On the Game-Theoretic Analysis of Dynamic VNF Service Chaining in Edge-Cloud EONs

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***Abstract*—Network function virtualization (NFV) enables flexible, cost-effective, and timely deployment of new network services in elastic optical networks (EONs). Nowadays, the integration of cloud and edge computing becomes a prevailing trend, which has promoted the idea of edge-cloud EON (EC-EON) (*i.e.*, a multi-domain EON that consists of a cloud domain and one or more edge domains). In this work, we study the dynamic provisioning of virtual network function based service chain (VNF-SC) requests in EC-EONs, and leverage game theory to explain why and how the cloud and edge domain managers (DMs) should collaborate when protecting their own interests. We first formulate the non-cooperative interactions between cloud and edge DMs as a two-stage Stackelberg game, prove the existence of Nash Equilibrium in the game, and propose an algorithm based on backward induction for the non-cooperative service provisioning. Next, we address the cooperative provisioning scheme where the DMs can reach an agreement for mutual benefit, and model it with Nash bargaining. Finally, we conduct extensive simulations to compare the non-cooperative and cooperative provisioning schemes with the traditional centralized approach in EC-EONs in-depth. Simulation results confirm the effectiveness of our non-cooperative and cooperative provisioning schemes on protecting the interests of DMs, and suggest that the cooperative provisioning scheme can outperform the traditional centralized approach in terms of blocking probability, when inter- and intra-domain VNF-SC requests both exist in an EC-EON.**

***Index Terms*—Network function virtualization (NFV), Service function chain, Virtual network functions (VNFs), Game theory, Edge-cloud optical networks, Elastic optical networks (EONs).**

I. Introduction

OVER past decades, the world has witness tremendous development of cloud computing to explore the advantages on adaptivity, cost-efficiency, and flexibility [1, 2]. However, as network services and application data are emerging explosively, the traditional way of concentrating cloud computing in data-centers (DCs) has been challenged from various perspectives, such as bandwidth, latency, robustness, *etc*. Therefore, the idea of edge computing was proposed and is attracting intensive attentions from both academia and industry [3]. Specifically, edge computing extends computing from the DCs in core/metro to edge networks, and promotes the edge-cloud (EC) network model that tries to integrate edge/cloud computing and optical networks seamlessly with the latest optical networking technologies [4].

Each EC optical network is in a multi-domain architecture, which consists of one cloud domain and one or more edge domains, as shown in Fig. 1. The DCs in the cloud domain possess abundant IT resources for the network functions that require heavy-loaded computing, while the edge domains use lightweight edge-computing platforms to support short-life-cycle or/and latency-sensitive network functions timely and cost-effectively [5]. Meanwhile, the cloud and edge domains are each built on an optical network [6], which can leverage advanced optical networking technologies such as flexible-grid elastic optical networking (EON) [7–11] and coherent optical pluggable transceivers [12] to set up lightpaths adaptively and spectrum-efficiently for realizing low-latency and energy-efficient service provisioning. In rest of the paper, we will refer to the multi-domain EC optical network whose optical layer is architected with EON as an *EC-EON*. Operators usually rely on virtualization technologies [13, 14] to provision network services in EC-EONs, especially the network function virtualization (NFV) [15, 16]. Specifically, with NFV, an operator can provision network services by deploying virtual network functions (VNFs) on general-purpose servers and steering application traffic through the VNFs in sequence, *i.e.*, building VNF-based service chains (VNF-SCs) [17]. In the process, both chaining and embedding need to be addressed [18]. The "VNF-SC" here means the same as service function chain (SFC). We choose VNF-SC to emphasize that the chains considered in this work are made of VNFs, since an SFC can also be built with special-purpose middleboxes [19].

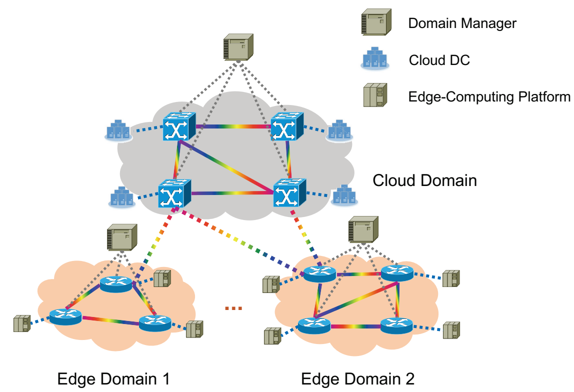

Fig. 1. Architecture of a multi-domain EC-EON.

Recently, there have been a few studies on the provisioning of VNF-SCs in EC optical networks, which considered both algorithm design [20–22] and system implementation [23–25], and relatively comprehensive surveys on NFV in EC networks can be found in [3, 26, 27]. These previous studies all assumed that the cloud and edge domains are managed in the centralized way (or if not, at least the cooperative

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manner). However, as shown in Fig. 1, an EC-EON naturally follows the multi-domain architecture, where each of the cloud and edge domains has its own domain manager (DM), and due to certain practical restrictions (*e.g.*, multi-operator scenarios, domain autonomy, and data privacy regulations), the DMs might not be willing to cooperate with each other [28, 29]. In other words, although each domain in an EC-EON can leverage software-defined networking (SDN) [30, 31] to realize centralized network control and management (NC&M) (*i.e.*, its DM is just the SDN controller), the DMs might not be coordinated by a global network orchestrator and need to set up the VNF-SCs, which have to go across multiple domains, based on autonomous and distributed decisions. Nevertheless, to the best of our knowledge, such a service scenario has not been fully explored yet, even though it is highly relevant to the provisioning of VNF-SCs in real-world EC-EONs.

Therefore, we conducted a preliminary study on this topic in [32] to tackle the assembling of VNF-SCs in an EC-EON, where the DMs were non-cooperative and adopted their own service provisioning strategies. Specifically, we assumed that non-overlapping types of VNFs can be deployed in cloud and edge domains, respectively, leveraged game theory [33] to model the provisioning of inter-domain VNF-SCs in such an EC-EON as a non-cooperative bimatrix game, and analyzed the Nash equilibrium of the game to design an algorithm for the non-cooperative provisioning. Our simulations revealed a few interesting insights, which cannot be observed in cooperative provisioning. For instance, the non-cooperative provisioning guaranteed the autonomy of each domain and protected its interest more fairly, especially for the less dominated party in the game (*i.e.*, the edge domains, because their spectrum and IT resources were less abundant than the cloud domain).

In this work, we significantly extend our study in [32] for a comprehensive game-theoretic analysis of dynamic VNF-SC provisioning in EC-EONs, with new theoretical models, new algorithms, much more extensive simulations, and new conclusions. More specifically, the major improvements made in this work are as follows. First of all, the non-cooperative game designed in [32] is static and thus cannot model the dynamic operations among the DMs accurately. In this work, we re-model the non-cooperative game between the DMs as a two-stage Stackelberg game, where each DM makes decisions autonomously to minimize the provisioning cost in its own domain. The new model is based on a dynamic process and thus becomes more practical to model the sequential interactions between the DMs. After proving the existence of pure-strategy Nash Equilibrium, we propose a brand-new algorithm based on backward induction to solve the non-cooperative provisioning problem. Next, we consider the cases in which the DMs are willing to cooperative to reach an agreement for their mutual benefits, and model the cooperation between the DMs as a cooperative game. This has not been addressed in [32] at all. We develop an optimization model based on Nash bargaining and solve it. Finally, extensive simulations are performed to compare the non-cooperative, cooperative, and centralized provisioning schemes in EC-EONs in-depth, in terms of provisioning cost, blocking probability, and resource usage. Therefore, compared with the simulations in [32], we analyze the performance of the DMs at different levels of cooperation much more comprehensively.

The rest of the paper is organized as follows. Section II conducts a brief survey on the related work. We explain the network model and formulate the problem of VNF-SC provisioning in multi-domain EC-EONs in Section III. In Section IV, the game-theoretic algorithms for VNF-SC provisioning in EC-EONs are designed. We discuss the simulations that compare the dynamic VNF-SC provisioning scenarios in which the degrees of cooperation among DMs are different in Section V. Finally, Section VI summarizes the paper.

