Multi-dimensional Resource Optimal Allocation Method for Service Function Chain Deployment

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Abstract. Aiming at the problem of multi-dimensional resource service function chain deployment in a resource-limited network, a resource allocation method based on optimal weighted graph matching is proposed. The node and link resources are embodied as weights of the weighted graph, and the eigenvector decomposition of the adjacency matrix is used to get graph matching method. The simulation results show that the algorithm optimizes the bandwidth required for the deployment of the service function chain, optimizes the balance of node load and link bandwidth, supports more service requests, and has low algorithm complexity.

1. Introduction

End-to-end network services typically require traffic to be processed through a chain of network functions (NFs) no matter in enterprise networks or carrier networks. This ordered sequence of NFs is referred to Service Function Chaining (SFC) [1]. With the leap-forward development of emerging technologies and information industry, new types of network service and business pattern have sprung up. This situation exacerbates the problem of traditional SFC deployment which require dedicated hardware [2, 3].

Network Functions Virtualization (NFV) has been an arising technology to provide a way solving the problem. Ensuring effective resource management to meet the needs of network services, which is one of the key problems in NFV deployment. It is called NFV resource allocation. Unreasonable resource allocation can lead to resource overload and underload. The impact of overload may be overall performance degradation and SLA violations, while underloading can result in significant waste of resources. Effective resource allocation needs to ensure that finding an SFC mapping scheme that best balances the physical resource load and satisfies multiple constraints.

Ref. [4] studied the optimal VNF layout in a mixed scenario where the physical network function (PNF) and the virtualized network function (VNF) coexist. The algorithm can make full use of physical and virtual resources to achieve scalability and flexibility in SFC deployment. Ref. [5] used graph theory to solve the resource allocation problem, and regarded virtual network functions and servers as two disjoint subsets in the bipartite graph, focusing on solving the failure of node function. In [6], the problem of deploying SFC is transformed into the weighted graph matching problem of functional topology and physical topology. The algorithm can quickly generate the deployment. But the virtual link with a large bandwidth requirement is mapped to a physical transmission path with a large number of hops, resulting in a large amount of bandwidth loss and poor bandwidth and load balancing. Ref. [23] used a greedy heuristic BBA for in the multi-resource setting which minimize average load of servers, but it will lead to utilization imbalance within VNFs.
Most existing resource allocation methods and algorithms ignore the need for other node resources, mainly considering the allocation of CPU resources. Simply balancing the load of CPU resources may result in inefficiencies in other hardware resources, which limits the performance of the entire NFV cluster. And they mainly assume homogeneous servers which have the same resource capacity. Considering to the previous issues, Multi-dimensional Resource Optimal Allocation method for service function chain deployment (MROA) is proposed in this paper. MROA contains the multi-resource load balancing strategy with heterogeneous server capacities included.

2. Problem formulation

2.1. Problem statement

In VNF placement, multiple physical VNFs may be deployed on the same server, and different types of VNFs require various heterogeneous resources. For example, IDS and security encryption requires a large amount of CPU resources, and software routers require a large amount of memory resources [7]. If the resource allocation only takes one single resource but other resources account together, it may easily lead to overload of server resources and degrade the network performance.

![Figure 1. An example of resource load balancing only CPU is considered.](image)

Consider servers with two kinds of resource (CPU and memory), as shown in Figure 1. The difference of CPU usage between servers is fairly small. However, memory usage of server 3 can be found much lower than other servers. Simply taking the load balancing of CPU for SFC deployment can’t achieve efficient SFC deployments. When it comes to heterogeneous servers, the load balancing of SFC deployment will be faced with more complex problems. So, we aim to solve the multi-dimensional resource optimization problem of load balancing in order to balance load distribution improve network performance.

2.2. Modelling

2.2.1. Substrate. The substrate is composed of nodes connected via physical links. And the substrate is represented by an undirected graph \( G = (N, E) \) characterized by: a). A set of service nodes \( N \); b). A set of physical links \( E \); c). The resources capacity of the service node \( C^k_n, \forall n \in N, k \in K \); The redundant resources of service node which are accessible \( C^{rem,k}_n, \forall n \in N, k \in K \); \( K \) denotes the types of limited resource of servers such as CPU, memory, storage, etc. d). The bandwidth capacity of each link \( C_e = C_{(u,v)}, \forall e = (u, v) \in E \); and the redundant resources of link \( C^{rem}_e = C^{rem}_{(u,v)}, \forall e = (u, v) \in E \).

