Service Function Chain Mapping Based on Joint Load Balancing in Computing Power Network

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***Abstract*—A joint load balancing algorithm is proposed to optimize the Service Function Chain (SFC) mapping in computing power network. The results indicate its benefit in terms of reducing service blocking and achieving load balancing.**

Keywords—Service Function Chain, joint load balancing, computing power network.

I. Introduction

The distribution of network services involves the allocation of multiple heterogeneous resources, such as computing, storage and network resources. Computing power network (CPN) can provision and deploy network resources through network control plane (e.g., centralized controllers, distributed routing protocols, etc.) based on network information and user requirements to achieve optimal allocation and utilization of heterogeneous resources [1]. CPN currently applies a three-level architecture consisting of Access Terminal, Edge, and Data Center[2]. In the inter-datacenter (inter-DC) networks, users and traffic are growing exponentially, and new network services are emerging. In traditional networks, in order to deploy new network services, network needs to be physically modified and many specialized network hardware needs to be deployed. NFV can be used as a new network technology for enabling network functions (NFs) to run on commercial universal servers. NFs, such as deep package inspections (DPIs), firewalls, gateways, etc., which used to run in dedicated middleboxes, will be replaced by Virtual Network Functions (VNFs) through virtualization technologies. VNF implement different network functions through software, which significantly reduces the Capital Expenditure (CAPEX) and Operating Expense (OPEX) [3] and can be dynamically deployed and flexibly extended. Furthermore, Software-Defined Networking (SDN) enables the supervision and scheduling of network resources by centralizing network control to the SDN controller.

A SFC is a collection of ordered VNFs connected by virtual links (VLs). Internet service provider (ISP) needs to deploy the VNF requested by the SFC on a suitable DC and connect them through light paths to form a complete end-to-end service. VNF deployments require IT resources, including CPU, memory, and storage. As the CPU is the most constrained host resource and dominates the cost [4], here we only consider CPU resources. VLs mapping requires fiber link resources (e.g., bandwidth) and node resources (e.g., optical transceiver). Flexible-grid Elastic Optical Networking (EON), the most promising network technology in inter-DC networks, is applied, which is implemented in a distance adaptive modulation format and can provide flexible optical paths between DCs [5].

Substrate network (SNT) has limited infrastructure resources, so many schemes want to reduce the cost of SFC mapping to reduce resource consumption. However, the lowest cost deployment schema may have network bottlenecks that result in the degradation of service quality or network congestion, as the preferred option is to select the shortest candidate paths and the lowest-cost DC node. Therefore, in order to ensure the QoS and the success rate of request deployment, network service providers need to consider bottleneck links and load balancing in inter-DC EON, in addition to reducing resource consumption.

To reduce the difficulty of problem-solving, the SFC mapping problem is usually split into two sub-problems, VNF deployment and virtual link mapping. Many researchers treat it as two separate steps, which greatly reduces the complexity but does not consider the dependencies between the two sub-problems. Many related works regard bandwidth resources as virtualized resource pools, which do not consider any bandwidth allocation constraints (e.g., the spectrum continuity constraint, spectrum contiguity constraint, and spectrum non-overlapping constraint).

In this paper, we focus on the SFC mapping problem and then propose a Joint Load Balancing (JLB) algorithm with the objective to achieve network load balancing and reduce resource consumption. The algorithm considers two characteristics of SFC requests, i.e., the correlation between nodes and links and the dependency between VNFs. Simulation results show that the JLB algorithm can improve the network performance and reduce the blocking ratio.

II. System Model

A. Network Model

We model the physical network as a directed graph $G = (V, E)$, where $V = \{v_1, v_2, \cdots, v_{\mathrm{m}}\}$ is the set of physical nodes and $E = \{e_1, e_2, \cdots, e_n\}$ is the set of physical links. There are two types of nodes in the network in total, DC nodes, which have VNF instances on them and can handle SFC requests, and switch nodes, which are the initial or end point for requests. To reduce resource consumption, VNF instances can be shared by the same VNFs in different SFC requests when they do not exceed the capacity limit. In this paper, multiple VNF instances can be deployed on a DC, and each VNF can be instantiated in multiple DCs. While the deployment of multiple same VNF instances on a DC can process requests faster or accommodate more requests, this can lead to a situation where the VNFs all prefer to deploy on a single node. Hotspot nodes have heavier loads than others, which can lead to poor network performance. Moreover, the limited bandwidth resources around it may result in block of request. It may also lead to higher spectrum occupation if the hotspot node is on a long path. Therefore, there cannot be more than one instance of the same VNF on a DC.