II. Related Work

Due to its flexibility and cost-efficiency, NFV has drawn widespread attentions from both academia and industry. For a comprehensive overview about NFV, one is recommended to check [15, 34], and its service frameworks and typical use-cases can be founded in [16]. Furthermore, various algorithms have been designed to optimize the service provisioning of NFV in various networks [14, 17, 20–22, 35–37]. However, these studies did not address multi-domain scenarios.

Due to reasons like multi-operator collaboration, domain autonomy, and data privacy regulations, real-world NFV systems can commonly use multi-domain scenarios [38]. By leveraging SDN, the authors of [39] proposed an architecture to facilitate NFV in multi-layer and multi-domain networks, and assumed that DMs can be managed by a centralized orchestrator. Also based on a centralized orchestrator, the ADRENALINE testbed has been demonstrated in [40] for deploying NFV over multi-domain transport networks and distributed DCs. The study in [41] designed a hierarchical orchestration architecture for supporting NFV in multi-domain networks, while the basic idea was still to coordinate DMs in a centralized way. As for the VNF deployment in multi-domain optical networks based on wavelength-division multiplexing (WDM), people have developed and demonstrated network orchestration systems in [42, 43]. In addition to these architectural/system studies, people have also considered how to provision NFV-related services in multi-domain networks from the algorithmic perspective [44–46]. Nevertheless, they all assumed that DMs were coordinated by a centralized orchestrator or at least willing to share intra-domain information.

There are only few studies on NFV in multi-domain networks, which did not assume the centralized provisioning scheme [47, 48]. However, they were on resource reservation/trading, but did not leverage non-cooperative or cooperative games to tackle the actual service provisioning procedure of NFV-related services or consider NFV in EC-EONs. Specifically, the study in [47] analyzed a non-cooperative game in which each DM needs to determine how to reserve IT and bandwidth resources to compete for utility during serving the VNF-SCs in a multi-domain network, while Dieye *et al.* [48] designed a market place where each DM can publish and make bids for the resources that are needed for multi-domain NFV orchestration. Therefore, although these studies did model N-FV in multi-domain networks as non-cooperative/cooperative games, they are fundamentally different from this work and the approaches developed in them cannot be leveraged to solve our service provisioning problems.

Previously, in [28, 29, 49], we modeled the lightpath provisioning in multi-domain EONs with game theory. Nevertheless, as both IT and spectrum resources need to be allocated, the provisioning of VNF-SCs in EC-EONs is much more complex than serving lightpaths in multi-domain EONs. For instance, the choice of border nodes to enter/exit domains can impact the performance of end-to-end VNF-SC provisioning much more than that of a lightpath, and improper choice can even make the provisioning of a VNF-SC infeasible. Hence, the game-theoretic models of the non-cooperative and cooperative provisioning schemes considered in this work are also totally different from those developed in [28, 29, 49]. This further justifies the motivation and novelty of this work.

III. Dynamic VNF-SC Provisioning in EC-EONs

In this section, we first introduce the problem of dynamic VNF-SC provisioning in a multi-domain EC-EON, then explain the network model of the game theory scenarios in which the degrees of cooperation among DMs are different, and finally formulate the game-theoretic analysis mathematically.

A. Problem Description

In an EC-EON, each network service can be set up as a VNF-SC, which is served by the DMs with either cooperative or autonomous decisions. Specifically, for the VNF-SC, the DMs need to solve two subproblems simultaneously: 1) finding proper locations (*i.e.*, cloud DCs or edge-computing platforms) to deploy/reuse required VNFs, and 2) setting up lightpaths within or cross domains to connect the VNFs in the required order. Note that, unlike the study in [32], this work assumes that the types of VNFs supported in cloud and edge domains can overlap. As the VNF-SC provisioning consumes spectrum and IT resources, there are costs to the related DMs. Meanwhile, if the VNF-SC cannot be provisioned for whatever reason, the quality-of-service (QoS) of the DMs is degraded. Hence, the DMs should try to first minimize their costs and then reduce the overall blocking probability of VNF-SCs.

Fig. 2 shows an example on VNF-SC provisioning in an EC-EON. Here, we assume that the source and destination of a VNF-SC are *Nodes* 1 and 4, which locate in the edge and cloud domains, respectively, and the complete VNF-SC is *Node* 1→*VNF*-1→*VNF*-2→*Node* 4. There are two instances of *VNF*-1 running on *Nodes* 2 and 7, respectively, while the instances of *VNF*-2 are both running in the cloud domain (*i.e.*, on *Nodes* 3 and 7, respectively). We assume that available computing capacity of the *VNF*-2 on *Node* 7 is much larger than that of the one on *Node* 3. The solid and dashed lines in Fig. 2 denote two feasible schemes to provision the VNF-SC.

The DM of the cloud domain will prefer *Scheme* 2 for serving the VNF-SC, because it balances the loads of related VNFs well, which is beneficial for provisioning future VNF-SC requests in the cloud domain. However, the DM of the edge domain might not like *Scheme* 2, as it needs to set up a lightpath that consumes more optical spectra in the edge domain than that in *Scheme* 1. Hence, if the VNF-SC is served by the DMs with autonomous decisions, they might not reach a consensus due to their conflicting interests, which might lead to the VNF-SC being blocked. On the other hand, if the DMs are coordinated with a centralized orchestrator, the VNF-SC can be served with *Scheme* 1 or *Scheme* 2, depending on the actual optimization goal of the orchestrator, but the interest of either the cloud domain or the edge domain will be sacrificed.

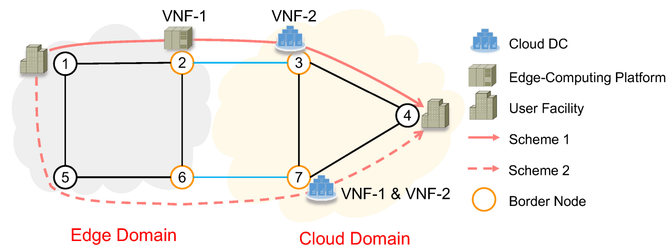


Fig. 2. Example on provisioning of inter-domain VNF-SCs in EC-EON.

B. Game-Theoretic Network Model

We model the topology of an EC-EON that consists of N domains as $G = \{G_n(V_n, E_n, \Omega_n), n \in [1, N]\}$, where V_n and E_n denote the sets of nodes and fiber links in the n-th domain, and Ω_n stores the types of VNFs that can be supported in the domain. Here, we assume that the first domain ($n = 1$) is the cloud domain and the remaining ones are edge domains. There are three types of nodes in each domain $G_n(V_n, E_n, \Omega_n)$: 1) **computing nodes** ($V_n^c \subseteq V_n$), each of which consists of a computing facility (*i.e.*, a DC in the cloud domain or an edge-computing platform in edge domains) and an optical switch, 2) **border nodes** ($V_n^e \subseteq V_n$), each of which connects to at least one inter-domain fiber link, and 3) **switch nodes**, each of which only includes an optical switch (*i.e.*, VNFs cannot be deployed on it). Note that, a node can simultaneously be a computing node and a border node (*e.g.*, *Nodes* 2, 3 and 7 in Fig. 2), and it can also be a switch node and a border node at the same time. For a computing node ($v \in V_n^c$), its IT resource capacity is C_v units, for carrying VNFs. Considering the domain heterogeneity, we assume that there are more computing nodes in the cloud domain and the IT resource capacity of each computing node in the cloud domain is much larger than that in the edge domain. The spectra on each link $e \in E_n$ can be allocated according to the flexible grids [50], *i.e.*, being divided into C_e 12.5-GHz frequency slots (FS'), each of which provides a capacity of 12.5 Gbps.

