy provisioning, and renting a lower number of resilient higher-cost elements. The cost difference between a resilient and non-resilient resource is called the resilience premium and is taken as a multiplication factor of two in this analysis because 1:1 link and data center protection is provided. The costs are defined as tuples: (Link Cost, Node Cost, Virtual Machine Cost), as shown in Fig. 5. The cost settings are designed to show the effect of dominance or equality of the cost components. We also differentiate between fixed link cost values and link cost depending linearly on the physical length (in kilometers) of a virtual link. Fixed values are shown with a 1 (unit cost) or x, which is a real value larger than 0, and the case with length dependence is specified with an L. The fixed and unit capacity cost values of each component are assumed to be equal to simplify the comparison. The simulation results are within a $\pm 5$ percent confidence interval with a confidence level of 95 percent. The results are shown for two randomly located data centers owned by a single PIP and 10 service source nodes, where a single virtual network solution can be computed within a few seconds on a computer with 16 cores and 60 Gbytes RAM memory. The results are scaled down to cost = 1 for PIP-Resilience for each case to allow comparison of the models with the different cases, but each alternative has different absolute values and can use different service routing and virtual resource mapping.

For (L,1,1), where virtual link cost is dependent on the physical length of the link, VNO-Resilience results in a virtual network cost value lower than half those with other resilience alternatives due to its routing advantage compared to PIP-Resilience and the usage of disjoint virtual paths containing virtual links using simple path mapping compared to the hybrid models. Having equal emphasis on all cost components, as in $(x,x,x)$ and $(L,x \sim A,x \sim A)$, causes VNO-Resilience and PIP-Resilience to perform very close to each other and better than both hybrid alternatives as node cost compensates the routing advantage of VNO-Resilience and increases the cost of hybrid models. If the virtual machine or node cost is the dominant cost component as in $(1,1,x >> 1)$ and $(1,x >> 1,1)$, VNO-Resilience, HAP, and HPP result in almost equal values, and PIP-Resilience has a lower cost due to its lowest virtual node resource requirements. If virtual machine cost dominates the cost, the cost with PIP-Resilience is only slightly better, but with
dominance of node cost the difference is significant. The results in Fig. 5 are observed for a single data center provider, where increasing the number of the data center providers, the distance between individual data centers, and the number of service nodes makes VNO-Resilience more favorable than PIP-Resilience, and reduces the excess cost in HAP and HPP for length-dependent virtual link cost. For the other three cases, the results remain in the same range.

In conclusion, the cost performance of resilience designs depends heavily on the actual cost values. PIP-Resilience is favorable if the node cost is dominant. With a dominant link cost, VNO-Resilience performs the best. For equal cost values, having resilience entirely in either the virtual or physical layer is a better option than hybrid designs. Where virtual machine cost dominates in terms of virtual network cost, the operator is rather free to decide on the layer of resilience provisioning. In such a case, other criteria to consider can be the required failure coverage and the level of network management knowledge at the VNO layer.

**CONCLUSION**

This article tackles the question of how to provide end-to-end resilience for cloud services in case of failures and disasters, and proposes a solution based on network virtualization. After the introduction of a detailed architecture and resilient virtual network design solutions, we investigate at which layer to provision resilience in terms of failure coverage and virtual network setup cost — the fee a VNO needs to pay to PIPs for rental of virtual resources and establishment of a virtual network. With the used cost model, we show that providing resilience against single link, node, or subnetwork failures have almost the same cost to a VNO and a PIP. Failures occurring in the virtual layer can only be detected and recovered from in the virtual layer. If protection against these failures is already in place, delegating protection against physical link and node failures to PIPs is not needed, since it is implicitly provided. We also provide a detailed analysis from the cost perspective with various pricing alternatives offering a framework in the decision on realizing resilience in the virtual or physical layer, or a combination of both. Future work may address analyzing the resilience layer in terms of, say, service latency, resource utilization, and complexity. Moreover, the effect of dynamic server resource allocation and redundant capacity sharing is a topic for further evaluation.

**REFERENCES**


**BIographies**

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