B. SFC Mapping in CPN

An SFC request is modeled as $R_i = (S_i, D_i, B_i, C_i)$, where S_i and D_i denote the source and destination nodes, respectively. B_i is the bandwidth requirement. The number of frequency slots (FS) in the modulation and spectrum as-

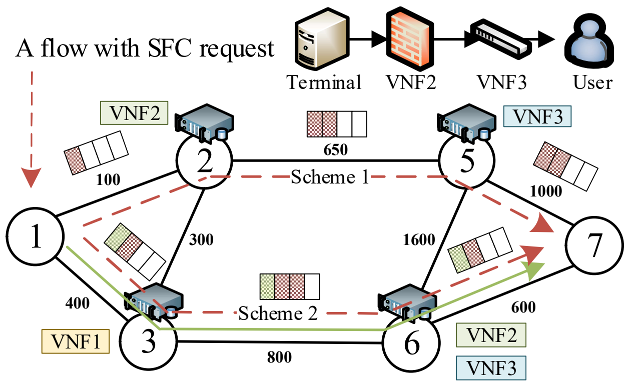

Fig. 1. Example of two schemes for SFC mapping in inter-DC EONs.

signment (RMSA) problem can be calculated as $\lceil B_i/(m \times B_{FS}) \rceil$, where B_{FS} is the bandwidth of each FS, i.e. 12.5 GHz, and $m \in [1,2,3,4]$ corresponds to BPSK, QPSK, 8-QAM and 16-QAM, respectively. It is assumed that the bandwidth requirement of a request does not change to simplify the calculation. $C_i = \{c_{i,1}, c_{i,2}, \cdots, c_{i,j}\}$ is the set of VNFs in the request, where $c_{i,j}$ denotes the type of VNF. Fig. 1 shows an example of SFC mapping in an Inter-DC EON. An SFC request $R_1 = (1, 7, 30Gbps, \{\text{VNF1}, \text{VNF2}\})$ initially enters the network with a path of 1→3→6→7, and VNF1 and VNF2 are deployed in nodes 3 and 6, respectively. Then comes a request $R_2 = (1, 7, 50Gbps, \{\text{VNF2}, \text{VNF3}\})$, whose two deployment schemes are shown in Fig. 1. Scheme 1 adopts path 1→3→6→7, and both VNF2 and VNF3 are deployed on node 6. The spectrum allocation solution is also shown beside the paths. Since optical/electronic/optical (O/E/O) conversion is performed during VNF processing, the spectrum is allocated through paths 1→3→6 and 6→7, respectively. Scheme 2 runs through path 1→2→5→7 and deploys VNF2 and VNF3 on nodes 2 and 3, respectively. The two different schemes result in different DC and spectrum occupation. Scheme 1 has less spectrum usage, but its path is longer and causes an unbalanced network load. In the solution of this paper, the two evaluation factors, resource consumption and load balancing will be weighed together to minimize spectrum occupation and achieve network load balancing.

III. Joint Load Balancing Based SFC Mapping Algorithm

This section proposes a joint load balancing based (JLB) SFC mapping algorithm to achieve higher service acceptance rates and more balanced network loads. In paper [6], the selection of individual VNFs is studied and the Global Balancing factor (GB-factor) and Local Balancing factor (LB-factor) are proposed to evaluate the impact of services on network load. Based on this study, we extend the problem to SFC mapping and based on the conclusions, use a global optimization method. Since SFC mapping has been proven to be a NP-hard problem [7], a heuristic algorithm is designed to solve it.

A. Construct Candidate Graph

The candidate node sets $V_l = \{V_l^1, V_l^2, \cdots, V_l^u\}$ corresponding to candidate instances of each requested VNF are first searched in the order of the VNF on the SFC. And the nodes in adjacent sets are interconnected to form $E_l = \{E_l^{1,1}, \cdots, E_l^{a,b}\}$. Specifically, $E_l^{a,b}$ is the virtual graph link we constructed between V_l^a and V_{l+1}^b. Then, we have a directed candidate graph $G_s = (V_s, E_s)$, where $V_s = \{V_1, V_2, \cdots, V_{j+2}\}$ and $E_s = \{E_1, E_2, \cdots, E_{j+1}\}$. It is noteworthy that in the subsequent calculation, i.e., when calculating the weights of the candidate graphs, since the paths are not finally selected at this point, we use the corresponding average value computed from the k-shortest paths between the two candidate nodes to assign the virtual link for the calculation. The weight of $E_l^{a,b}$ can be calculated by:

Algorithm 1. Construct candidate graph

Input: $G = (V, E)$, $R_i = (S_i, D_i, B_i, C_i)$
Output: candidate graph $G_s = (V_s, E_s)$

```
for each c_{i,j} ∈ C_i do
    Find the node corresponding to the candidate instance and
    place it in the candidate node set V_{j+1};
end
Construct the collection of candidate graph nodes set V_s =
    {{S_i}, V_2, ⋯ , V_{j+1}, {C_i}};
for each adjacent set pair V_l, V_{l+1} ∈ V_s do
    Connect each node V_l^a and V_{l+1}^b between them to form E_l;
    Put E_l in E_s;
end
for each E_l ∈ E_s do
  for each E_l^{a,b} ∈ E_l do
    Calculate the weight of E_l^{a,b} according to (1);
  end
end
return G_s = (V_s, E_s)
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$$W_l^{a,b} = \alpha \frac{\varphi_{V_l^a} + \varphi_{V_{l+1}^b}}{2} + (1-\alpha)\overline{D_{E_l^{a,b}}} \times \overline{\varphi_{E_l^{a,b}}} \tag{1}$$

Equation (1) evaluates the network-weighted occupancy. φ_v is the ratio of computing resources required by the VNF to those available in the instance. The second part of (1) calculates the combined virtual graph link score, which is the product of the path length D and the ratio of the required FS to the free FS.

B. Joint Load Balancing Algorithm

After the candidate graph of the flow is obtained, we use a recursive approach to solve the global optimal traffic path from V_1 to V_i. $S(V_i^b)$ denotes the optimal path from the source node V_1^1 to node V_i^b, i.e., the path with the smallest weighted sum, which can be obtained using:

$$S(V_i^b) = \min_{V_{i-1}^a \in V_{i-1}} \{S(V_{i-1}^a) + W_{i-1}^{a,b}\} \tag{2}$$

For each node in $V_l \in V_s$, we use (2) to solve its best path solution based on the optimal path solution of the previous nodes in V_{l-1} and the matching path of this hop with the corresponding nodes in V_{l-1}. V_1 includes only one source node, and we set its shortest path value $S(V_1^1)$ to 0. The recursion ends with the last candidate node set V_i, which is a set of nodes containing only the destination node. Thus the optimal path from the source node to the destination node is found with the value $S(V_i^1)$. Then the instance on the path is the DC node to be routed through. With the nodes on the path obtained, the k-shortest paths for each node pair are sorted

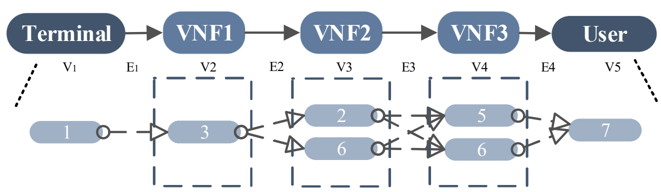

Fig. 2. An example of constructing a candidate graph based on Fig. 1 network topology.

Algorithm 2. Joint Load Balancing Algorithm

Input: $G = (V, E)$, R
Output: Deployment scheme for each R_e

Compute the sets $L_{p,q}$ of K-shortest paths between each node pair v_p and v_q;
for each $R_i = (S_i, D_i, B_i, C_i)$ **do**
  Construct candidate graph $G_s = (V_s, E_s)$;
  Calculate the optimal path p_i on the G_s according to (2);
  for each adjacent node pair V_l', V_{l+1}' in p_i **do**
    for $p' \in V_l', V_{l+1}'$ in descending order of $D_{p'} \times \varphi_{p'}$ **do**
      Calculate RMSA solution with the **first-fit principle**;
    end
  end
  Deploy $c_{i,j}$ on node V_{j+1}' and allocate the FS according to the RMSA scheme.
  Update $G = (V, E)$;
end

according to $D_p \times \varphi_p$ and traversed to find the solution for RMSA using the First-Fit Principle. A request is finally successfully deployed if the candidate node set is not empty and the RMSA solution is found for all node pairs on the shortest path.

IV. Simulation Results And Discussion