A VNF-SC request is denoted as $r = \{s, d, F, b, \Delta t\}$, where s and d are its source and destination nodes, F is the required VNF-SC, and b and Δt represent its bandwidth demand in Gbps and life-time, respectively. If s and d are in different domains, the VNF-SC request is an inter-domain one, and an intra-domain one otherwise. The VNF-SC can be denoted as $F = [f_1, \cdots, f_K]$, where K is the total number of VNFs in it, and $f_k (k \in [1, K])$ is the k-th VNF that traffic needs to be steered through. We assume that the provisioning of each inter-domain VNF-SC only involves two domains (*i.e.*, the cloud domain and an edge domain), because it is the most common case in EC optical networks [4, 23]. Then, for an inter-domain VNF-SC $F = [f_1, \cdots, f_K]$, we select the first K_1 VNFs from those that can only be supported in the source domain, the last K_2 VNFs from those that are dedicated to the destination domain, and the remaining $(K - K_1 - K_2)$ VNFs from those that can be deployed in both domains. The rationale behind the settings of edge-only and cloud-only VNFs is that certain VNFs should only be deployed in the edge or cloud domain due to their QoS requirements or resource demands. For example, latency-sensitive VNFs have to be deployed in the edge domain, while the VNFs that are compute-intensive or storage-intensive can only be instantiated in the cloud domain, for getting sufficient IT resources.

As shown in Fig. 1, each domain in an EC-EON is managed by a DM, which calculates several feasible provisioning schemes (*i.e.*, the placement of required VNFs and the RSA of the lightpaths that connect the VNFs in its domain) upon receiving an inter-domain VNF-SC request. Specifically, each feasible provisioning scheme is defined by a border node[1] to the peer domain of the inter-domain VNF-SC. For instance, in the source domain, the DM computes each feasible provisioning scheme from the source node s to each of the border nodes to the destination domain. Each feasible provisioning scheme should satisfy the common constraints used in provisioning VNF-SCs in an inter-DC EON [17], and thus it can be obtained by leveraging the well-known algorithms in the literature. Specifically, this work combines the longest-common-subsequence-based algorithm (LCS) [17] (*i.e.*, for VNF placement) and the fragmentation-aware RSA (FA-RSA) [10] (*i.e.*, for lightpath setup).

For an inter-domain VNF-SC request r, if we assume that the indices of its source and destination domains are n_1 and n_2 ($n_1, n_2 \in [1, N]$), the feasible provisioning scheme obtained by *DM* n_1 related to a border node $v \in V^e_{n_1}$ is referred to as $S_{n_1,v}$, and the similar definition is given to $S_{n_2,u}$ for the feasible provisioning scheme related to a border node $u \in V^e_{n_2}$ in the n_2-th domain. Then, by concatenating the possible pairs of feasible provisioning schemes in the source and destination domains, we obtain the whole solution space for serving r as

$$\mathcal{S}_r = \{S_{n_1,v},\ \forall v \in V^e_{n_1}\} \times \{S_{n_2,u},\ \forall u \in V^e_{n_2}\}. \tag{1}$$

Then, based on the solution space in Eq. (1), this work considers three dynamic VNF-SC provisioning scenarios with different degrees of cooperation among DMs:

- *Full Cooperation*: The DMs in EC-EON are coordinated by a global orchestrator, which will check all the possible end-to-end (E2E) provisioning schemes in $\mathcal{S}_r$ for a VNF-SC request r and instruct the related DMs to serve r with the one whose cost is the smallest. We will define the cost of a provisioning scheme in the following discussions.
- *Non-cooperative Game*: The two related DMs compete to protect their own interests during the provisioning of each VNF-SC request r. This forms a non-cooperative game between the two DMs, and each DM figures out the best provisioning scheme in its domain, with which no DM can decrease the price of its effort in the provisioning of r by changing its provisioning scheme unilaterally. In other words, the DMs determine the E2E provisioning scheme of r based on the non-cooperative game's Nash equilibrium [52]. Here, the price of a DM's provisioning scheme is calculated based on the cost of the provisioning scheme, and we will define it in the next section. Hence, the provisioning scheme of r is obtained in the distributed manner, where the DMs only exchange the prices of their feasible provisioning schemes but do not need to disclose the actual provisioning schemes to competing peers.
- *Cooperative Game*: The two related DMs are willing to negotiate to improve the provisioning quality of each VNF-SC request r, but they still want to protect their own interests during the provisioning. This forms a Nash bargaining [53] between the two DMs, which is a cooperative game in which the players seek for a mutual agreement that is beneficial to all of them. Therefore, the E2E provisioning scheme of r is still obtained in the distributed manner, and the DMs still only exchange the utilities of their feasible provisioning schemes.

When serving a VNF-SC request r, a related DM n normally needs to consider the cost from the resource utilization in its domain. In other words, the cost to *DM* n becomes smaller when r uses less resources and impacts the balance of resource usage in its domain less. To this end, we define the cost of a feasible provisioning scheme of r in the domain of *DM* n as

$$\begin{aligned}\delta_{n,v} =& \eta_s \cdot B \cdot hops(S_{n,v}) \cdot \Delta t + \eta_c \cdot C(S_{n,v}) \cdot \Delta t \\ &+ \eta_d \cdot dply(S_{n,v}),\end{aligned} \tag{2}$$

where $S_{n,v}$ denotes the feasible provisioning scheme of r, which is defined by a border node v in the n-th domain, B is the number of FS' for supporting the bandwidth demand b of r, $hops(S_{n,v})$ is the number of fiber links used in $S_{n,v}$, $C(S_{n,v})$ tells the total IT resources used by $S_{n,v}$, $dply(S_{n,v})$ returns the number of newly-deployed VNFs in $S_{n,v}$, and η_s, η_c, and η_d are the unit prices of FS usage, IT resource consumption, and VNF instantiation, respectively. We simply add the three terms in Eq. (2) because they are independent cost components.

IV. Design of Game-Theoretic Algorithms

In this section, we analyze the VNF-SC provisioning scenarios of non-cooperative and cooperative games, and design algorithms for DMs to obtain E2E provisioning schemes.

A. VNF-SC Provisioning based on Non-cooperative Game

For the dynamic VNF-SC provisioning scenario that is based on a non-cooperative game, our previous work in [32] oversimplified it as a bimatrix game. The model was not practical enough because it ignored the case where the cloud and edge domains in an EC-EON can support overlapping types of VNFs and did not address the non-cooperative interactions

[1]The reason why we only consider each feasible provisioning scheme to/from a border node is that the domains can be owned and operated by different operators, and thus optical-to-electrical-to-optical (O/E/O) conversions have to be applied on both ends of each inter-domain link to protect domain autonomy and privacy [51]. Hence, for an inter-domain VNF-SC, the actual spectrum assignment on each related inter-domain link is trivial, *i.e.*, the VNF-SC can be provisioned over the inter-domain link as long as it has sufficient spectrum resources to carry the bandwidth demand.

between the DMs. Therefore, in the following, we model the scenario as a non-cooperative game that is more practical.

First of all, we notice that for each inter-domain VNF-SC request r, the DM of its source domain is the one who submits it to the control plane of EC-EON, while the DM of its destination domain is the one who responses to the demand. This can be modeled as a Stackelberg game [33], which involves two players (*i.e.*, a leader and follower) and has the players interact sequentially to make decisions independently based on their own interests. Specifically, the two DMs in the Stackelberg game generally need to accomplish two tasks for serving r: 1) determining how to distribute the VNFs in its VNF-SC $F = [f_1, \cdots, f_K]$ in the two domains, and 2) finalizing the E2E provisioning scheme of r. Therefore, we design the Stackelberg game to include two stages, corresponding to the two tasks, respectively, based on the prices of DMs' effects.

