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A Virtual Network Function Backup Method Based on Backup Cost Importance Postprint

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Abstract

Under 5G mobile communication network virtualization scenarios, redundancy-based backup approaches are typically adopted to ensure network service reliability. To mitigate backup resource cost overhead, the backup cost importance of each virtual network function is first computed within the initial mapping view. During each iteration, the virtual network functions exhibiting the maximum and second-maximum backup cost importance are selected for joint backup, thereby deriving the optimal backup strategy through corresponding selection and update models. Finally, comparative experiments are conducted against three alternative methods, demonstrating that the proposed algorithm achieves favorable performance across backup cost overhead, physical node occupation, service request acceptance rate, and backup resource utilization.

Full Text

A Virtual Network Function Backup Method Based on Backup-Cost Importance

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Abstract: In 5G mobile communication network virtualization scenarios, redundant backup methods are typically adopted to ensure network service reliability. To reduce backup resource cost overhead, this paper first calculates the backup-cost importance of each virtual network function in the initial mapping view. In each iteration, the VNFs with the largest and second-largest backup-cost importance values are selected for joint backup. Through corresponding selection and update models, the optimal backup strategy is ultimately obtained. Finally, comparative experiments with three other methods demonstrate that the proposed algorithm achieves favorable performance in backup cost overhead, number of physical nodes occupied, number of accepted service requests, and backup resource utilization.

Keywords: network function virtualization; virtual network function; service function chaining; backup-cost importance; joint backup

0 Introduction

In 5G mobile communication networks, Network Function Virtualization (NFV) will become a key technology for promoting network innovation and flexible service deployment. By decoupling network functions from dedicated hardware platforms, NFV enables mobile network operators to achieve flexibility and scalability in network management. Simultaneously, implementing these network functions on low-cost commodity hardware significantly reduces capital and operational expenditures for mobile network operators. Traditional mobile core networks employ highly reliable dedicated hardware equipment that can achieve 99.999% reliability, whereas 5G networks will use general-purpose servers to implement network functions, whose reliability is significantly lower than that of traditional dedicated hardware equipment.

Network services are realized in the form of service function chains, which consist of multiple virtual network functions arranged in a specific sequence. The reliability of end-to-end network services is not determined by a single component but by all components of the entire service function chain. Enhanced Mobile Broadband, Massive Machine-Type Communications, and Ultra-Reliable Low-Latency Communication are typical application scenarios for 5G communication networks. The high-reliability scenarios in 5G mobile communication networks impose stringent requirements on mobile communication service reliability, necessitating support for end-to-end network services with a reliability level of five nines (99.999%). Therefore, how to meet network service reliability requirements under resource constraints is one of the key issues that needs to be addressed when applying NFV technology in 5G networks.

Redundant backup is a general method for improving system reliability. One research focus is how to select backup VNFs to meet end-to-end network service reliability requirements. Existing redundant backup methods adopt a two-phase approach to solve this problem through iterative selection and mapping processes until service reliability requirements are satisfied. For backup VNF selection, reference [6] backs up entire service function chains, leading to wasted cost overhead and increased capital expenditures for mobile operators. The GREP algorithm proposed in reference [5] backs up VNFs with lower reliability in each service function chain, while reference [7] employs hybrid routing for VNF backup and proposes the GSP algorithm based on a greedy algorithm. Both algorithms overlook the fact that VNFs can be shared by multiple service function chains, resulting in low resource utilization.

To address the shortcomings of the above VNF backup methods, this paper proposes a VNF backup method based on backup-cost importance that integrates the selection and mapping processes into a single phase. First, the backup-cost importance of each VNF is calculated based on the initially deployed VNF forwarding graph to select backup VNFs. These are then mapped onto physical nodes using a joint backup approach. Subsequently, the VNF forwarding graph is updated according to an update model. Through iteration, the final solution yields backup VNFs and their mapped physical nodes that meet reliability requirements. This method can effectively reduce backup resource cost overhead while meeting network service reliability requirements and demonstrates good performance in service request acceptance rate and operational expenditures.