2.2.2. SFC request. For each SFC request \( i \in I \), its virtual topology is denoted by a weighted directed graph \( G_i = (V, L) \). Unlike proprietary hardware middleboxes, VNFs can be carried by physical nodes
with certain resources. Different VNFs have different resource requirements for handling the SFC traffic. a). Because of the directionality of the edge, \( v_i \) implies the VNF context of SFC, which can also expresses as \( \{v_i',v_i',\ldots,v_i^{(r)}\} \), such as Firewall \( \rightarrow \) IDS \( \rightarrow \) Proxy; c). A set of virtual links \( L \); each virtual link is represented as \( L_r=(v_r^{(r)},v_r') \in L, \forall r \in \{1,2,\ldots,|V_r|+1\} \); d). The resource used by VNF to handle the unit bandwidth traffic \( q^k_i \), where \( k \) denotes the type of resource; e). The traffic demand of SFC \( B \).

2.2.3. Constraints.

\[
\sum_{n \in N} x^n_v = 1, \quad \forall v \in V \tag{1}
\]

\[
\sum_{v \in V} x^n_v q^k_i B_i \leq C^r_{n,k}, \quad \forall k \in K, \forall n \in N \tag{2}
\]

\[
\sum_{i \in L} y^e_i B_i \leq C^e_{e \in E}, \quad \forall k \in K, \forall e \in E \tag{3}
\]

Constraint (1) indicates that each VNF in the SFC request can only be deployed on one server node. Constraint (2) indicates resources used by VNFs of deployed SFCs cannot exceed the remaining amount of resources of each server. Constraint (3) indicates that the bandwidth occupied by all virtual links in the deployment request cannot exceed the remaining bandwidth capacity.

3. Algorithm design

In this section, we present the algorithm MROA which is designed to solve the problem of multi-dimensional resource load balancing for VNF deployment. In order to reduce and balance network resource consumption and quickly generate deployment methods that meet the transmission requirements, this paper draws on the optimal weighted graph matching method [8] and motivate it.

3.1. node and path evaluation criteria

As mentioned in section 2.2.4, node resource capability and link resource capability are considered as the optimal object. They are defined as follows:

3.1.1. node resource capability \( W_n^t \). Node resource capability indicates the remaining node resource over the total resource of physical node. Equation (5) refers to the resource capability of the node at time \( t \). The larger the resource capacity of a node, the more likely the node will be deployed. Among them, the resource weight \( \lambda^k \) (4a) adjusts the proportion of each resource. The resources that occupy larger amount of resource account for higher proportion in the resource allocation.

\[
\lambda^k = \frac{\sum_{n \in N} (C^k_n - C^k_{n,rem})}{\sum_{n \in N} \sum_{k \in K} (C^k_n - C^k_{n,rem})} \tag{4}
\]

\[
W_n^t = \sum_{k \in K} \lambda^k C^k_{n,rem}, \forall n \in N \tag{5}
\]

3.1.2. path resource capability \( W_{(s,d)}^t \). In the link mapping, there is a case where a virtual link is mapped to multiple physical link sets. Therefore, \( P_e(s,d) \) is used to represent the path between the physical node \( s \) and \( d \). The link resource capability \( W_{(s,d)}^t \) (6) represents the capability of optimal path between \( s \) and \( d \). (6) represents the dispersion of resources on the path. A large dispersion means
the probability of a link with low resource utilization on the path is high. So, we more likely to select this path.

\[ \theta_{\text{path}} = \frac{\sum_{e \in \text{path}} C_{\text{rem}}}{\max_{e} C_{\text{rem}} - \min_{e} C_{\text{rem}}} \]  

(6)

\[ W_{\text{path}}^t = \left( \frac{\theta_{\text{max}}}{\theta_{\text{max}} - \theta} \right) \frac{\min_{e} C_{\text{rem}}}{\text{hop}_{\text{path}}}, \text{path} \in P_e \]  

(7)

\( \theta_{\text{max}} \) is a constant much larger than \( \theta \); \( \text{hop}_{\text{path}} \) is the hop of \( \text{path} \). you can select a path through high communication capability, which has strong communication capability, small hop count, and much remaining resource. And it will greatly reduce the problem of poor physical resources utilization when the topology is sparse.

