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Resilient virtual communication networks using multi-commodity flow based local optimal mapping

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ABSTRACT

Network virtualization has been considered a promising approach for promoting heterogeneous services and mechanisms towards the next-generation network architectures, which can greatly improve the global utilization efficiency of network resources, and hence the capacity of service delivery. However, virtual network invulnerability has long been ignored and little research effort has been made. In this paper, we presented a novel virtual network restoration approach, MFP-VNMH, which could enhance the VN mapping and service restoration subject to the physical link failure in the physical substrate whilst avoiding the remapping of the overall VNs. The performance of proposed MFP-VNMH is assessed through extensive numerical experiments for a range of network scenarios in comparison with the overall VN remapping approach and the end-to-end link remapping approach. The result is encouraging and demonstrates its effectiveness and efficiency for VN mapping update and service restoration upon physical substrate failures.

1. Introduction

Network virtualization (e.g., GENI; Ghoda et al., 2016; Hammad et al., 2016) supporting a set of embedded virtual networks (VNs) to coexist in a shared infrastructure has been considered a promising approach for accommodating and promoting novel heterogeneous services and mechanisms towards the next-generation network architectures. Current large-scale networks, e.g., Internet, are facing "ossification" and many technical challenges which need to be addressed by more advanced networking architectures. Multiple virtual networks can share the underlying physical substrate to deliver a variety of tailored services by adopting heterogeneous network technologies in an isolated manner. In addition, the provision of standardized interfaces among virtual networks could enable seamless and transparent communications across multiple domains. From the network management perspective, network virtualization can greatly improve the global utilization efficiency of network resources, and hence the capacity of network service provision.

However, it should be noted that the virtual network invulnerability which is one of the key aspects of network virtualization has been long ignored and little research effort has been made yet. The self-healing capability virtual networks involves several aspects, which can be summarized in four aspects: 1) proactively detecting the potential faults of physical components in the substrate to prevent service interruption due to reorganization of virtual networks (i.e. remapping of links and nodes); 2) keeping the load balance of the physical substrate to avoid or alleviate network resource bottleneck; 3) restoring the service delivery in the failed virtual networks as quick as possible upon physical network failures; and 4) protecting the services delivered by the virtual networks against a range of network attacks, e.g., Denial of Service (DoS) and network worms propagation. Fig. 1 illustrates a scenario that a failed physical link can result in the unavailability virtual link, and as a consequence, the overall virtual network can no longer deliver expected services. In general, following to the physical substrate faults, the affected virtual networks need to be remapped to establish a new set of virtual networks through network mapping algorithms which may often impose prohibitive complexity in network management, particularly in large-scale networks.

In this paper, a novel approach, MFP-VNMH, is exploited and presented by adopting the Multi-commodity Flow Problem (MFP)

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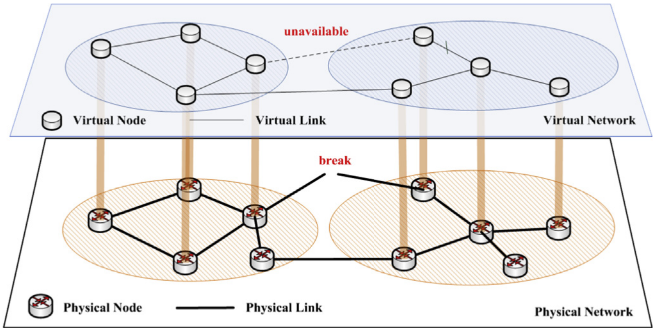

Fig. 1. An example of virtual network mapping.

(Ahuja et al., 1993) based network management strategy to enable the self-healing capability in network virtualization. More specifically, this approach aims to achieve fast service restoration upon VN failures by improving the service restoration success ratio, minimizing the restoration time, whilst maintaining the load balance across the overall physical substrate.

The remainder of this paper is organized as follows: Section 2 summarizes and discusses the related work, followed by the description of problem formulation in Section 3. Section 4 overviews the proposed MFP-VNMH strategy, with a particular focus on its control protocols and procedures, and Section 5 presents the key architecture and mechanism of MPF-VNMH in details; Section 6 presents the performance evaluation through numerical simulation experiments and a set of key numerical results; finally, some conclusive remarks are given in Section 7.

