To Cooperate or Not to Cooperate: Service Function Chaining in Multi-Domain Edge-Cloud Elastic Optical Networks

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Abstract: We study the the non-cooperative provisioning of service function chains in a multi-domain edge-cloud elastic optical network (EC-EON), leverage game theory to design an algorithm for it, and analyze its performance difference from the cooperative scheme with simulations.

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1. Introduction

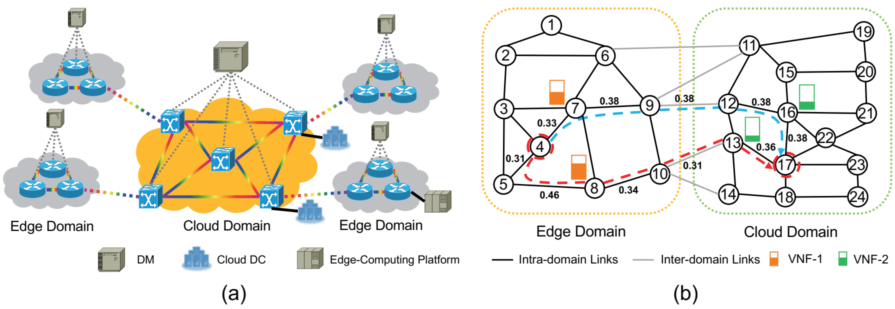
With the ever growing of network services and data [1], traditional centralized deployment of cloud computing can no longer meet the more stringent quality-of-service (QoS) demands on bandwidth, latency, and security. This promotes the idea of edge computing, which extends the computing capacity of cloud from core to edge network domains. Hence, the edge-cloud (EC) network model has attracted intensive interests to integrate edge/cloud computing and optical networks seamlessly [2]. Meanwhile, EC optical networks also accelerate the deployment of network function virtualization (NFV), which realizes network services with virtual network functions (VNFs) running on general-purpose servers. Specifically, in EC optical networks, a network service can be set up timely and flexibly by 1) deploying the required VNFs in cloud datacenters (DCs) or edge-computing platforms, and 2) establishing lightpaths to steer traffic through the VNFs in sequence. This essentially forms a VNF service chain (VNF-SC) to support the network service.

Recently, there have been several studies on the service provisioning of VNF-SCs in EC optical networks, including both algorithm designs [3] and experimental demonstrations [4]. However, they all assumed that the optical networks for cloud DCs and edge-computing platforms are managed in the centralized and cooperative manner. Note that, an EC optical network naturally consists of multiple domains. Specifically, as shown in Fig. 1(a), there is one cloud domain interconnecting several edge domains, and each edge domain is assumed to use the optical metro/access network architecture designed in [4]. Hence, for various practical considerations (*e.g.*, different operators, domain autonomy and data security), the domains might not always be managed by a global and centralized network orchestrator. Then, it is relevant to study the service provisioning of VNF-SCs in a multi-domain environment where the domain managers (DMs) do not cooperate with each other. This, to the best of our knowledge, has not be considered in the literature yet.

In this work, we consider the assembling of VNF-SCs in a multi-domain EC optical network, where the DMs of cloud and edge domains can be non-cooperative and adopt their own service provisioning strategies. We assume that the optical infrastructure of each domain is based on flexible-grid elastic optical network (EON) [5], and non-overlapping types of VNFs can be instantiated in cloud DCs and edge-computing platforms, respectively, to match to their privileges. For instance, the VNFs that require powerful computing capabilities (*e.g.*, those for data analytics) will be deployed in DCs, while those that should incur ultra-low latency (*e.g.*, those for video transcoding) will run on edge-computing platforms to move them close to end-users or data sources. Then, we model the provisioning of inter-domain VNF-SCs in such a multi-domain EC-EON as a *non-cooperative bimatrix game* between the DMs of cloud and edge domains. We leverage game theory to analyze the *Nash equilibrium* of the game, and in turn design an algorithm to tackle the non-cooperative provisioning. Through extensive simulations, we compare the performance of cooperative and non-cooperative provisioning schemes in different aspects, and analyze their pros and cons quantitatively.