[Figure 1: see original paper]

1 Problem Formulation

1.1 Physical Network and Service Function Chain Requests

Let $G^P = (N^P, E^P)$ denote the physical network topology, where N^P represents the set of physical nodes, each capable of instantiating multiple VNFs, and E^P represents the set of physical links. Each node $n \in N^P$ has corresponding attributes, including computing resource capacity $c(n)$, storage resource capacity $s(n)$, and network resource capacity $b(n)$. Define r_n as the reliability value of physical node n, which can be calculated based on Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR) [8]:

$$r_n = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}}$$

Define the service function chain set as $S = \{s_i | i \in [1, z]\}$. For each service function chain s_i, there is a set of data traffic that needs to pass through VNFs in a fixed order. Define $VNF_i = \{vnf_{i,j} | j \in [1, z_i]\}$ as the set of VNFs in service function chain s_i, where $vnf_{i,j}$ represents the j-th VNF in service function chain s_i. Define θ_i^{req} as the reliability requirement of service function chain s_i.

After the initial mapping deployment of service function chain requests, the logical connection view on the physical network is called the VNF forwarding graph, as shown in Figure 1. Define $FG = (G^F, FL)$ as the topology of the VNF forwarding graph, where G^F represents the set of VNFs deployed on the physical network, and FL represents the set of logical links between adjacent VNFs. Each $f \in G^F$ has corresponding resource requirements, including computing resource requirement $c'(f)$, storage resource requirement $s'(f)$, and network resource requirement $b'(f)$.

1.2 Reliability Evaluation

There are many causes of VNF failures, such as hardware failures, software failures, and operational failures. This paper only considers hardware failures, so the reliability of a VNF can be evaluated by the reliability of the physical node on which it is instantiated. Define the decision variable:

$$x_{fn} = \begin{cases} 1 & \text{if VNF } f \text{ is backed up and instantiated on physical node } n \\ 0 & \text{otherwise} \end{cases}$$

Define Δr_f as the reliability increment of VNF f after redundant backup:

$$\Delta r_f = 1 - (1 - r_f) \prod_{n \in N} (1 - r_n)^{x_{fn}}$$

Define θ_i as the reliability value of service function chain s_i:

$$\theta_i = \prod_{f \in VNF_i} (r_f + \Delta r_f)$$

1.3 Optimization Objective

After the initial mapping deployment of service function chain requests, the deployment solution cannot meet the reliability requirements of some service function chain requests. Meanwhile, backed-up VNFs cannot generate revenue for a long period. Therefore, this paper takes the cost-effectiveness of redundant backup resources as the optimization objective to find the corresponding backup redundancy solution.

Optimization Objective:

$$\max \mathrm{Cost} = \frac{\sum_{f \in G^F} \Delta R_f}{\sum_{f \in G^F} \sum_{n \in N} x_{fn} \delta_f}$$

Constraints:

$$\theta_i \geq \theta_i^{req}, \quad \forall i \in S \tag{6}$$

$$\sum_{f \in G^F} x_{fn} c'(f) \leq c(n), \quad \forall n \in N \tag{7}$$

$$\sum_{f \in G^F} x_{fn} s'(f) \leq s(n), \quad \forall n \in N \tag{8}$$

$$\sum_{f \in G^F} x_{fn} b'(f) \leq b(n), \quad \forall f \in G^F, n \in N \tag{9}$$

Equation (5) represents maximizing the cost-effectiveness of the backup redundancy solution. Equation (6) ensures that the reliability value of each service function chain meets its reliability requirement. Equations (7)-(9) ensure that the computing, storage, and network resources occupied by backup VNFs do not exceed the computing, storage, and network resource capacities of the physical nodes where they are instantiated. The main parameter symbols and definitions used in this paper are shown in Table 1 .

