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Energy-efficient and traffic-aware service function chaining orchestration in multi-domain networks

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HIGHLIGHTS

- We study the problem of energy-efficient orchestration of SFC requests across multiple domains.
- We extend node aggregation to construct a domain-level graph of the substrate network.
- We propose an energy-efficient algorithm to orchestrate SFC requests across multi-domains.
- We implement our proposed algorithm and compare it with existing algorithms.

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ABSTRACT

Service function chaining (SFC) provisioning is helpful not only for saving the capital expenditure (CAPEX) and operational expenditure (OPEX) of a network provider but also for reducing energy consumption in the substrate network. However, to the best of our knowledge, there has been little research on the problem of energy consumption for orchestrating online SFC requests in multi-domain networks. In this paper, we first formulate the problem of an energy-efficient online SFC request that is orchestrated across multiple clouds as an integer linear programming (ILP) model to find an optimal solution. Then, we analyze the complexity of this ILP model and prove that the problem is NP-hard. Additionally, we propose a low-complexity heuristic algorithm named energy-efficient online SFC request orchestration across multiple domains (EE-SFCO-MD) for near-optimally solving the mentioned problem. Finally, we conduct simulation experiments to evaluate the performance of our algorithm. Simulation results show that EE-SFCO-MD consumes less energy than existing approaches while the online SFC's requirements are met and the privacy of each cloud is effectively guaranteed. The low computational complexity of the heuristic approach makes it applicable for quickly responding to online SFC requests.

1. Introduction

In traditional networks, network functions (e.g., firewalls, network address translation, etc.) are implemented by middle-boxes coupled to the hardware [1]. However, with the development of the Internet, the cost of maintaining these hardware-implemented network functions has increased, and the hardware devices cannot easily meet the customization demand of end-users. To mitigate this problem, network function virtualization (NFV) [2,3] is proposed to implement a network function on commodity components, which is called a virtual network function (VNF). In addition, NFV can also be used to solve security problems in cloud computing [4,5].

A service function chaining (SFC) [6] request typically needs to specify several ordered VNFs; moreover, the source and destination should also be specified to represent the start point and end point of the request, as shown in Fig. 1(a). The mapping of an SFC request is to find several physical servers to host the VNFs and physical paths to connect the servers while satisfying various constraints. Therefore, a good mapping strategy can not only save capital expenditure (CAPEX) and operational expenditure (OPEX) but also reduce energy consumption in the substrate network [7,8]. In a single-cloud/domain network, the mapping decider can obtain the global information of the physical network, which makes it possible to complete the mapping policy based on a global perspective. However, SFC makes it feasible for NFV to be a flexible

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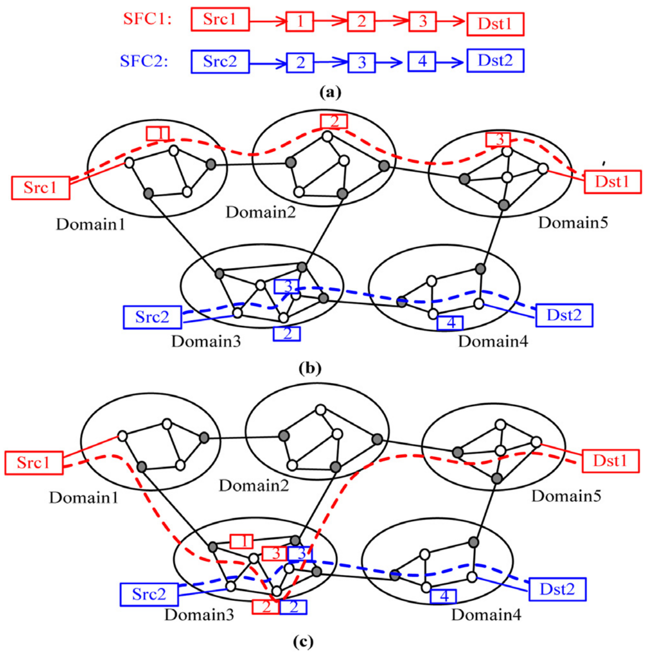

Fig. 1. Online SFC orchestration based on energy-unaware and energy-efficient schemes. (a) Two online SFC requests. (b) Energy-unaware SFC orchestration. (c) Energy-efficient SFC orchestration.

and effective alternative for the service assignments across multiple providers or a multi-domain network [9–11]. However, in a multi-domain network, the detailed information of each domain should be confidential from other domains or third parties to maintain the privacy of each domain, which makes it more difficult to orchestrate the SFC requests [12,13].