In *Stage* I, the leader DM (*i.e.*, the DM of the source domain of r) tries to determine how to allocate the VNFs in its VNF-SC $F = [f_1, \cdots, f_K]$ to the two domains. As we have explained before, for F, the first K_1 VNFs should be those that can only be supported in the source domain, the last K_2 VNFs should be those that are dedicated to the destination domain, while the remaining $(K - K_1 - K_2)$ VNFs can be deployed in either the source domain or destination domain. Hence, the middle $(K - K_1 - K_2)$ VNFs in F define the solution space Γ of *Stage* I, and if the leader DM would like to place one VNF in them in the follower DM's domain, it needs to pay the price of renting the required IT resources there for the VNF. Specifically, the solution space Γ contains $(K - K_1 - K_2 + 1)$ schemes for allocating the VNFs in F to the two domains. The m-th scheme in Γ can be simplified as $[F^s_m, F^d_m]$, where F^s_m and F^d_m are the middle $(K - K_1 - K_2)$ VNFs allocated to the source and destination domains, respectively, and to use this scheme, the price paid by the leader DM can be calculated as

$$\Theta_m = \sum_{f_k \in F^d_m} (1 + p) \cdot \eta_c \cdot C(f_k) \cdot \Delta t, \tag{3}$$

where p denotes the price ratio, η_c is the unit cost of IT resources in the destination domain, and $C(f_k)$ tells the IT resource utilization of VNF f_k.

Then, in *Stage* II, the follower DM (*i.e.*, the DM of the source domain of r) tries to finalize the E2E provisioning scheme of r based on the leader DM's decision. Specifically, it chooses a border node $v \in V^e_{n_2}$ to finalize the provisioning scheme for r in its domain. Here, we assume that the leader and follower DMs are the n_1-th and n_2-th DMs in the EC-EON. When the provisioning scheme in the destination domain is chosen, the leader DM can simply select the provisioning scheme in its domain by finding the one that can connect to v through an inter-domain link and has the smallest cost. Note that, the choice of the leader DM in *Stage* II will not affect the decision of the follower DM, because it is determined after the follower DM has made its decision.

Therefore, the outcome of the Stackelberg game can be represented with the results of the two stages, *i.e.*, m and v, and we denote it as a strategy profile (m, v). Then, with Eqs. (2) and (3), we can calculate the prices of the DMs' efforts for serving r with strategy (m, v) as

$$\begin{cases} U_{n_1} = \delta_{n_1,u} + \Theta_m, & \text{Leader DM}, \\ U_{n_2} = \delta_{n_2,v} - \Theta_m, & \text{Follower DM}, \end{cases} \tag{4}$$

where $u \in V^e_{n_1}$ is the border node selected by the leader DM.

Next, we design the game-theoretic algorithm for the DMs by considering *Stage* II first. We can see that with the solution m chosen by the leader DM in *Stage* I, the follower DM needs to solve the following optimization.

$$\begin{aligned} &\text{Minimize} \quad U_{n_2}, \\ &s.t. \quad v \in V^e_{n_2}. \end{aligned} \tag{5}$$

This optimization can be easily solved in linear time $O(|V^e_{n_2}|)$ by checking each border node in $V^e_{n_2}$. Then, if we loop through each VNF allocation scheme in Γ, we can obtain the optimal responses of the follower DM to all the allocation schemes and store the optimal strategies $\{(m, v)\}$ in set Λ. Then, the leader DM solves the optimization below in *Stage* I.

$$\begin{aligned} &\text{Minimize} \quad U_{n_1}, \\ &s.t. \quad (m, v) \in \Lambda. \end{aligned} \tag{6}$$

To this end, it can be seen that the optimal decisions of the DMs (m^*, v^*) defined by Eqs. (5) and (6) actually represent the Nash equilibrium of the Stackelberg game. Specifically, the Nash equilibrium of the non-cooperative Stackelberg game is the strategy profile in which no DM can decrease its price by changing its decision unilaterally [53].

Theorem 1. *The non-cooperative Stackelberg game between DMs has a pure-strategy Nash equilibrium.*

Proof: In the Stackelberg game, the leader and follower DMs operate in the sequential manner, and thus the follower DM always knows all the feasible strategies of the leader DM, and *vice versa*. Hence, it is an extensive-form game of perfect information [52]. Meanwhile, the solutions to the optimizations in the two stages are both discrete and finite. To this end, the Stackelberg game defined by Eqs. (5) and (6) is a finite extensive-form game with perfect information, and according to [54], such a game has a pure-strategy Nash equilibrium, *i.e.*, a deterministic strategy. ■

As there always exists a pure-strategy Nash equilibrium for the Stackelberg game between DMs, we can find the Nash equilibrium by leveraging the technique of backward induction [55]. *Algorithm* 1 shows the overall procedure of our algorithm to calculate the Nash equilibrium, which is an exact algorithm. *Lines* 1-4 are for the initialization. The for-loop of *Lines* 5-8 find the optimal strategy of the follower DM in response to each specific solution m from *Stage* I. All the pairs of the optimal strategy v and its corresponding m are stored in set Λ (*Line* 7). Finally, *Lines* 9-14 check all the strategies in Λ to find the solution of the optimization in *Stage* I (*i.e.*, (m^*, v^*)), which is just the Nash equilibrium for the two DMs to obtain the E2E provisioning scheme of VNF-SC request r. The first for-loop traverses the whole solution space Γ, thus with a time complexity of $O((K - K_1 - K_2 + 1) \cdot |V^e_{n_2}|)$, which equals the number of VNF allocation schemes multiplied by the number of inter-domain connection schemes from the perspective of the follower domain. The second for-loop determines the actual VNF allocation scheme and has a time complexity of $O((K-K_1-K_2+1))$. Therefore, the overall time complexity of *Algorithm* 1 is $O((K-K_1-K_2+1)\cdot|V_{n_2}^e|)$.

Algorithm 1: Get Nash equilibrium of Stackelberg game

Data: an inter-domain VNF-SC request r.
Output: Nash equilibrium (m^*, v^*) for serving r.

store indices of leader and follower DMs in n_1 and n_2;
get the whole solution space for serving r with Eq. (1);
get solution space Γ for *Stage* I based on F, K_1 and K_2;
$\Lambda=\emptyset$, $U_{\min}=+\infty$;
for *each allocation scheme* $m\in\Gamma$ **do**
  solve the optimization in Eq. (5) with m to get the best border node v in the follower DM's domain;
  insert strategy (m,v) into Λ;
end
for *each strategy* $(m,v)\in\Lambda$ **do**
  calculate U_{n_1} by applying (m,v) to Eq. (4);
  if $U_{n_1}<U_{\min}$ **then**
    $U_{\min}=U_{n_1}$, $m^*=m$, $v^*=v$;
  end
end

Fig. 3 shows an illustrative example to explain the procedure of the backward induction in *Algorithm* 1. Specifically, the decision process in the Stackelberg game, which is a finite extensive-form game with perfect information, can be represented with the decision tree in Fig. 3. Here, the numbers in each parentheses are for (U_{n_1}, U_{n_2}), *i.e.*, the prices of the leader and follower DMs, respectively. We can see that the solution space of *Stage* I contains two solutions (m_1 and m_2), which suggests that there is only one middle VNF ($K-K_1-K_2=1$) in the VNF-SC F of r, while the solution space of *Stage* II includes four border nodes ($\{v_1,v_2,v_3,v_4\}$). The algorithm first finds the optimal strategies of the follower DM for m_1 and m_2. More specifically, for m_1, the optimal strategy is (m_1,v_1), which leads to the smallest U_{n_2} of 0.5, and for m_2, the optimal strategy is (m_2,v_3), which leads to the smallest U_{n_2} of 2.5. Next, for the two optimal strategies (m_1,v_1) and (m_2,v_3), the lead DM compares its prices in them and selects (m_2,v_3) because it provides a smaller U_{n_1} of 0.4. Finally, the DMs finalize the E2E provisioning scheme of r with the strategy in the Nash equilibrium (m_2,v_3).

Note that, due to competition between the two DMs, the Nash equilibrium of the non-cooperative game might not point to the solution that is optimal to both parties (*i.e.*, the Pareto optimal) [33]. For instance, in the example in Fig. 3, the Pareto optimal is (m_1,v_2), which provides the prices of $U_{n_1}=1.9$ and $U_{n_2}=0.6$ and represents the E2E provisioning scheme whose total cost is the smallest.