2 VNF Backup Method Based on Backup-Cost Importance

2.1 Selection Model

The degree to which component reliability changes affect system reliability is called probability importance, also known as Birnbaum importance, which effectively describes the impact of component state changes on system changes [9]. In a reliability system, the probability importance of a component f is defined as:

$$BIM_f = \frac{\partial \theta}{\partial r_f}$$

To better allocate various resources, define δ_f as the resource requirement of backup VNF f:

$$\delta_f = \lambda_1 c'(f) + \lambda_2 s'(f) + \lambda_3 b'(f)$$

where $\lambda_1, \lambda_2, \lambda_3 \in [0,1]$ and $\lambda_1 + \lambda_2 + \lambda_3 = 1$. Here, $\lambda_1, \lambda_2, \lambda_3$ are constants representing weights, which can be adjusted according to specific network environments to improve resource allocation flexibility. For example, to reduce computing resource overhead, the value of λ_1 can be appropriately increased.

Based on the reliability increment and resource requirements after redundant backup, the unit cost of redundant backup VNFs can be derived:

$$d_f = \frac{\Delta r_f}{\delta_f}$$

To further reduce backup redundancy overhead, this paper defines the Backup Cost Importance (BCI) of VNFs based on probability importance to evaluate their importance in the VNF forwarding graph:

$$BCI_f = \frac{BIM_f}{\delta_f}$$

BCI effectively evaluates the importance of VNFs in the VNF forwarding graph, particularly reflecting the importance of VNFs shared by multiple service function chains [10]. The BCI value is the ratio of the probability importance BIM_f to the unit resource cost δ_f, accurately reflecting VNF importance. Specifically, VNFs with higher BCI values achieve the highest system reliability increment with the smallest resource consumption when backed up. Failures of these VNFs would cause more widespread network service disruptions, severely affecting mobile users' service experience. Additionally, if a single physical node backs up multiple VNFs, its failure would lead to multiple network service interruptions. Through comparative experiments, this paper finds that setting a maximum of 2 VNFs backed up per physical node yields the maximum reliability increment. Therefore, selecting VNFs with the largest and second-largest BCI values for joint backup can improve the cost-effectiveness of redundant backup resources and effectively reduce backup resource overhead. The proposed algorithm iteratively performs joint backup of VNFs with the largest and second-largest BCI values, achieving better cost-effectiveness for redundant backup.

2.2 Update Model

To improve the convergence speed of the algorithm, the VNF forwarding graph needs to be updated after deploying redundant backup VNFs. Since mapping too many backup VNFs to the same physical node reduces system reliability, each physical node is limited to instantiating at most 2 backup VNFs. As the algorithm selects VNFs with the largest and second-largest BCI values for joint backup, there are two update forms:

a) A physical node instantiates 2 backup VNFs from the same service function chain. The original VNFs and backup VNFs are updated into new VNFs, as shown in Figure 2 [Figure 2: see original paper]. The reliability value of the new VNF is:

$$r_{vnf_{3,4}} = r_{vnf_3} + r_{vnf_4} - r_{vnf_3} \cdot r_{vnf_4}$$

b) A physical node instantiates 2 backup VNFs from different service function chains. The VNFs are updated in their respective service function chains, as shown in Figure 3 [Figure 3: see original paper]. The new reliability values are:

$$r_{vnf_{1,2}} = 1 - (1 - r_{vnf_1})(1 - r_{vnf_2})$$
$$r_{vnf_{8,9}} = 1 - (1 - r_{vnf_8})(1 - r_{vnf_9})$$

To represent the resource requirements of backup VNFs, define $d_{vnf_{3,4}} = d_{vnf_3} + d_{vnf_4}$ and $d_{vnf_{1,2}} = d_{vnf_1} + d_{vnf_2}$. For specific network environments, these can be adjusted accordingly.

