Guaranteed-Availability Network Function Virtualization with Network Protection and VNF Replication

Jian Kong[1], Inwoong Kim[2], Xi Wang[2], Qiong Zhang[2],
Hakki C. Cankaya[3], Weisheng Xie[3], Tadashi Ikeuchi[2], and Jason P. Jue[1]
[1]The University of Texas at Dallas, Richardson, TX 75080
[2]Fujitsu Laboratories of America, Richardson, TX 75082, [3]Fujitsu Network Communications, Richardson, TX 75082

***Abstract*—Network function virtualization (NFV) provides an efficient and flexible way to deploy network services in the form of service function chains (SFCs) by adopting generalized equipment. However, software-based virtualized network functions (VNFs) bring new challenge for network operators in providing service availability guarantees. Traditionally, network-level protection mechanisms are considered separately from function-level VNF backup mechanisms. However, a SFC's availability cannot be guaranteed if only network-level protection mechanisms or only function-level VNF backup mechanisms are considered. In this paper, we propose a coordinated protection mechanism that adopts both backup path protection in the network and VNF replicas at nodes to guarantee a SFC's availability. The proposed mechanism determines the number of replicas required for each VNF in the SFC, and allocates the replicas to physical nodes on the working and backup paths while maintaining ordered dependency among VNFs. Simulation results show that the proposed algorithms contribute to reducing the SFC blocking and the cost of computing resources.**

***Index Terms*—Network function virtualization, Service function chain, Availability, Protection**

I. Introduction

With the increasing growth of dynamic network services such as cloud computing and big data, a key challenge for network providers is how to flexibly and efficiently deploy new network functions or change existing network services. Traditionally, network functions are deployed as physical appliances that are tightly coupled with specific hardware. Physically deployed network functions hinder the rapid deployment of new services and result in operational challenges. Network function virtualization (NFV) provides a more agile network by implementing the virtual network functions (VNFs) in software that is decoupled from the underlying hardware [1] [2], and which therefore, significantly decreases the OPEX and CAPEX. Based on the service provider's demand, end-to-end network services may consist of an ordered set of VNFs, and such ordered functions connected by logical links is defined as a service function chain (SFC) [3].

Availability, which is defined as the fraction of time that a system is providing service to its users [4], is an important factor in measuring the quality of service in a network and can also be applied as a metric to measure the service quality in one SFC [5]. In general, VNFs are deployed on generalized hardware that may lack the robustness of standard telecommunications equipment. Physical hardware failures may also affect several VNFs in one SFC. Furthermore, the malfunction of the software-based VNFs and the loss of logical connections in one SFC may also result in the unavailability of the service [6]. Therefore, software-based VNFs and flexible SFC mapping bring new challenges for network operators to provide availability-guaranteed network services. The availability-guaranteed SFC mapping problem is to determine the mapping of the VNFs in one SFC to guarantee the SFC's availability.

The availability of both the network service and the SFC can be improved by adopting different protection mechanisms. Typically, network-layer protection (e.g., backup path) is provided to improve the availability of traditional network services. For software-based VNFs (one VNF may be deployed on one virtual machine), several replicas of each VNF are provided to guarantee its availability [7] [8] [9] [10]. However, the existing work provide replicas of each VNF while ignoring the availability of each physical network component. As pointed out in this paper, only providing backup paths in the network-layer or only allocating replicas for each VNF in the application layer cannot guarantee the SFC's availability, especially in the inter-datacenter network. Different from the existing work, we address the availability-guaranteed SFC mapping problem by considering path protection in the network-layer and replicas for each VNF in the application layer in a coordinated manner.

In this paper, we analyze SFC availability, considering both network link availability and VNF availability, and we develop an approach for guaranteeing the availability requirement of a SFC utilizing both network-layer protection and application-layer VNF replicas. By analyzing how to distribute VNF replicas between the working path and backup path in order to maximize the SFC's availability, we determine the number of replicas for each VNF in the SFC, and we allocate the replicas to physical nodes while maintaining ordered dependency among VNFs.