B. VNF-SC Provisioning based on Cooperative Game

Although the non-cooperative game discussed in the previous subsection helps to protect the interests of DMs to the maximum extent, its Nash equilibrium might not point to the Pareto optimal of inter-domain VNF-SC provisioning (such as the case in Fig. 3). This motivates us to consider the dynamic VNF-SC provisioning based on a cooperative game, where the two related DMs are willing to negotiate to improve the quality of the E2E provisioning scheme of each inter-domain VNF-SC request r, under the consensus that their interests should be protected. Therefore, the DMs need to perform a Nash bargaining [53] for the VNF-SC provisioning.

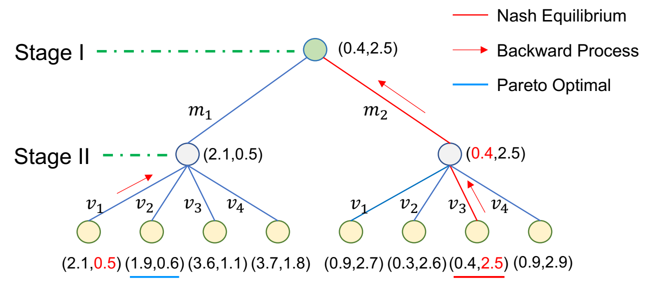


Fig. 3. Example on the backward induction to find Nash equilibrium of a non-cooperative Stackelberg game.

The problem of our Nash bargaining is defined by two basic elements, which are the set of the utilities that DMs can achieve when they agree to cooperate, and the disagreement point if they fail to reach an agreement [53]. For an inter-domain VNF-SC r, if its provisioning involves the n-th DM, all the feasible provisioning schemes in its domain are $\{S_{n,v},\ \forall v\in V_n^e\}$, each of which associates a cost $\delta_{n,v}$ according to Eq. (2). The maximum/minimum of the costs are

$$\begin{cases}\delta_{n,v}^{\max}=\max\limits_{v\in V_n^e}\ (\delta_{n,v}),\\ \delta_{n,v}^{\min}=\min\limits_{v\in V_n^e}\ (\delta_{n,v}).\end{cases}\tag{7}$$

Then, we define the utility, which can be achieved by *DM* n if it selects $S_{n,v}$ for r in its domain, as

$$U_{n,v}=\frac{\delta_{n,v}^{\max}-\delta_{n,v}}{\delta_{n,v}^{\max}-\delta_{n,v}^{\min}}.\tag{8}$$

We can see that a larger utility suggests a better provisioning scheme for the DM. Therefore, in the Nash bargaining, each DM tries to maximize its utility through cooperation. Then, we can denote the utility set as $\mathbf{U}=\{U_{n,v}:U_{n,v}\geq\widetilde{U}_n,\ v\in V_n^e\}$, where $\widetilde{U}_n$ denotes the utility of the disagreement point (*i.e.*, the utility that DM n can get if it decides not to be cooperative). Based on the theory of Nash bargaining [53], the solution of a Nash bargaining is the Pareto optimal, and it is proven to be unique. Specifically, the solution can be obtained by solving the following optimization [56].

$$\begin{aligned}&\text{Maximize}\quad \prod_{n\in\{n_1,n_2\}}\left(U_{n,v}-\widetilde{U}_n\right),\\ &s.t.\quad v\in V_n^e,\\ &\qquad\ \ U_{n,v}\geq\widetilde{U}_n,\end{aligned}\tag{9}$$

where we still assume that the two related DMs are the n_1-th and n_2-th DMs in the EC-EON. The optimization in Eq. (9) can be solved exactly by checking all the possible E2E provisioning schemes in the solution space for serving r defined in Eq. (1), with a time complexity of $O(\mathcal{S}_r)$. The Nash

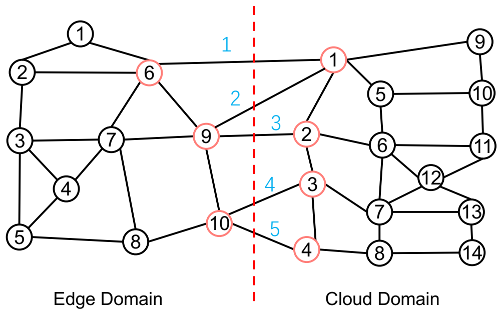


Fig. 4. EC-EON topology used in simulations (indices of inter-domain links are marked with blue numbers).

bargaining solution is the unanimous agreement between DMs on the provisioning of inter-domain request, by which we can characterize the outcome of DMs when they cooperate.

V. Performance Evaluations

In this section, we perform simulations for a comprehensive game-theoretic analysis of dynamic VNF-SC provisioning in EC-EONs, to compare the three provisioning schemes whose degrees of cooperation among DMs are different.

A. Simulation Setup

The simulations consider an EC-EON with the two-domain topology in Fig. 4, where the border nodes are marked with red cycles. We assume that each fiber link in the topology can accommodate $C_e = 358$ FS', according to the bandwidth of C-band. Half of the nodes in each domain are assumed to be computing nodes and their locations are randomly chosen as shown in Table I, where the IT resource capacity of computing nodes in the cloud domain is set much larger than that in the edge domain to emulate the case in EC-EONs. We set the number of VNF types that can be supported in the EC-EON as 7, according to the commonly-used VNF types in the literature [57], and the types of VNFs that can be deployed in the cloud and edge domains are listed in Table I.

The information about each inter-domain VNF-SC request $r = \{s, d, F, b, \Delta t\}$ is also shown in Table I, where the source s and destination d are randomly selected in the two domains, respectively. In each simulation, VNF-SC requests are dynamically generated according to a Poisson traffic model, which sets the average life-time (Δt) as 10 time-units, and the distribution of the required VNFs in the VNF-SCs is set as [*VNF-1* : *VNF-2* : *VNF-3* : *VNF-4* : *VNF-5* : *VNF-6* : *VNF-7*] = [12 : 16 : 12 : 15 : 16 : 10 : 10]. Then, by changing the average interval between the arrivals of VNF-SC requests, we can simulate different traffic loads. In Table I, we introduce the price ratio p for the IT resource usages of VNFs according to the "pay-by-usage" scenario in Eq. (3), which is used by a number of cloud providers (*e.g.*, Amazon [58]). To normalize the cost in Eq. (2), the unit prices are set as $\eta_s = \frac{1}{C_e \cdot |E_n|}$, $\eta_c = \frac{1}{C_v \cdot |V_n^c|}$, and $\eta_d = \frac{1}{|\Omega_n| \cdot |V_n^c|}$ (*i.e.*, the reciprocals of total resource amounts). Note that, as we assume that in the cloud domain, there are more computing nodes (*i.e.*, larger $|V_n^c|$) and the IT resource capacity of each computing node (*i.e.*, C_v) is also much larger, the unit price of IT resource usage in the cloud domain will be much lower than that in the edge domain, which is in line with the actual cases in edge-cloud environment [3]. To ensure sufficient statistical accuracy, we perform 5 independent runs, average them to get each data point in the simulations, and plot the 95% confidence intervals.