The pseudo-code of the proposed algorithm is as follows:

Backup-Cost Importance based VNF Backup Algorithm (BCIA) - Input: Physical network $G^P = (N^P, E^P)$, service function chain requests S, initially deployed VNF forwarding graph FG - **Output:** Backup redundancy solution $\{x_{fn}\}$

```
1. Calculate the reliability value $\theta_i$ for each service function chain $s_i$
2. while $\exists i \in S$ such that $\theta_i < \theta_i^{req}$ do
3. Generate new VNF forwarding graph $FG'$
4. According to the selection model, select VNF $f'$ with the maximum BCI value and VNF $f''$ with the second-maximum BCI value, and find physical node $n'$ that can instantiate 2 VNFs based on their resource requirements
5. if $n' \in N$ then
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        $x_{f'n'} = 1$ and $x_{f''n'} = 1$
    end if
    if $f'$ and $f''$ belong to the same service function chain then
        Update according to form one
    else
        Update according to form two
    end if
    for all $i \in S, f \in VNF_i$ do
        Update $\theta_i$
    end for
end while
return $\{x_{fn}\}$
```

3 Simulation Experiments and Performance Analysis

To evaluate the feasibility of the model and the effectiveness of the algorithm, this paper uses total backup cost, number of physical nodes occupied by backup resources, backup resource benefit, and request acceptance rate as performance metrics, and compares the proposed method with the MinCost algorithm [10], MaxRbyInr algorithm [10], and GREP algorithm [5].

3.1 Simulation Settings

We use a network topology with 116 nodes [11] as the physical network. Each physical node has 2000 units of resource capacity. The reliability value of each physical node is randomly distributed between [0.9, 0.99]. Each service function chain consists of 2 to 6 VNFs in series. According to Google' s Service Level Agreement [12], the reliability requirements of service function chains are selected from {0.95, 0.98, 0.99, 0.995, 0.999}.

Assume there are 1100 service function chains in the VNF forwarding graph. Each service function chain request consists of multiple VNFs in series, with the number of VNFs following a uniform distribution between 2 and 6. Each VNF' s resource requirements follow a random distribution in [1, 30]. The algorithm runs on a personal computer with an Intel i7 4790 CPU and 4GB of RAM, and simulation experiments are conducted using Matlab.

3.2 Performance Analysis

Figure 4 [Figure 4: see original paper] shows the backup cost of different algorithms under different reliability requirements. As the reliability requirements increase, the backup costs of all three algorithms gradually increase. Even when the reliability requirement is 0.999, the BCIA algorithm still has the lowest backup cost.

Figure 5 [Figure 5: see original paper] shows the number of physical nodes occupied by backup resources for different algorithms under different reliability requirements. As reliability requirements increase, the number of physical nodes occupied by backup resources for all three algorithms gradually increases. Compared with the MinCost and MaxRbyInr algorithms, the BCIA algorithm reduces the number of physical nodes by 32% and 12%, respectively. When the reliability requirement is 0.95, the MaxRbyInr algorithm occupies fewer physical nodes than the other two algorithms due to its maximum reliability increment in the selection stage. However, as reliability requirements increase, the BCIA algorithm occupies the fewest physical nodes.

Figure 6 [Figure 6: see original paper] shows the request acceptance rates of different algorithms under different numbers of service function chain requests. The BCIA algorithm demonstrates significantly higher request acceptance rates compared with the other two algorithms, especially when the number of requests increases, proving the effectiveness of the BCIA algorithm. This simulation demonstrates the excellent performance of the proposed method in environments with large numbers of service function chain requests. The main reason is that the BCIA algorithm has higher granularity in the selection stage, which can effectively improve resource utilization.

Figure 7 [Figure 7: see original paper] shows the backup resource utilization rates of different algorithms under different reliability requirements. The other three schemes do not optimize resource utility, and their resource utilization rates are similar. In contrast, the BCIA method improves resource utilization by approximately 15-20% compared with the other three schemes, clearly outperforming them by achieving maximum backup redundancy benefits with minimum resource overhead.

4 Conclusion

NFV technology enables the softwareization of network functions, realizes network service virtualization through constructing service function chains, enhances resource allocation scalability, and promotes infrastructure resource sharing. To ensure high service reliability, VNF nodes require redundant backup, which demands substantial backup resource overhead. To address this issue, the BCIA algorithm proposed in this paper effectively reduces backup resource overhead while guaranteeing network service reliability requirements, increases backup resource benefits, and can meet the demands of mobile communication services in high-reliability scenarios of 5G.

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