There are two ways to address the problem of orchestrating SFC across multiple domains: the centralized approach and the distributed approach. The centralized approach depends on each domain sharing its information with other domains or a third party, similar to [14], which violates the privacy among various domains. However, the distributed method maintains the privacy of each domain during SFC orchestration requests, resulting in higher costs and longer response times [15,16].

To reduce energy consumption, the orchestration result of an SFC should turn on as few servers as possible while still satisfying the SFC's requirements. For offline scenarios, the SFC requests are given in advance, and the mapping strategy usually redesigns the topology of SFC requests to reduce the number of VNFs by consolidating the same VNFs for different requests, such as in [17]. However, for online SFC requests, the request arrives and leaves dynamically, which makes it impossible to know all the SFC requests in advance. Therefore, we cannot orchestrate online SFC requests as easily as offline requests. Fig. 1 presents an example of orchestrating online SFC requests based on energy-unaware and energy-efficient schemes. In Fig. 1(c), the two VNF2s in SFC1 and SFC2 are consolidated and hosted in a physical server, which can reduce the number of servers and save energy.

In previous work, we studied the problem of orchestrating SFC requests. [18] proposes a reliability-aware approach that ensures reliability and reduces mapping cost during the deployment of VNFs on an SFC request. Moreover, [19] utilizes workflow to implement low-latency orchestration SFC requests in edge computing. Although these algorithms have excellent performance on their own goals, they consider only single-domain physical networks. In [20], we examine the problem of orchestrating SFC requests into a multi-domain physical network, although the paper does not consider reducing power consumption.

In this paper, we analyze the power consumption in substrate networks and formulate the problem of orchestrating an online SFC request in an energy-aware fashion across multiple domains as an integer linear programming (ILP) model. The model's objective is to minimize power consumption, and we provide the constraints that must be met while mapping an SFC, such as resource constraints, VNF order constraints, etc. Because the problem of orchestrating SFC requests across multiple domains is *NP-hard*, we also propose a low-complexity heuristic algorithm named energy-efficient online SFC request orchestration across multiple domains (EE-SFCO-MD) to quickly and near-optimally solve the above model. To fully exploit useful information, the EE-SFCO-MD algorithm first extends node aggregation [21,22] to build a domain-level function graph of the physical network. Then, the algorithm generates all domain-level reachable paths between the source and destination of the SFC request. For each domain-level reachable path, EE-SFCO-MD generates a local candidate graph and computes a partitioning result of the SFC request based on the local candidate graph. Next, the bidding mechanism is used to select the minimal energy consumption partitioning result as the final SFC segment scheme. Finally, according to the SFC segment result, EE-SFCO-MD maps each sub-SFC (namely part of SFC request) to a corresponding domain for generating the final orchestration solution of the SFC request. In summary, the main contributions of this paper are as follows:

- We study the problem of energy-efficient orchestration of online SFC requests across multiple domains and first formulate the problem as an ILP model.
- We extend node aggregation to construct a domain-level function graph of the substrate network to help orchestrate an SFC request.
- We propose a heuristic algorithm named EE-SFCO-MD to orchestrate online SFC requests across multi-domains in an energy-efficient approach.
- We implement our proposed algorithm and compare it with existing algorithms and analyze its performance for reducing energy consumption.

The remainder of the paper is organized as follows. The related work is summarized in Section 2. Section 3 describes and formulates the problem of energy-efficient online SFC request orchestration across multiple domains. Section 4 introduces the heuristic algorithm, and Section 5 presents the simulation results. Finally, we conclude the paper in Section 6.

2. Related work

2.1. Service function chaining orchestration

As network function virtualization is attracting increasing attention, there has been a large amount of research into service function chaining orchestration. Most of these papers have proposed corresponding orchestration strategies to address the problem of the resource-efficient orchestration of SFC requests under a different substrate network, such as single-domain networks [23–27] and multi-domain networks [14–16,28–31].

To better utilize the substrate network, [23] proposes a novel *Cut-and-Solve* based approach to address the joint issues of VNF assignment and embedding path selection. Ye Zilong et al. [24] propose a heuristic algorithm for redesigning the topology of multiple SFC requests by combining VNFs for the purpose of solving the joint topology design and mapping problem efficiently. The research in [25] focuses on the problem of VNF orchestration (VNF-OP), and proposed an ILP formulation and a dynamic programming-based heuristic for addressing larger instances of VNF-OP. The problem of congestion mitigation is considered in [26], which first analyzed