TABLE I
Simulation Parameters

Multi-domain Topology	
$G = \{(G_1, G_2)\}$	Cloud domain: G_1, Edge domain: G_2
C_e	358
Nodes in EC-EON	
V_1^c	*Nodes* $\{1, 2, 3, 4, 6, 7, 12\}$
C_v in cloud	3000 units
V_2^c	*Nodes* $\{2, 3, 6, 7, 8\}$
C_v in edge	1500 units
V_1^e	*Nodes* $\{1, 2, 3, 4\}$
V_2^e	*Nodes* $\{6, 9, 10\}$
VNF types in cloud	$\{1, 2, 3, 4, 5\}$
VNF types in edge	$\{4, 5, 6, 7\}$
VNF-SC Requests	
b	$[1, 10]$ FS'
$\lvert F \rvert$	$[1, 6]$ VNFs
$C(f_k), f_k \in F$	$[12.5, 62.5]$ units
Average of Δt	10 time-units
p	0.3

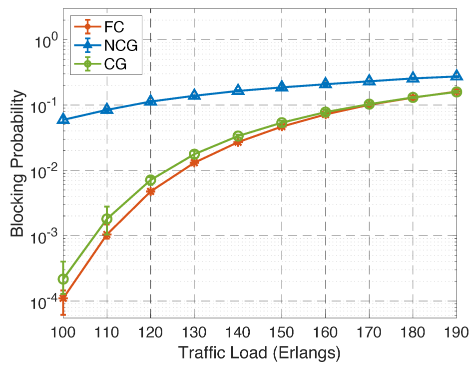
TABLE II
Average Running Time of Algorithms per Request (seconds)

Provisioning Schemes	FC	NCG	CG
Running Time	0.0984	0.1022	0.1029

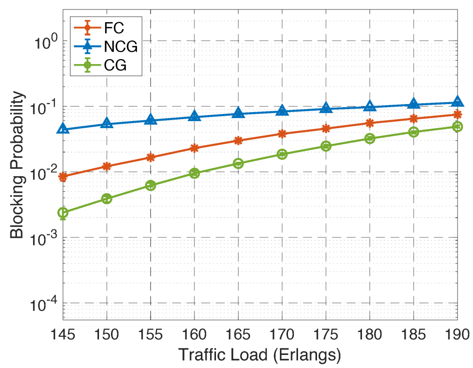
B. Performance on Blocking Probability

We first compare the performance of non-cooperative game, cooperative game, and full cooperation (*i.e.*, the traditional centralized scheme) based VNF-SC provisioning schemes in the EC-EON, in terms of request blocking probability. For convenience, we refer to the three provisioning schemes as NCG, CG, and FC, respectively, in the following discussions.

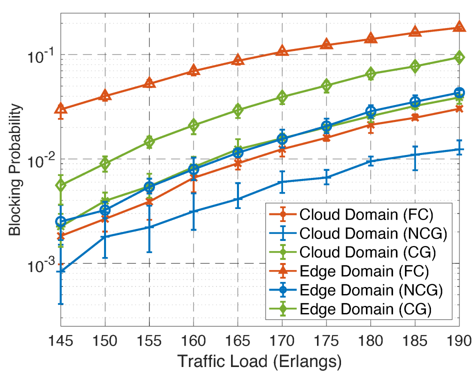
First of all, we assume that all the VNF-SC requests in the EC-EON are inter-domain ones. Table II lists the average running time taken by the VNF-SC provisioning algorithms for each inter-domain request. It can be seen that the average running time of NCG and CG is only slightly longer than that of FC, and the average running time is all around 0.1 second, which satisfies the requirement of dynamic service provisioning in EC-EONs. We plot the results on blocking probability in Fig. 5(a). As expected, the blocking probability of FC is the lowest, which is followed by that of CG, while the blocking performance of NCG is the worst (actually much worse than that of FC and CG). These results confirm that



(a) Inter-domain requests only



(b) Inter-domain and intra-domain requests

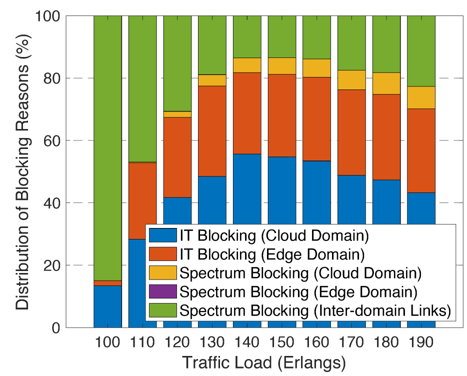


(c) Intra-domain requests in edge and cloud domains

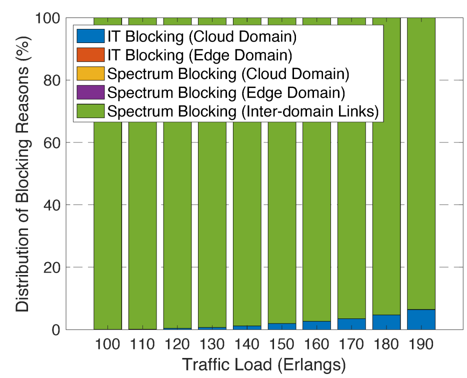
Fig. 5. Results on blocking probability.

improving the degree of cooperation among DMs helps to reduce the blocking probability in EC-EONs. Meanwhile, we notice that the results on blocking probability from CG and FC are very close, which suggests that even though CG protects the autonomy of DMs, it will not cause severe performance degradation on blocking probability.

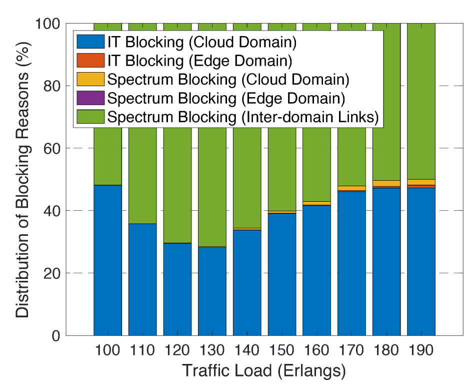
Next, we further analyze the blocking performance of the schemes by considering a more realistic scenario where there are both inter-domain and intra-domain requests in the EC-EON, with a ratio of 2 : 1. Fig. 5(b) shows the overall blocking probability, while the blocking probability of intra-domain requests in edge and cloud domains is plotted in Fig. 5(c). This time, it is interesting to notice that the blocking probability of CG becomes the lowest in Fig. 5(b), and the gap between the results from FC and NCG decreases significantly. This phenomenon can be explained as follows. Although FC can always obtain the global view of the EC-EON to optimize the provisioning of each VNF-SC request, it does not pay much attention on maintaining balanced resource utilization in each domain. Therefore, FC can lead to excessive blocking of intra-domain requests, especially in the edge domain where IT and spectrum resources are much less abundant, and this pushes up its overall blocking probability. On the other hand, CG leverages the Nash bargaining between the DMs to protect their own interests, and thus the resource utilization in each domain can be balanced after each VNF-SC provisioning, which helps to reduce the overall blocking probability.



(a) Distribution of blocking reasons with FC



(b) Distribution of blocking reasons with NCG



(c) Distribution of blocking reasons with CG

Fig. 6. Reasons of VNF-SC request blockings.

The analysis above can be verified by the blocking probability of intra-domain requests in Fig. 5(c). It can be seen that the

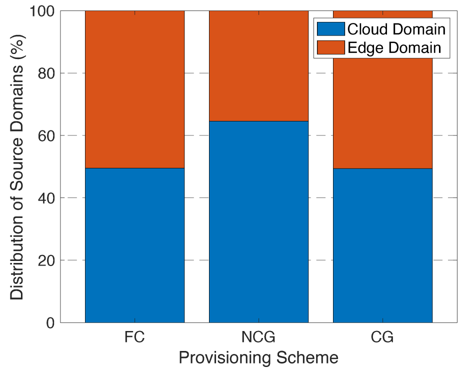


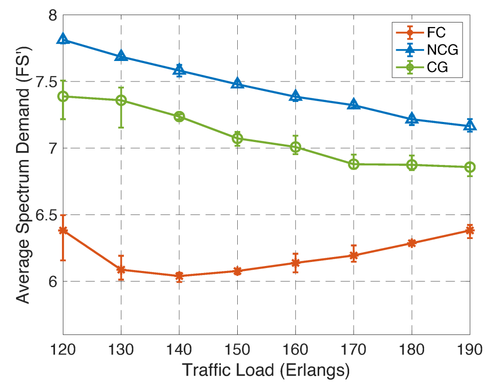
Fig. 7. Distribution of source domains of blocked VNF-SC requests.

blocking probability of FC in the edge domain is the highest. This is because FC does not apply any protection on the interest of each DM, and thus it can exploit the less dominated party (*i.e.*, the edge domain since its IT and spectrum resources are much less) too much. On the other hand, Fig. 5(c) also shows that the blocking probabilities of NCG are always much lower than those of FC and CG, in both the edge and cloud domains. This confirms that NCG protects the interest of each DM the best. However, the protection applied by NCG is too much, *i.e.*, the DMs are too selfish to cause excessive blocking of inter-domain requests, which is the reason why the overall blocking probability of NCG in Fig. 5(b) is still the highest.