The rest of this paper is organized as follows. In Section II, we present the SFC mapping problem and show the avail-

978-1-5090-5019-2/17/$31.00 ©2017 IEEE

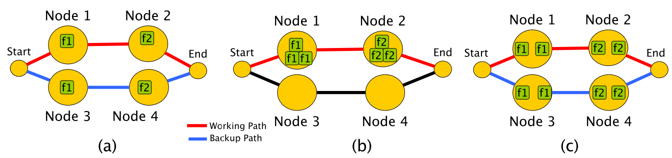

Fig. 1. Different layer protection mechanisms

ability calculation when both network-layer protection and application-layer VNF replicas are implemented. In Section III, we illustrate the heuristic algorithm for the availability-guaranteed SFC mapping problem, which determines the working path, the backup path, the number of replicas for each VNF, and how to distribute the replicas to the working path and the backup path. We also present a replica allocation algorithm that allocates replicas to the physical nodes in a way that balances the number of replicas among the nodes. In Section IV, numerical results are presented, and we conclude the paper in Section V.

II. Problem Statement

In this paper, we aim to find out the availability-guaranteed SFC mapping, and we investigate protection mechanisms for increasing SFC availability.

A. Availability of the SFC mapping

The availability of a SFC can be affected by many factors, such as physical network component failures or the malfunction of the virtual machines for one VNF. We categorize those factors into two different layers: the physical network layer and the application layer. SFC availability is affected by both the physical network availability and the VNF availability in the SFC.

1) network-layer protection: One possible approach to improve a SFC's availability is to provide a backup path in the physical network layer. For example, as shown in Fig. 1.(a), a SFC is protected with a dedicated path, and has only one replica for each VNF on the working path and backup path. The SFC's availability can be represented as:

$$A_w = \prod \alpha_{w_i} \prod \alpha_{f_i} \tag{1}$$

$$A_b = \prod \alpha_{b_i} \prod \alpha_{f_i} \tag{2}$$

$$A_{sfc} = A_w + A_b - A_w A_b < \prod \alpha_{f_i}, \tag{3}$$

where α_{w_i} is the availability of physical network component i in the working path , α_{b_i} is the availability of physical network component i on the backup path, and α_{f_i} is the availability of VNF f_i. We observe that the SFC's availability is limited by the VNF's availability.

2) application-layer protection: Another way to improve the SFC's availability is to provide several replicas for each VNF. As shown in Fig. 1.(b), the availability of the SFC with k_i replicas for one VNF f_i can be represented as:

$$A_{sfc} = \prod \alpha_{p_i} \prod (1-(1-\alpha_{f_i})^{k_i}) < \prod \alpha_{p_i}, \tag{4}$$

where α_{p_i} is the availability of the physical network component i. We note that the SFC's availability with only application-layer protection is limited by the physical path's availability.

3) coordinated protection: To eliminate the limitations in the above two protection mechanisms, we adopt a coordinated protection mechanism by providing both physical network-layer protection as well as application-layer protection, as shown in Fig. 1.(c). The SFC availability is calculated as:

$$A_w = \prod \alpha_{w_i} \prod (1-(1-\alpha_{f_i})^{kw_i}) \tag{5}$$

$$A_b = \prod \alpha_{b_i} \prod (1-(1-\alpha_{f_i})^{kb_i}) \tag{6}$$

$$A_{sfc} = A_w + A_b - A_w A_b, \tag{7}$$

where kw_i is the number of replicas for VNF f_i on the working path, and kb_i is the number of replicas for VNF f_i on the backup path.

B. Problem definition

In this paper, we focus on the availability-guaranteed SFC mapping problem with the coordinated protection mechanism. We are given a physical inter-datacenter network $G(V_p, E_p)$, where V_p is a set of the physical nodes, and CN_v is the number of computing resources units at physical node $v \in V_p$. E_p is the set of the physical links connecting the physical nodes, α_l is the availability of physical link l, and, CL_l is the link cost of physical link $l \in E_p$.

We are also given a SFC request $S(F_s, B, SA)$, where F_s is a set of the VNFs in the SFC, CR_i is the number of computing resource units required by VNF f_i ($f_i \in F_s$), and β_i is the availability of the VNF f_i. B is the traffic bandwidth, and SA is availability requirement of the SFC.

In this problem, we aim to find the working path and backup path (if needed) for the SFC, the number of replicas for each VNF, and the placement of replicas along the working and backup path. The objective is to minimize SFC blocking and to minimize the use of computing resources while guaranteeing the SFC's availability requirement. In this paper, we make the following assumptions:

- We consider a generalized inter-datacenter network where VNFs are deployed to physical nodes (datacenters).
- For one specific VNF, its replicas have the same availability and consume the same amount of computing resources.