We use simulations to evaluate the performance of the JLB algorithm. 14-node NSFNET topology in Fig. 3 is used, which contains 7 DC nodes. The detailed simulation parameters are summarized in Table 1. We only consider the static network scenario in this paper and a batch of static SFC requests will be randomly modeled and arrive at once.

A benchmark based on Greedy algorithm is considered for comparison, which considers the two subproblems of SFC separately in a greedy way. It first selects the node with the most prominent remaining capacity in the candidate node set and then chooses the shortest path in the path set of each node pair for deployment.

In Fig. 4(a), the blocking ratio increases with the number of requests because the resources are limited. With a 300 request, we set the number of fiber spectrum slots sufficiently large, and the optimization rate of blocking exceeds 50% except for JLB_0.5, where JLB_1 and Greedy reach 85% and 88%, respectively. Therefore, the blocking factor is mainly bandwidth. Although spectrum utilization is not high, the three limitations of RMSA deployment can lead to fragmentation and, as a result, blocking services. When the number of requests is equal, $\alpha = 0.5$ is the lowest blocking point in the JLB algorithm, and the blocking ratio raise to both ends. The scheme that considers the mutual limitations of

TABLE I. Simulation Parameters

Number of VNF types	8
VNF Instance Capacity	[20, 160] GOPS
Capacity requirements for VNF processing	[1, 8] GOPS
Number of VNFs in an SFC	[1, 3]
Bandwidth requirements of an SFC	[20, 200]Gbps
Number of FS on each fiber link	300

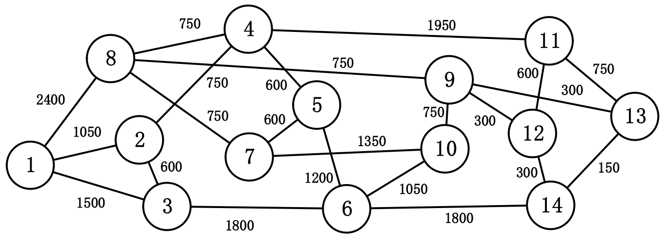

Fig. 3. NSFNET topology.

both spectrum and computing resources in a balanced manner can balance the network performance. JLB _1 and Greedy are two algorithms with the same VNF deployment scheme, which only consider the computing capacity. The Greedy blocking ratio is significantly larger than JLB_1 because it always chooses the shortest path when VL mapping without considering the network bottlenecks.

Fig. 4(b) indicates the results of CPU utilization in network. As shown in Fig. 4(a) and Fig. 4(b), computing capacity usage is directly related to the number of deployments and negatively correlated with the blocking ratio. In Fig. 4(c), JLB with different values of α generates similar results in terms of link utilization variance because they have the same VL mapping scheme. The comparison between Greedy and JLB_1 shows that the shortest path deployment scheme does not result in a significant improvement in spectrum consumption because the transmission network (i.e., EON) is distance adaptive.

Fig. 5(a) gives discrete results about the spectrum utilization of the link, in which JLB has great advantage. The variance of link utilization for the JLB scheme rises until 220 requests and then decreases slightly. In the early stages, the link load is balanced. In this case, for the impact factor $D_p \times \varphi_p$, D_p has a large impact. At this point, the algorithm does not tend to choose the path with a lower load, but rather the shorter path. When the load imbalance rises to a certain level, φ_p has more impact. Then the tendency is to choose the path with lower load and the utilization rate is balanced. Compare to Fig. 4(a) and find that at the same time, the links

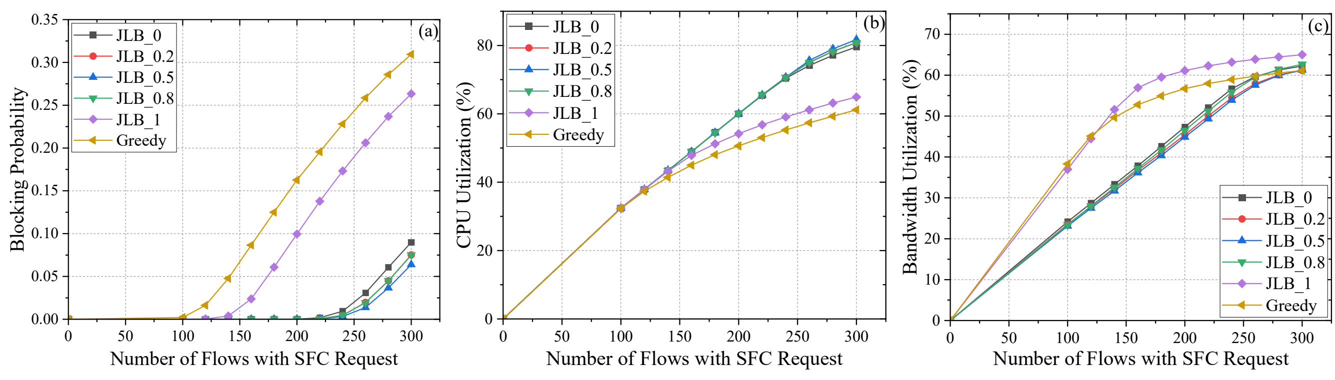

Fig. 4. Simulation results. (a) blocking rate, (b) CPU utilization and (c) bandwidth utilization

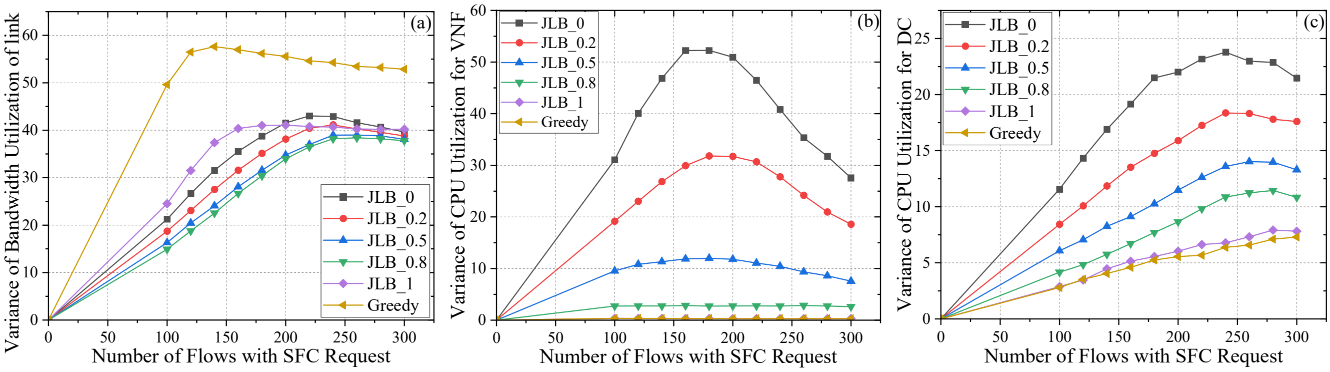

Fig. 5. Simulation results. (a) variance of bandwidth utilization, (b) variance of CPU utilization for VNF and (c) variance of CPU utilization for DC.