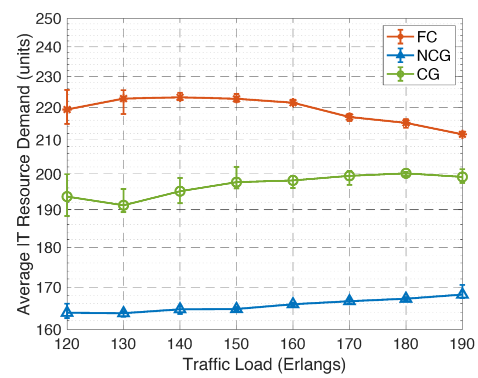
To this end, the results in Figs. 5(b) and 5(c) suggest that CG achieves the best tradeoff between domain autonomy and blocking performance, and thus it can perform the best in terms of blocking probability in an EC-EON where both inter-domain and intra-domain VNF-SC requests exist. Finally, Fig. 5(c) indicates that the performance gaps among the three schemes are much smaller in the cloud domain than in the edge domain, respectively. This is because the resources in the cloud domain are much more abundant, and thus unbalanced resource utilization there has a smaller impact on the blocking probability of intra-domain requests.

We then investigate the actual reasons of request blockings in the EC-EON. Specifically, for each inter-domain request, it can be blocked due to two reasons: 1) the spectrum resources in domains or on inter-domain links are not enough (namely, **spectrum blocking**), and 2) the IT resources in domains are insufficient (namely, **IT blocking**). Fig. 6 shows the distributions of blocking reasons with the three provisioning schemes. We can see that the majority of the request blockings with FC are due to IT blocking, with an average ratio of 67.7%, while spectrum blocking on inter-domain links is the major cause of request blockings with NCG and CG, contributing to 97.8% and 60.1% of their request blockings on average, respectively. Hence, FC optimizes the spectrum usage on inter-domain links the best, which is well expected because it always uses the global view of the EC-EON to serve inter-domain requests. Meanwhile, as NCG and CG both focus on protecting the interest of each domain and do not pay much attention on inter-domain links, they encounter resource bottlenecks there.

Fig. 7 shows the distributions of source domains of blocked inter-domain VNF-SC requests. We observe that with FC and CG, the source domains of the blocked requests generally distribute equally between the cloud and edge domains, *i.e.*, the ratios of the blocked requests that use the cloud domain as their source domains are 49.5% and 49.4%, respectively. As we choose the source domain of each request randomly in the simulations, these results suggest that FC and CG do not treat inter-domain requests differently based on their source domains. As for NCG, the ratio of the blocked requests that use the cloud domain as their source domains is 64.6%. This actually confirms the effectiveness of our proposed algorithm for NCG. Specifically, our algorithm allows the less dominated party (*i.e.*, the edge domain) to reject more requests originating from the dominated party for protecting its own interest.



(a) Average spectrum demand of blocked requests



(b) Average IT resource demand of blocked requests

Fig. 8. Resource demands of blocked VNF-SC requests.

Fig. 8 illustrates the characteristics of the blocked requests in terms of their resource demands. In Fig. 8(a), we can see that NCG tends to block the requests whose spectrum demands are relatively large, to protect the interest of each domain and reserve certain spectrum resources for intra-domain requests. On the other hand, FC is more likely to block an inter-domain request if its IT resource demand is larger (as shown in Fig. 8(b)), because IT blocking is the major reason for the request blockings with FC (as indicated in Fig. 6(a)). In both Figs. 8(a) and 8(b), CG performs in between NCG and FC, showing good balance of spectrum and IT resource usages with it.

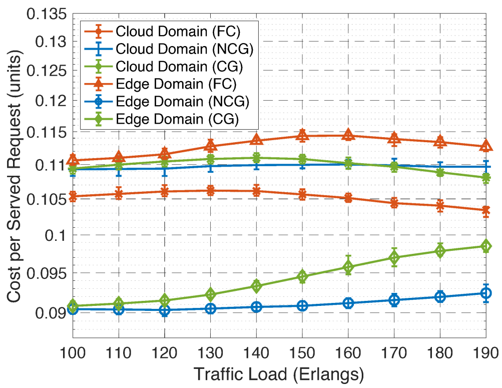


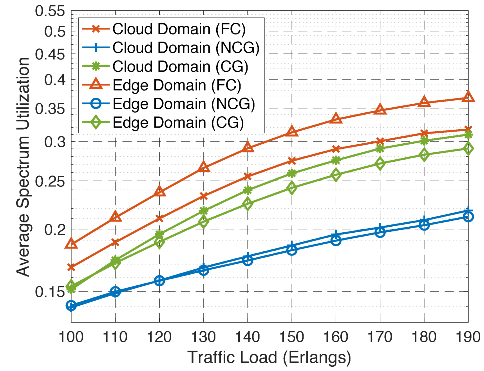
Fig. 9. Average cost per served request.

C. Performance on Resource Utilization

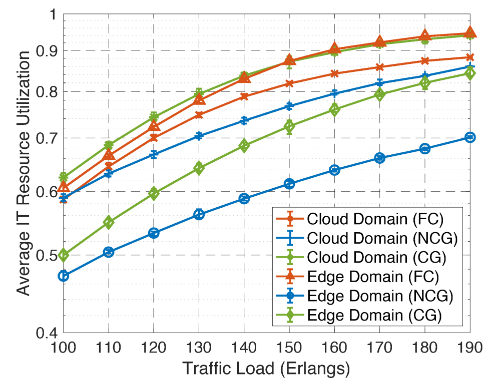
Next, we compare the costs and resource usages of the three schemes. Fig. 9 plots the average cost per served inter-domain VNF-SC request in each domain, which is calculated with Eq. (2). It can be seen that the overall cost with FC is the highest, mainly due to the highest average cost in the edge domain. This is because FC tries to use global optimization to minimize the blocking probability of requests, but does not pay much attention on reducing the cost of each served request. Since NCG lets the DMs compete for lower provisioning costs in their own domains, its average cost is generally the lowest among the three schemes, especially in the edge domain. Meanwhile, because the resources in the cloud domain are abundant, the average costs with NCG and CG in it are similar, and when the traffic load is relatively large (*i.e.*, higher than 170 Erlangs), the average cost with CG can even be slightly smaller. This is because CG can provision more requests than NCG, and thus at a higher traffic load, it can make more requests share the deployed VNFs, which helps to reduce its average cost to certain extent, especially for high traffic loads.

Fig. 10 shows the average resource usages in the domains. In Fig. 10(a), FC provides the highest spectrum usages in the domains, of which the spectrum utilization in the edge domain is higher, because of the global optimization conducted by it. NCG achieves almost the same spectrum utilizations in the cloud and edge domains, which once again verifies that our proposed algorithm can effectively protect the interest of each domain. Meanwhile, compared with FC, CG also reduces the gap between the spectrum utilizations in the two domains.

The results on average IT resource usage are plotted in Fig. 10(b), which still indicates that FC generally provides the highest IT resource usages in the domains. However, this time, the gaps between the IT resource usages in the cloud and edge domains with NCG and CG are actually much larger than that with FC. This is because the IT resources in the cloud domain are much more abundant than those in the edge domain. Note that, for both NCG and CG, the IT resource usage in the edge domain is smaller than that in the cloud domain, while the situation is opposite with FC. This suggests that FC actually exploits the edge domain too much. On the other hand, by deploying more VNFs in the cloud domain when provisioning inter-domain requests, NCG and CG can effectively reduce the IT resource usage in the edge domain to protect its interest.



(a) Average spectrum utilization



(b) Average IT resource utilization

Fig. 10. Average resource utilizations in domains.