2. Problem Description and Network Model

Fig. 1(b) provides an example to explain the difference between cooperative and non-cooperative provisioning of inter-domain VNF-SCs in a multi-domain EC-EON. Here, we assume that the VNF-SC is *Node* 4→*VNF*-1→*VNF*-2→*Node* 17, and there are instances of *VNF*-1 running on *Nodes* 7 and 8 in the edge domain, and those of *VNF*-2 running on *Nodes* 13 and 16 in the cloud domain. Hence, for the cooperative manner, the provisioning scheme marked with red dash-line can be obtained, as it uses the shortest path whose total normalized latency is 1.78. However, we can also find that it actually sacrifices certain interest of the edge domain, because it uses three fiber links there and lets the VNF-SC go through the busier *VNF*-1 on *Node* 8. This causes more-than-necessary spectrum usage and unbalanced VNF utilization in the edge domain, which will degrade its service provisioning performance (especially for intra-domain VNF-SCs) in the future. On the other hand, the scheme marked with blue dash-line is the result of non-cooperative provisioning, which protects the interests of the edge and cloud domains more fairly. Specifically, in the edge domain, the VNF-SC only uses two fiber links (*i.e.*, less spectrum usage) and selects the *VNF*-1 on *Node* 7 for load-balancing. Nevertheless, the non-cooperative provisioning scheme results in a longer total latency (*i.e.*, 1.85).



C2 / C1	Node 6	Node 9	Node 10
Node 11	4, 2	4, 1	+∞, +∞
Node 12	+∞, +∞	2, 1	+∞, +∞
Node 13	+∞, +∞	+∞, +∞	1, 3
Node 14	+∞, +∞	+∞, +∞	3, 3

(c)

Fig. 1. Service provisioning of inter-domain VNF-SCs in multi-domain edge-cloud elastic optical network (EC-EON), (a) Network topology, (b) Provisioning schemes, and (c) Example on cost matrices $\mathbf{C}_1$ and $\mathbf{C}_2$ and Nash equilibrium.

We model the topology of the multi-domain EC-EON as $G = \{G_n(V_n, E_n, V_n^c), n \in [1, N]\}$, which consists of N domains. Here, we assume that the first domain ($n = 1$) is the cloud domain and the remaining $(N-1)$ ones are the edge domains. As for the n-th domain, V_n and E_n denote the sets of nodes and fiber links, respectively, and $V_n^c \subseteq V_n$ is the set of nodes that have the computing resources to support VNFs (*i.e.*, DCs in the cloud domain, and nodes with edge-computing platforms in the edge domains). An inter-domain VNF-SC request from s to d is modeled as $R\{s, d, F, b, \Delta t\}$, where F denotes the required VNF-SC, and b and Δt are its bandwidth demand and life-time, respectively. Specifically, the VNF-SC can be represented as $F = [f_1, f_2, \cdots, f_K]$, where f_i ($i \in [1, K]$) is the i-th VNF that traffic should be steered through. In this work, we assume that the provisioning of each inter-domain VNF-SC only involves two domains (*i.e.*, the cloud domain and an edge domain), which is the most common case in EC optical networks [2,4]. Hence, in F, the first K_1 VNFs can be supported in one domain, while the remaining VNFs should be deployed in the other domain.

For the non-cooperative provisioning scheme, the DMs of the cloud and edge domains are two rational players, each of which independently determines the provisioning scheme of the VNF-SC segment in its own domain as follows. We denote the DMs as *DMs* 1 and 2 and assume that they need to serve the VNF-SC segments $[s, f_1, \cdots, f_{K_1}]$ and $[f_{K_1+1}, \cdots, f_K, d]$, respectively. As for the domain of *DM i*, there are m_i border nodes connecting to the other domain. First of all, for each of its border nodes, *DM i* tries to get a feasible provisioning scheme for the VNF-SC segment in its domain, using the combination of the longest common subsequence based algorithm (LCS) [6] and fragmentation-aware routing and spectrum assignment (RSA) [7]. For instance, for a border node v in the domain of *DM* 1, the VNF-SC segment that needs to be served is $[s, f_1, \cdots, f_{K_1}, v]$. Next, if a feasible provisioning scheme can be obtained for the j-th border node, *DM i* records it as a strategy $s_{i,j}$ and calculates its cost $\delta_{i,j}$ with the following expression:

$$\delta_{i,j} = \alpha \cdot B \cdot hop(s_{i,j}) + \beta \cdot delay(s_{i,j}) + \gamma \cdot cut(s_{i,j}) + \varepsilon \cdot \sigma_{FS}(s_{i,j}) + \zeta \cdot \bar{\sigma}_{VNF}(s_{i,j}), \tag{1}$$

where B denotes the number of frequency slots (FS') to support bandwidth demand b, $hop(s_{i,j})$ returns the hop-count of fiber links in *DM i* when strategy $s_{i,j}$ is used, $delay(s_{i,j})$ tells the delay in *DM i* with $s_{i,j}$, $cut(s_{i,j})$ is the number of spectrum cuts [7] caused by $s_{i,j}$, $\sigma_{FS}(s_{i,j})$ is the standard deviation change of spectrum usages in *DM i* caused by $s_{i,j}$, $\bar{\sigma}_{VNF}(s_{i,j})$ is the average standard deviation change of VNF usages caused by $s_{i,j}$, and α, β, γ, ε and ζ are the coefficients for normalization. In other words, the cost in Eq. (1) considers five terms to measure a strategy's impact on *DM i*. Otherwise, if a feasible provisioning scheme cannot be got, *DM i* records the cost of strategy $s_{i,j}$ as $\delta_{i,j} = +\infty$.

Hence, for each round of the game, the strategy sets of the DMs are $S_1 = \{s_{1,1}, \cdots, s_{1,m_1}\}$ and $S_2 = \{s_{2,1}, \cdots, s_{2,m_2}\}$. Then, if *DMs* 1 and 2 chooses strategies $\hat{s}_1 \in S_1$ and $\hat{s}_2 \in S_2$, respectively, the strategies form an outcome of the game (*i.e.*, a strategy profile): $\hat{s} = (\hat{s}_1, \hat{s}_2) \in S_1 \times S_2$. Note that, the DMs make their decisions simultaneously and independently, based on two cost matrices (*i.e.*, $\mathbf{C}_1$ and $\mathbf{C}_2$). The dimensions of $\mathbf{C}_1$ and $\mathbf{C}_2$ are both $m_1 \times m_2$, and an element of the matrices, $\mathbf{C}_i[j,k]$, denotes the price of the strategy profile $(s_{1,j}, s_{2,k})$ to *DM i*. Here, if the j-th and k-th border nodes of the two domains are connected by an inter-domain link and there are enough spectrum resources on it to support the bandwidth demand b, the strategy profile $(s_{1,j}, s_{2,k})$ is a feasible overall provisioning scheme for VNF-SC request R. Then, we have $\mathbf{C}_1[j,k] = \delta_{1,j}$ and $\mathbf{C}_2[j,k] = \delta_{2,k}$, *i.e.*, denoting the corresponding strategy costs of the DMs. Otherwise, if $(s_{1,j}, s_{2,k})$ does not represent a feasible overall provisioning scheme, we have $\mathbf{C}_1[j,k] = \mathbf{C}_2[j,k] = +\infty$.

As each DM has a finite number of strategies, the aforementioned procedure is essentially a two-player and one-round non-cooperative bimatrix game, whose Nash equilibrium can be obtained with the Lemke-Howson algorithm [8]. Specifically, the Nash equilibrium points to the strategy profile that contains the provisioning schemes selected independently by the DMs, and thus the overall scheme to serve the inter-domain VNF-SC request R can be obtained. Fig. 1(c) gives an example of the cost matrices $\mathbf{C}_1$ and $\mathbf{C}_2$ for the request R in Fig. 1(b), where the underlined elements denote the Nash equilibrium. Finally, if the overall provisioning scheme derived with the Nash equilibrium is feasible,