start to block. Some heavy load links cannot be deployed, so traffic can only go to some path where the load is lower, and thus the load is balanced. The results of the different schemes are compared, and it is found that more consideration of path weights does not enable more stable links. Because the second part of (1) considers the path length and is the average weight of the k-shortest paths, the node with the overall well-performing path is selected, not the one with the lowest single path load. Since there is a correlation between link and node, selecting a more idle node when considering the overall link performance is more likely to choose a path with a lower load, thus balancing the load.

Fig. 5(b) show the variations in CPU utilization of the same VNF instance on different DC nodes. The results show that the more consideration of computing resources leads to a higher degree of similarity in CPU utilization between different instances. Since Greedy and JLB_1 consider only the instance capacity and are able to always select the node corresponding to the instance with the smallest capacity for deployment, the variance is extremely small. The variance fluctuations of the remaining schemes stem from the link weights in (1). The variance of CPU utilization for VNF increases up to 160 requests and then decreases. As analyzed in Fig. 5(a), when the load imbalance reaches a certain level, i.e., the impact of φ_p can be greater than the impact of D_p, the deployment scheme will pay more attention to the load. Traffic will go to nodes with less load on the surrounding paths, rather than nodes with shorter surrounding paths.

Fig. 5(c) depicts the results of the CPU utilization variance of different VNF instances on the same DC node. Some nodes are more likely to be selected by the algorithm than others due to the number of connected links, the number of deployed instances, etc., and thus there is variance among different nodes. In addition, the comparison results between different schemes similar to Fig. 5(b), i.e., when the instance load is considered more, the node load is more balanced. The variance trend of the scheme also increases and then decreases. We set the bandwidth to be large enough, and then rerun the simulation to get the blocking optimization rate for each scheme in different numbers of requests. By comparing the optimized rate with the inflexion point in Fig. 5(c), we find that the inflexion point is the point at which the VNF instance capacity starts to become insufficient and thus starts to cause service blocking. At this moment, the traffic has to flow to the less load node, so the DC load becomes balanced.

V. Conclusion

An JLB algorithm is proposed for SFC deployment in CPN. The objective is to achieve network load balancing and reduce the spectrum consumption. Results show that JLB outperforms the benchmark with its ability to optimize the overall network load and acceptance rate. JLB_0.8 can have the best network synthesis performance, and its blocking ratio and bandwidth utilization variance can be optimized by 76% and 30% compared with the benchmark.

Acknowledgment

This work is supported in part by the Project of Jiangsu Engineering Research Center of Novel Optical Fiber Technology and Communication Network, Soochow University (SDGC2117), Beijing Natural Science Foundation (4232011), and NSFC (61831003, 62021005, 62101063).

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