III. Heuristic Algorithm

In this section, we propose heuristic algorithms that guarantee the SFC's availability by providing a coordinated protection mechanism. The algorithms first find the physical-layer working path (as well as a backup path if needed), then determine the number of replicas for each VNF in the SFC, and finally deploy the VNF replicas to the physical nodes.

A. Is there a need to provide physical layer protection?

Physical layer protection is not needed if the SFC availability requirement can be easily met using a single path. We propose two different approaches to find the physical layer path(s) as follows:

1) Link-cost-based path algorithm: We assume that each VNF has a maximum of L replicas. We first find the shortest path by deploying Dijkstra's algorithm. If the path can meet the availability requirement with L replicas for each VNF along the path, then there is no need to provide physical layer protection. Otherwise, we find two link-disjoint paths with the least total cost as the working path and the backup path by deploying Suurballe's algorithm [11].

2) Availability-based path algorithm: To maximize the physical layer availability, we propose an $availability-based$ algorithm by constructing an auxiliary graph G_a, in which the edge weights are determined by the following transformation:

$$c_i = -\log \alpha_i, \tag{8}$$

where α_i is the availability of physical link l_i. Given the maximum number L of replicas for each VNF, we first find the minimum-weight path in G_a and assign this path as the working path. We then check whether the SFC's availability can meet its requirement if each VNF has L replicas along this path. If the SFC's availability can meet its requirement, no physical layer protection is needed. Otherwise, we find two link-disjoint paths on G_a by applying Suurballe's algorithm. We follow the conclusion in [12] to maximize the availability of the two paths, and we allocate one path as the working path, and the other path as the backup path.

B. How to distribute the replicas between the working and backup paths?

If path layer protection is needed, after finding the working and the backup path, we need to determine how many replicas are needed for each VNF, and how to distribute the replicas among the working and backup path. We provide three different algorithms for determining the number of replicas on each path.

1) Vulnerable-vnf-first replicas algorithm: This algorithm attempts to provide replicas for the VNFs that have the lowest availability. Initially, there is one replica for each VNF on the working path and one replica for each VNF on the backup path. We first determine the VNF with the lowest availability by using the following equation:

$$a_{vnf_i} = 1 - (1 - a_{f_i})^{n_i} \tag{9}$$

where a_{f_i} is availability of one replica of VNF f_i, and n_i is the number of replicas of VNF f_i on the working or backup path. After determining the most vulnerable VNF and the path it belongs to, we provide one additional replica for that VNF along that path, and then check whether the SFC's availability is reached. If not, we repeat the process of finding a VNF with the lowest availability and provide an additional replica for that VNF.

Even if the SFC's availability can be improved by providing more replicas for each VNF, it may not be reasonable to provide an unlimited number of replicas due to the physical node's computing resource limitation and the cost to the service provider. Based on the availability calculation (Eq. 7), the SFC's availability is significantly affected by both the number of replicas for each VNF as well as the distribution of VNFs between the working path and backup path. For example, in Fig. 2, there is a SFC with one VNF f_1 mapped to both the working path and the backup path. The availability of the working path is α_w while the availability of the backup path is α_b. There are six replicas for f_1. We can allocate one to five replicas to the working path while the other replicas are allocated to the backup path. The SFC will have different availability under different replica distribution solutions. Therefore, we propose the following replica distribution algorithm:

2) Path-balance replicas algorithm: Given a total of K replicas, we try to determine the distribution of replicas to the working path and the backup path such that availability is maximum. If availability cannot meet the SFC's requirement, we increase K until the SFC's availability can be reached. We propose the following lemma:

Lemma 1: Given a SFC with one VNF, f_1 mapped to the working path and the backup path, the availability α_f of VNF f_1, the availability α_1 of the working path, and the availability α_2 of the backup path. If there are total of K ($K > 1$) replicas for f_1, the SFC's maximum availability solution is to distribute k_w replicas in the working path and $k_b = K - k_w$ replicas in the backup path, where

$$k_w = \begin{cases} \lfloor k_1 \rfloor & \text{if} \quad 0 < \lfloor k_1 \rfloor < K \\ 1 & \text{if} \quad \lfloor k_1 \rfloor \leqq 1 \\ K-1 & \text{if} \quad \lfloor k_1 \rfloor \geqq K, \end{cases} \tag{10}$$

and

$$k_1 = \frac{K}{2} + \frac{1}{2}(\log_{1-\alpha_f}^{\frac{1}{\alpha_1}-1} - \log_{1-\alpha_f}^{\frac{1}{\alpha_2}-1}). \tag{11}$$