3.2. Optimal weighted graph matching.

For two weighted graphs \( G_1 = (V_1, E_1) \) and \( G_2 = (V_2, E_2) \) with \( n \) nodes, find the mapping function \( P \) between the node sets \( V_1 \) and \( V_2 \), so that the difference between the newly generated weighted graph under this function and \( V_2 \) is the smallest. The difference between the weighted graphs is the Frobenius norm of the difference between the adjacency matrices of the two weighted graphs. The optimal weighted graph matching problem can be expressed as Equation (7). Where \( \lambda \) is the node mapping function; \( J(P) \) is Frobenius norm of the difference between two matrix; \( A_1 \) and \( A_2 \) respectively represent the adjacency matrix of the two graphs.

\[ \min J(P) = \|PA^t - A_2\| \]  

(8)

3.2.1. Service function chain composition.

The algorithm supports deployment of multiple SFCs simultaneously. The SFC needs to be combined into an SFC topology diagram. Taking the two SFCs shown in Figure 2 as an example, the same functions in the two SFCs are combined. The VNF weight in the figure indicates the node capability (8) required by the function, and the link weight indicates the traffic bandwidth.

Figure 2. Service function chain composition.

It should be noted that the weights of the overlapping parts of the two SFCs are the sum of the two. The node capability is the product of the multi-dimensional resource and the coefficient weight \( \lambda^k \).

\[ C_v = \sum_{k \in K} x^k q^k v, \forall v \in V \]  

(9)

3.2.2. Adjacent matrix extension. Let \( A_1 \) and \( A_2 \) represent the adjacency matrix corresponding to the SFC topology and the substrate topology. Among them, the diagonal elements in \( A_1 \) represent the node capabilities of each VNF, the other elements represent the required bandwidth between VNFs; the
diagonal elements in $A_2$ represent the resource capabilities $W_n^t$ of each node, and the other elements represent the remaining bandwidth of links. In order to meet the requirements for the same number of vertices in the graph matching problem, it is necessary to expand $A_1$ to the same dimension as $A_2$.

3.2.3. Matrix element replacement. During the SFC deployment, the virtual link between two adjacent functions can be mapped to one physical link or multiple physical links. In order to meet requirements in the process of link mapping, it is necessary to replace the weights representing the non-adjacent links in the substrate topology adjacency matrix, and select an optimal path for each pair of nodes. This paper chooses the path that maximizes the path resource capacity $W_{path}^t$ between each pair of nodes and replaces the weight with $W_{path}^t$.

After obtaining two adjacency matrices with approximate isomorphism, the mapping function is calculated according to the algorithm flow of [8]. The efficiency matrix is solved by the Hungarian algorithm to obtain the optimal mapping.

4. Evaluation

In order to verify the effectiveness of the proposed resource allocation method, the simulation was carried out by MATLAB. The simulation scenario is designed as a random network topology consisting of 20 nodes according to the Waxman-Salam model [9]. Each kind of node resources are randomly selected within 40~80MHz and the total bandwidth of each link is 50 Mbit/s. The network can provide 8 functions. Each SFC to be deployed is composed of 2~6 different functions arranged in any order. Multiple resources of function are between 0~10MHz, and each SFC bandwidth is between 0 and 5 Mbit/s. Functional topology map is generated by combining two SFCs. In order to improve the accuracy of the algorithm evaluation, 100 sets of simulation tests were carried out in each test scenario using the Monte Carlo method, and the average value was taken as the test result.

In this paper, node load balancing degree and link bandwidth balancing degree are taken as evaluation indexes of algorithm performance. Node load balancing degree refers to the mean square deviation of residual processing capacity of nodes, and link bandwidth balancing degree refers to the mean square deviation of residual link bandwidth. The algorithm is compared with the BBA and BBD algorithm proposed in [10].

![Figure 3. The performance of node and link load balancing.](image)

Figures 3(a) and (b) show the load balance performance of each algorithm for node load and link load, respectively. Since the BBA only considers the average load of the nodes, the mean square error of the remaining capacity of the nodes is the highest. The BBD algorithm considers the dominant load, but the load of the remaining resources is not considered, so the bandwidth and load balancing performance are between BBA and the method in this paper. At the same time, neither BBA nor BBD considers the optimization of the link, so the link load is unbalance. Since the method in this paper...
homogenizes the adjacency matrix in the matching process, the optimal matching can be achieved with a high probability, therefore, the node and link load balance are significantly better than other algorithms.

5. Conclusion
In this paper, we investigated the SFCs deployment problem considering multi-dimensional node resource and link resource constraints. We introduced MROA algorithm based on optimal weighted graph matching, and propose the resource weight to balance multiple node resource. Compared with other algorithms, this method reduces the link bandwidth required for SFCs deployment, provides better balance between multiple node resource. Possible extensions of our work include the consideration of verifying the method in a real environment.

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