2. Related work

It is well-known that many virtual network mapping problems are with NP-Complete (NPC) complexity. In recent years, to address such computational intractability, a collection of heuristics or linear programming based proposals has been reported (e.g., Chen et al., 2012, 2016; Li et al., 2015; Assiset al, 2016; Xu et al., 2016; Yang and Guo, 2016; Zhang et al., 2012; Miao et al., 2013; Yang et al., 2012; Ilhem Nadjibet al, 2011) from different aspects. In (Chen et al., 2016), a novel mixed integer linear programming (MILP) formulation was proposed for different schemes of protection in scenarios where multiple virtual topologies run over an elastic optical network. The proposed MILP formulation uses the concept of bandwidth squeezing to guarantee a minimum bandwidth for surviving virtual topologies. In (Li et al., 2015), the authors introduced an software-defined network (SDN)-based RAN virtualization framework, and stated the problem of maximizing the number of SIoT groups with limited SDN rule space. With the observations of benefits of SDN for programmability and automation in network control, the work in (Assiset al, 2016) proposed a dynamic resource management scheme (EnterpriseVisor engine) that manages the distribution of network resources among slices based on the OpenFlow/FlowVisor network virtualization layer. In (Xu et al., 2016), the work addressed the virtual network mapping problem by proposing a new and comprehensive revenue model, which is employed as a ranking criterion for VN requests before mapping. The authors in (Chen et al., 2012) presented a new VN mapping algorithm that can guarantee the network robustness by the use of node resources and connected link resources as the metric of available node resources in node mapping. An exact virtual network embedding algorithm based on integer linear programming for virtual network request with location constraints was presented in (Yang and Guo, 2016). A novel hierarchical algorithm to address this issue by formulating such VN mapping problem as a hierarchical linear programme model has been presented in one of our studies (Zhang et al., 2012). In (Miao et al., 2013), we exploited the multicast networks mapping for enabling Multiple Description Coding (MDC) based video applications. In (Yang et al., 2012), we tackled the virtual network mapping problem and proposed a novel hierarchical algorithm in conjunction with a substrate network decomposition approach. The authors in (Ilhem Nadjibet al, 2011) proposed a new scalable VN embedding strategy based on the Ant Colony metaheuristic to deal with the computational hardness, which aimed to map virtual networks in the substrate network with minimum physical resources while satisfying its required QoS in terms of bandwidth, power processing and memory. However, the aforementioned solutions have not explicitly address the virtual network mapping problem considering the presence of link or node failures in substrate networks.

In addition, the fault-tolerant technology has been extensively studied (e.g., Sahasrabuddhe et al., 2002; Fajjari et al., 2011; Guo et al., 2011; Yalian et al., 2011). In (Sahasrabuddhe et al., 2002), the authors considered two fault-management techniques in an IP-over-WDM network where network nodes employ optical crossconnects and IP routers to provide protection in WDM layer and provide restoration in IP layer. However, such approach cannot be directly applied to the virtual network environment. An automatic pilot virtual network architecture which is able to monitor the virtual network failures, together with the concept “self-healing” for failed VNs is presented in (Fajjari et al., 2011). However, the specific approach and algorithmic solution to heal the failed VNs is not given. In (Guo et al., 2011), the shared backup network is designed to protect the embedded virtual network. Each VN will receive some pre-allocated backup resources to avoid the VN failure when the physical substrate suffers to faults. Such shared backup network is an off-line approach to VN protection, but with restricted flexibility and low efficiency of network resources utilization. In (Yalian et al., 2011), the authors proposed a fault diagnosis mechanism in network virtualization environment, which attempts to restore the VNs through fast fault detection and restoration of the physical network. Such approach can be time-consuming and suffer from an undeterminable long period of time. In fact, the VN service restoration upon physical network failures is expected to be processed as soon as possible, as well as minimize the interruption of other VNs and guarantee the physical network operational efficiency and flexibility.

In summary, current VN mapping solutions, either for random or specific topologies, merely focus on addressing the virtual network mapping problem and resource allocation without considering the fast service restoration upon network failures. In addition, the existing studies on fault-tolerant network either focus on fast detection and repair of physical substrate faults to protect the embedded virtual networks, or adopting the VN remapping algorithms, e.g., the overall VN remapping (Chen et al., 2016) and the end-to-end link remapping (Assiset al, 2016). Fig. 2 illustrates an example to demonstrate the available VN mapping strategies after link failures in the physical substrate. Fig. 2(a) shows the original VN mapping before the physical substrate failure occurs. Upon the failures at link $A-C$ and $C-F$ in the physical substrate, the VN needs to be remapped for service restoration. For the overall VN remapping solution (Chen et al., 2016), the remapping of both virtual nodes and links of the failed VN are carried out over the physical substrate, e.g., the virtual nodes a_1, b_1 and c_1 are remapped to F, G and H, respectively, as shown in Fig. 2(b). For the end-to-end link remapping solution (Assiset al, 2016), only the virtual links in the failed VN are remapped over the physical substrate, and the mapping of virtual nodes remains unchanged, as shown in Fig. 2(c). However, the aforementioned VN service restoration solutions may be not efficient and scalable in large-scale virtual network infrastructure which calls for more research exploitations. To this end, the key contribution made in this paper can be summarized as follows: 1) a Multi-Commodity based approach, MFP-VNMH, is proposed to restore the failed VNs through remapping of the virtual links and evaluated its performance against the existing overall VN remapping and end-to-end link remapping approaches; 2) through remapping the affected virtual links to available physical resources rather than the overall VN or end-to-end path due to the physical network failures, the scale of the VN