Proof: We assume that the unavailability of f_1 is β where $\beta = (1 - \alpha_f)$, and $k_2 = K - k_1$ is the number of replicas deployed to the backup path. Therefore, the availability of the SFC is:

$$\begin{aligned} A_{sfc} &= \alpha_1(1-\beta^{k_1}) + \alpha_2(1-\beta^{k_2}) - \alpha_1(1-\beta^{k_1})\alpha_2(1-\beta^{k_2}) \\ &= \alpha_1 + \alpha_2 - \alpha_1\beta^{k_1} - \alpha_2\beta^{k_2} \\ &\quad -\alpha_1\alpha_2 + \alpha_1\alpha_2(\beta^{k_1} + \beta^{k_2}) - \alpha_1\alpha_2\beta^{k_1+k_2} \\ &= \alpha_1 + \alpha_2 - \alpha_1\alpha_2(1+\beta^K) - \alpha_1\beta^{k_1} \\ &\quad -\alpha_2\beta^{k_2} + \alpha_1\alpha_2(\beta^{k_1} + \beta^{k_2}) \\ &= \alpha_1 + \alpha_2 - \alpha_1\alpha_2(1+\beta^K) - \alpha_1\alpha_2\Delta, \end{aligned} \tag{12}$$

where

$$\begin{aligned} \Delta &= \tfrac{\beta^{k_1}}{\alpha_2} + \tfrac{\beta^{k_2}}{\alpha_1} - \beta^{k_1} - \beta^{k_2} \\ &= (\tfrac{1}{\alpha_2} - 1)\beta^{k_1} + (\tfrac{1}{\alpha_1} - 1)\beta^{k_2} \\ &= (\tfrac{1}{\alpha_2} - 1)\beta^{k_1} + \tfrac{(\frac{1}{\alpha_1}-1)\beta^K}{\beta^{k_1}} \\ &\geqq 2\sqrt{(\tfrac{1}{\alpha_2} - 1)(\tfrac{1}{\alpha_1} - 1)\beta^K}. \end{aligned} \tag{13}$$

Therefore, the function A_{sfc} reaches the peak point (maximum availability) when the following holds:

$$(\frac{1}{\alpha_2}-1)\beta^{k_1}=\frac{(\frac{1}{\alpha_1}-1)\beta^{K}}{\beta^{k_1}}. \quad (14)$$

We obtain:

$$k_1=\frac{K}{2}+\frac{1}{2}(\log_{\beta}^{\frac{1}{\alpha_1}-1}-\log_{\beta}^{\frac{1}{\alpha_2}-1}). \quad (15)$$

The conclusion holds. □

Lemma 2: Given the same conditions as in **Lemma 1**, we assume that there are at least two replicas ($k_w > 1$ and $k_b > 1$) for one VNF f_1 on the working path and at least two replicas on the backup path. If we can reduce two replicas of the VNF f_1, the SFC's maximum availability solution is to remove one replica from both the working path and the backup path.

Proof: As shown in Eq. 15, the SFC's availability is maximized when:

$$k_w-k_b=\log_{\beta}^{\frac{1}{\alpha_1}-1}-\log_{\beta}^{\frac{1}{\alpha_2}-1}, \quad (16)$$

which means that the difference between the number of replicas on the working path and the number of replicas on the backup path is a fixed number. Therefore, if the total number of replicas of VNF f_1 is reduced by two, we can remove one replica from the working path and another one from the backup path to keep the SFC's availability maximized. □

3) Vulnerable-vnf-path-balance replicas algorithm: Different from the $vulnerable\text{-}vnf\text{-}first\ replicas\ algorithm$, this algorithm determines the VNF with the lowest availability by considering the replicas on the working path and the backup path together. Initially, each VNF has one replica on the working path and one on the backup path. We determine the VNF f_i with the lowest availability based on Eq.(9), where n_i is the total number of replicas of VNF f_i on the working path and backup path combined. We increase the number of replicas of f_i, distribute these replicas among the working path and the backup path based on **Lemma 1**, and repeat to find the replicas for all VNFs until the SFC's availability can meet its requirement.