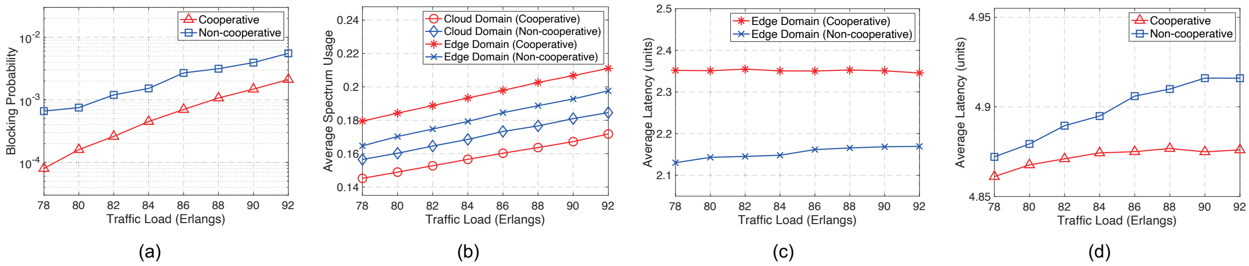


Fig. 2. (a) Blocking probability, (b) Average spectrum usage, (c) Latency in edge domain, and (d) Total latency.

R is provisioned accordingly, and it is rejected, otherwise.

In the non-cooperative provisioning scheme, the DMs share domain information with each other. Hence, we simply apply the combination of LCS and fragmentation-aware RSA on the merged topology of the two domains to serve R.

3. Simulation Results

We simulate an EC-EON with the two-domain topology in Fig. 1(b), where each link can accommodate 358 FS'. In each domain, half of the nodes are assumed to have computing facilities (*i.e.*, edge-computing platforms or cloud DCs). Each domain can support 4 types of VNFs, and the VNF types in the two domains do not overlap with each other. The capacities of the VNFs in cloud DCs and edge-computing platforms are randomly distributed within $[800, 1000]$ units and $[600, 800]$ units, respectively. Each VNF-SC request $R\{s,d,F,b,\Delta t\}$ is dynamically generated according to the Poisson traffic model, where s and d are randomly selected from the two domains, respectively, the types of the VNFs in F are also randomly chosen and we have $|F| \leq 5$, the required capacity of each VNF is uniformly distributed within $[12.5, 75]$ units, and the bandwidth demand b is randomly selected within $[1, 6]$ FS'.

As expected, Fig. 2(a) indicates that the cooperative provisioning scheme provides lower blocking probability. The benefit of the non-cooperative scheme can be seen in Fig. 2(b), which shows that it balances the spectrum usages in the two domains better, but the cooperative scheme makes the average spectrum usage in the edge domain significantly higher. Hence, the non-cooperative scheme protects the interests of both domains more fairly. Note that, even for the non-cooperative scheme, the average spectrum usage in the edge domain is higher. This is because in the EC-EON, the cloud domain has more fiber links and thus more spectrum resources than the edge domain. For each VNF-SC, Figs. 2(c) and 2(d) compare the average normalized latency in the edge domain and the average total normalized latency, respectively. In Fig. 2(c), we observe that the non-cooperative scheme can reduce the average latency in the edge domain, which is another evidence that the game between the two DMs protects the interest of the edge domain. Meanwhile, Fig. 2(d) shows that the non-cooperative scheme makes the average total latency per VNF-SC longer and increase faster with the traffic load. This is because the average fiber length in the cloud domain is longer than that in the edge domain, and thus if the game between the two DMs pushes a VNF-SC to use a path other than the shortest one, the additional latency incurred in the cloud domain can be relatively long. Moreover, this effect becomes more devastating when the traffic increase makes the alternative paths of each VNF-SC longer. In all, Fig. 2 suggests that compared with the cooperative scheme, the non-cooperative one can ensure the autonomy of each domain and protect their interests more fairly, especially for the edge domain whose spectrum and IT resources are less abundant (*i.e.*, the less dominated party), while the price is the degradations on blocking probability and average total latency.

4. Summary

We studied the cooperative and non-cooperative provisioning of VNF-SCs in a multi-domain EC-EON, designed an algorithm to tackle the non-cooperative scheme, and compared the two schemes quantitatively with simulations.

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