C. Replicas balance deployment algorithm

After determining the working path (and backup path if needed) and the number of replicas for each VNF, we deploy the replicas to the physical nodes in a way that balances the number of replicas among the nodes [13] [14].

Lemma 3: Assume there are unlimited computing resources on each physical node. We are given a SFC consisting of a set of VNFs without dependency among the VNFs, and the SFC is mapped to two link-disjoint paths as its working chain and backup chain. For VNF f_i, there are n_{w_i} replicas in the working chain and n_{b_i} replicas in the backup chain. The availability of the SFC will not be affected by how the n_{w_i} replicas are deployed along the physical nodes on the working chain or how the n_{b_i} replicas are deployed along the physical nodes of the backup chain. In other words, we can deploy the replicas of the VNFs on the working path (or backup path) to

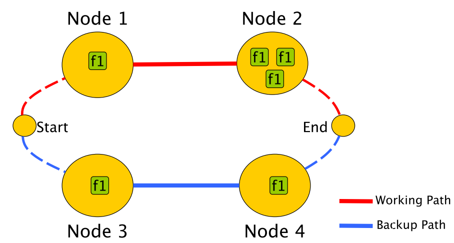

Fig. 2. Replicas distribution among the working and backup paths

any physical nodes along the working path (or backup path) without changing the SFC's availability.

Proof: As shown in Eq. 7, we see that the availability of the SFC is determined by the physical path availability and each VNF's availability. For example, there is a SFC with one VNF f_1, as shown in Fig. 2. There are four replicas for f_1 on the working path and two replicas on the backup path. Given the two link-disjoint paths as the mapping of the working path and the backup path, we can deploy the four replicas on the working path to $Node_1$ or $Node_2$ along the working path without changing the SFC's availability. □

Furthermore, if some VNFs are dependent on other VNFs in the SFC, we can also conclude that the replicas of the working chain can be mapped to the physical nodes in the working path without changing its availability as long as the dependencies among the VNFs are maintained.

Therefore, after the number of replicas on the working path (and the number of replicas on the backup path) is determined, we can deploy the replicas for the working and backup chains separately without changing the SFC's availability. We provide an example to show the details of the replica deployment along the working path. As shown in Fig. 3, there is a SFC S with four VNFs, f_1, f_2, f_3, and f_4. The number of replicas for the four VNFs are 3, 2, 2, 3, and the replica computing resource unit requirements are 2, 2, 1, and 1. There may also be dependencies among different VNFs. In this example, f_3 is dependent on f_1 ($f_1 \rightarrow f_3$), and f_4 is dependent on f_2 ($f_2 \rightarrow f_4$). S is mapped to a physical network with two nodes, and the available number of computing resource units at $Node_1$ and $Node_2$ is 10 and 8, respectively.

As shown in Fig. 4(a), we first separate the SFC into several sub-chains according to the dependencies s_1 ($f_1 \rightarrow f_3$) and s_2 ($f_2 \rightarrow f_4$). Then we construct a set Θ by choosing the first VNF from each sub-chain (f_1 from s_1 and f_2 from s_2). Then we deploy the replicas of the VNF with the maximum total resource consumption to $Node_1$ and then update Θ and each node's available capacity, as shown in Fig. 4(b). We can deploy all the VNFs to the nodes in the same way, as shown in Fig.4(c),(d),(e). Note that, if the available capacity of one node cannot support all the replicas of one VNF, we deploy as many replicas as possible in the current node, and then allocate the remaining replicas to the following node.

D. SFC mapping heuristic algorithms

Based on the above analysis and details, we propose five algorithms to address the availability-based SFC mapping problem. Algorithms 1 to 3 utilize $availability\text{-}based$

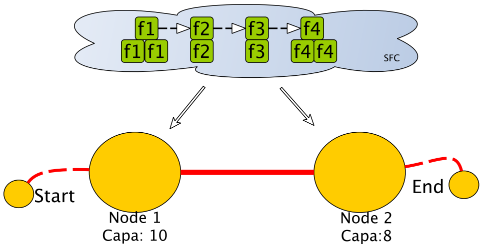

Fig. 3. VNFs with dependency

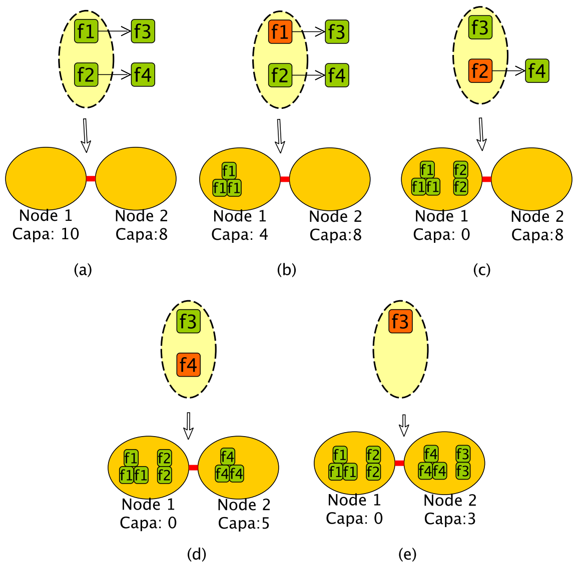

Fig. 4. Replicas deployment example

route selection, while Algorithms 4 and 5 utilize *link-cost-based* route selection. For determining the number of replicas and the distribution of replicas between the working and backup paths, Algorithms 1 and 4 utilize the *path-balance* replicas algorithm, while Algorithms 2 and 5 utilize the *vulnerable-vnf-first replicas* algorithm. Algorithm 3 utilizes the *vulnerable-vnf-path-balance* algorithm. All of the proposed heuristics use the same balance deployment algorithm for determining at which node along a path replicas should be deployed. A summary of the proposed heuristics is shown in Table I.

TABLE I
SUMMARY OF THE PROPOSED HEURISTIC ALGORITHMS

Alg.	Route selection	Replicas # and distribution	Replica deploy.
1	Avail.-based	path-balance	balance deploy.
2	Avail.-based	vulnerable-vnf-first	balance deploy.
3	Avail.-based	vulner.-vnf-path-balance	balance deploy.
4	Link-cost-based	path-balance	balance deploy
5	Link-cost-based	vulnerable-vnf-first	balance deploy.

IV. SIMULATION RESULTS

In this section, we evaluate the performance of the proposed heuristic algorithms in both the 24-node and 75-node U.S. mesh network (Fig. 5) [15] [16]. The availability of the physical links ranges from 0.999 to 0.99999. We randomly generate 100 SFCs for the 24-node mesh network topology and 200 SFCs for the 75-node mesh network topology. There

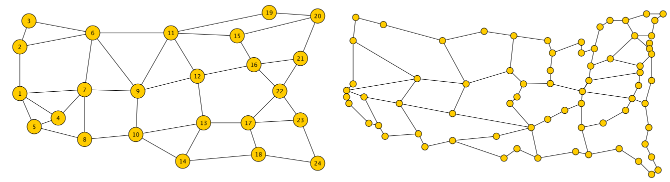

Fig. 5. 24-node and 75-node U.S. mesh network

are 10 types of VNFs with availability between 0.99 and 0.9999, and with required number of computing resources units ranging from 1 to 3. For each SFC, we randomly determine the number of the VNFs ranging from 2 to 6. The availability requirement of each SFC is distributed between 0.99 and 0.99999.

We first evaluate the performance of the algorithms in terms of the SFC request acceptance. If one SFC's availability cannot be met even when the backup path and the VNF replicas are provided, the SFC request is blocked. As shown in Fig. 6 and Fig. 7, when the SFC's availability requirement is low (0.99 and 0.999), the proposed algorithms can guarantee availability for all the SFCs. When the SFCs' availability requirements are 0.9999 or 0.99999, some SFC requests are blocked. We observe that *Algorithm* 1 performs the best in reducing the SFC requests blocking. In *Algorithm* 1, we try to find a higher availability SFC mapping by distributing the replicas of the VNFs among the working chain and the backup chain based on the theoretical analysis in **Lemma 1**. A higher availability of the SFC means that we can remove some replicas to further reduce the computing resources while guaranteeing the SFC's availability. Comparing between *Algorithm* 1 and *Algorithm* 3 (or *Algorithm* 2 and *Algorithm* 4), we observe that the availability-based approach contributes to finding the paths with higher availability, which results in a lower blocking ratio. By comparing the results among *Algorithm* 1, *Algorithm* 2 and *Algorithm* 3, we also observe that the proposed *path-balance replica algorithm* contributes to higher availability.

We then evaluate the performance of the algorithms in terms of the total cost of computing resources and the total link cost. The cost of computing resources is calculated by determining the number of replicas for each VNF along the working path and backup path and multiplying by the number of computing resource units required for each VNF replica. The total link cost is obtained by calculating the total length of the links along the working path and backup path and multiplying by the SFC's traffic bandwidth. We compare the results when the SFC's availability is 0.99 (there is no request blocking). As shown in Fig. 8 and Fig. 9, we observe that the *path-balance replica algorithm* based algorithms (*Algorithm* 1 and *Algorithm* 4) consume the least computing resources because the *path-balance replica algorithm* maximizes the SFC's availability, and therefore contributes to reduce the number of replicas. The *link-cost-based* algorithms consume less link resources because they attempt to find the shortest cost paths, as shown in Fig. 10 and Fig. 11.

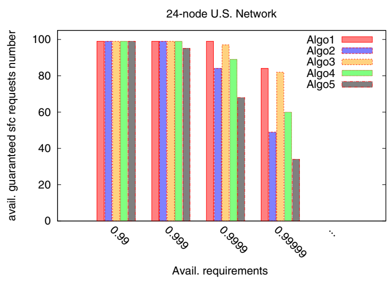

Fig. 6. SFC requests acceptance in 24-node network

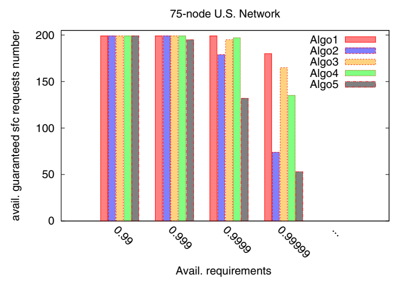

Fig. 7. SFC requests acceptance in 75-node network

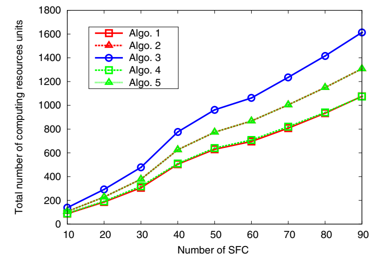

Fig. 8. Total number of computing resource units in 24-node mesh network (each SFC's avail. requirement: 0.99)

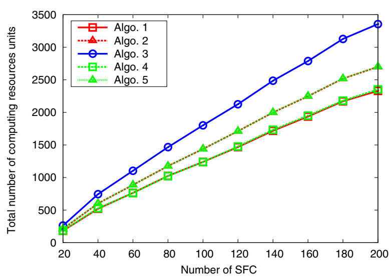

Fig. 9. Total number of computing resource units in 75-node mesh network (each SFC's avail. requirement: 0.99)

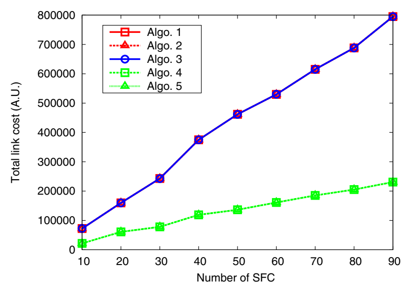

Fig. 10. Total link cost in 24-node mesh network (each SFC's avail. require.: 0.99)

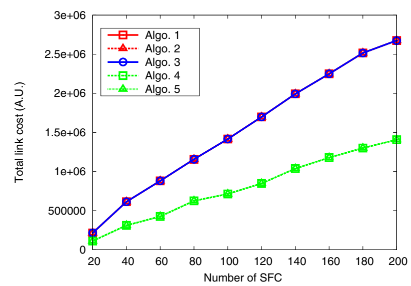

Fig. 11. Total link cost in 75-node mesh network (each SFC's avail. require.: 0.99)

V. Conclusion

In this paper, we consider the problem of availability-guaranteed service function mapping, and provide an efficient coordinated protection mechanism to guarantee each SFC's availability. By analyzing how to distribute the replicas of one VNF to the working path and the backup path in order to maximize the SFC's availability, we propose efficient heuristic algorithms to determine the number of the replicas for each VNF of the SFC, and then allocate the replicas to the physical node by considering the dependencies among different VNFs. Numerical results show that the algorithms based on the $path\text{-}balance\ replica\ algorithm$ perform better in terms of reducing the total computing resources as well as reducing the SFC blocking.

References

[1] B. Han, V. Gopalakrishnan, L. Ji, and S. Lee, "Network function virtualization: Challenges and opportunities for innovations," *IEEE Communications Magazine,* 53, no. 2, 2015, pp. 90-97.

[2] J. Herrera, and J. Botero, "Resource allocation in NFV: A comprehensive survey," *IEEE Transactions on Network and Service Management* 13, no. 3, 2016, pp. 518-532.

[3] IETF.org, "Service Function Chaining (SFC) Architecture," 2015. [Online]. Available: https://tools.ietf.org/html/rfc7665

[4] J. Kong, J. P. Jue, I. Kim, X. Wang, Q. Zhang, H. C. Cankaya, W. Xie, and T. Ikeuchi, "Availability-Guaranteed Virtual Optical Network Mapping with Shared Backup Path Protection," *IEEE Global Communications Conference (GLOBECOM)*, 2016.

[5] Opnfv.org, "High Availability For OPNFV," 2017. [Online]. Available: https://wiki.opnfv.org/display/availability/High+Availability+For+OPNFV".

[6] R. Potharaju, and N. Jain, "Demystifying the dark side of the middle: a field study of middlebox failures in datacenters," *Proceedings of the 2013 conference on Internet measurement conference*, ACM, 2013, pp. 9-22.

[7] S. Herker, X. An, W. Kiess, S. Beker, and A. Kirstaedter, "Data-center architecture impacts on virtualized network functions service chain embedding with high availability requirements," *IEEE Globecom Workshops (GC Wkshps)*, 2015.

[8] J. Fan, Z. Ye, C. Guan, X. Gao, K. Ren, and C. Qiao, "Grep: Guaranteeing reliability with enhanced protection in NFV," *Proceedings of the 2015 ACM SIGCOMM Workshop on Hot Topics in Middleboxes and Network Function Virtualization*, 2015, pp. 13-18.

[9] Z. Ye, X. Cao, J. Wang, H. Yu, and C. Qiao, "Joint topology design and mapping of service function chains for efficient, scalable, and reliable network functions virtualization," *IEEE Network,* 30, no. 3, 2016, pp. 81-87.

[10] L. Qu, C. Assi, K. Shaban, and M. Khabbaz. "Reliability-aware service provisioning in NFV-enabled enterprise datacenter networks." *International Conference on Network and Service Management (CNSM),* 2016, pp. 153-159.

[11] J. W. Suurballe, and R. E. Tarjan, "A quick method for finding shortest pairs of disjoint paths," *Networks* 14, no. 2 (1984): 325-336.

[12] Q. She, X. Huang, and J. P. Jue, "How reliable can two-path protection be?" *IEEE/ACM Transactions on Networking*, 18, no. 3, 2010, pp. 922-933.

[13] F. Carpio, S. Dhahri, and A. Jukan, "VNF Placement with Replication for Load Balancing in NFV Networks," *arXiv preprint* arXiv:1610.08266, 2016.

[14] A. M. Medhat, T. Taleb, A. Elmangoush, G. A. Carella, S. Covaci, and T. Magedanz, "Service Function Chaining in Next Generation Networks: State of the Art and Research Challenges," *IEEE Communications Magazine* 55, no. 2, 2017, pp. 216-223.

[15] N. Wang, and J. Jue. "Holding-time-aware routing, modulation, and spectrum assignment for elastic optical networks." *Global Communications Conference (GLOBECOM)*, 2014 IEEE, pp. 2180-2185.

[16] J. Kong, N. Wang, J. Jue, I. Kim, X. Wang, Q. Zhang, H. C. Cankaya, W. Xie, and T. Ikeuchi. "Correlated-failure-aware VON mapping." *Optical Fiber Communications Conference and Exhibition (OFC),* 2017, pp. 1-3.