Then, we analyze the spectrum usages on inter-domain links and the usages of different types of VNFs. The average spectrum usage of each inter-domain link is plotted in Fig. 11. As for NCG, DMs make decisions independently based on their utilities and try to minimize their own provisioning costs. Therefore, the spectrum resources on inter-domain links cannot be used as effectively as in the cases with FC and CG. Fig. 12 shows the total capacity of each type of VNFs deployed by each scheme in the cloud domain, when the traffic load is 140 Erlangs. We can see that NCG and CG instantiate more VNFs whose types can be supported in both the cloud and edge domains (*i.e.*, *VNF-4* and *VNF-5*), suggesting that they try to use more IT resources in the cloud domain when provisioning inter-domain requests. This further justifies our analysis on the results in Fig. 10(b).

D. Evaluations on Universality

Finally, we perform more simulations to verify that the analysis and conclusions above on our game-theoretic algorithms are generic. First, we double the capacity of each inter-domain link (*i.e.*, $C_e = 716$ FS'), because it is the main reason of request blocking with CG and NCG, as shown in Fig. 7. We plot the results on blocking probability in Fig. 13. Fig. 13(a) shows that the blocking performance of NCG becomes better than that in Fig. 5(a). Moreover, we observe that NCG even performs as good as CG in terms of overall blocking

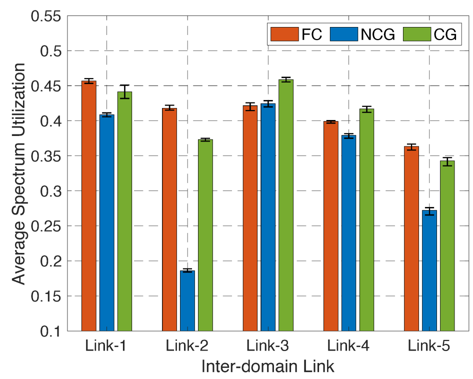


Fig. 11. Average spectrum utilization of each inter-domain link.

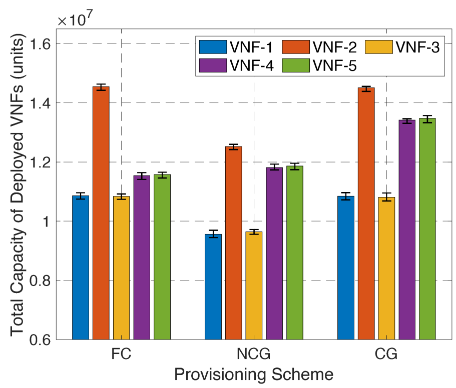
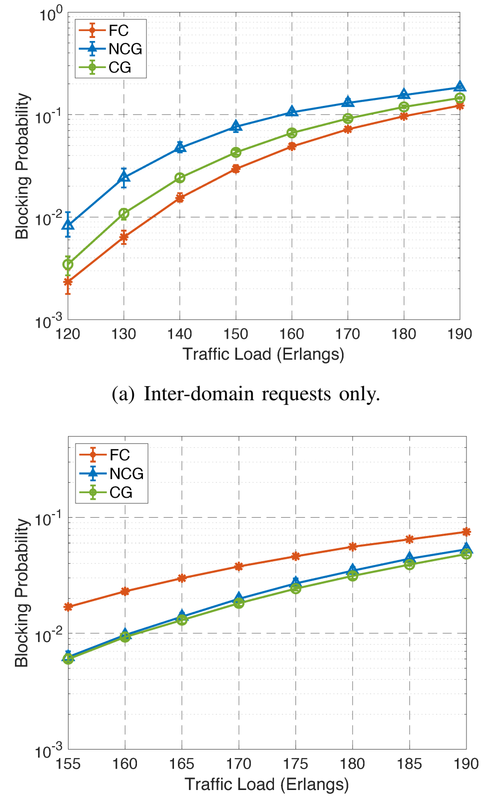


Fig. 12. Capacities of deployed VNFs (at the traffic load of 140 Erlangs).



(a) Inter-domain requests only.

(b) Inter-domain and intra-domain requests.

Fig. 13. Results on blocking probability with $C_e = 716$.

probability. This further confirms the effectiveness of CG and NCG on protecting the interest of each domain.

Then, we change the allocation of VNF types in the cloud and edge domains by setting $K - K_1 - K_2 = 4$ (*i.e.*, the VNF types that can be supported in the cloud and edge domains are $\{1, 2, 3, 4, 5, 6\}$ and $\{3, 4, 5, 6, 7\}$, respectively). The results on blocking probability are shown in Fig. 14, which follows the similar trends as those in Figs. 5(a) and 5(b). Meanwhile, we can see that compared with that in Fig. 5(a), the blocking probability of NCG increases in Fig. 14(a). This is due to the fact that more overlapped types of VNFs lead to more conflicts that the cloud and edge domains may encounter when provisioning inter-domain VNF-SCs. We also observe a decrease of blocking probability of FC, when being compared to the results in Fig. 5(a). This is because more overlapped types of VNFs also bring more flexibility in terms of IT resource utilization to FC. In all, the results in Figs. 13 and 14 confirm that the general validity of our conclusions in previous subsections still hold, with respect to different settings of border links and VNF allocations.

VI. Conclusion

In this paper, we performed comprehensive game-theoretic analysis of dynamic inter-domain VNF-SC provisioning in a multi-domain EC-EON. We first formulated the problem as a non-cooperative game, and designed an algorithm to find the Nash equilibrium for inter-domain VNF-SC provisioning. Then, we considered the cooperative provisioning scheme where the DMs can reach an agreement for mutual benefit, and modeled it with Nash bargaining. Finally, with extensive simulations, we compared the performance of the non-cooperative (NCG), cooperative (CG), and centralized (FC) provisioning schemes in EC-EONs. The simulation results indicated that 1) both NCG and CG take care of the autonomy of DMs, and they can balance the resource utilizations in the cloud and edge domains better than FC, to protect the interest of each DM, and 2) CG achieves the best tradeoff between domain autonomy and blocking performance, and can outperform FC in terms of blocking probability when both inter-domain and intra-domain VNF-SC requests exist in an EC-EON.

Acknowledgments

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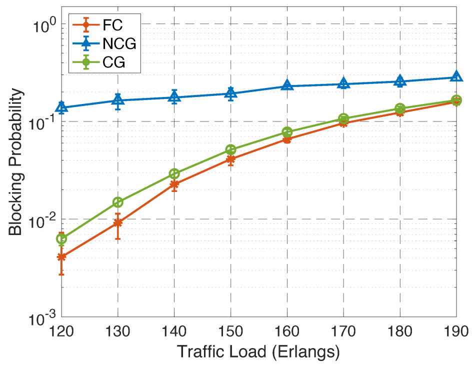
References

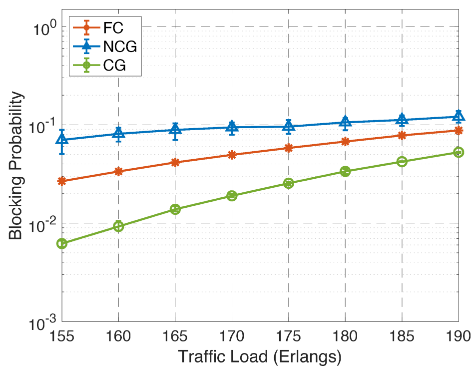
[1] "Cisco Annual Internet Report (2018-2023)," *Online White Report*. [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html.

[2] P. Lu *et al.*, "Highly-efficient data migration and backup for Big Data applications in elastic optical inter-datacenter networks," *IEEE Netw.*, vol. 29, pp. 36–42, Sept./Oct. 2015.

[3] T. Taleb *et al.*, "On multi-access edge computing: A survey of the emerging 5G network edge cloud architecture and orchestration," *IEEE Commun. Surveys Tuts.*, pp. 1657–1681, Third Quarter 2017.



(a) Inter-domain requests only.



(b) Inter-domain and intra-domain requests.

Fig. 14. Results on blocking probability with $K - K_1 - K_2 = 4$.

[4] N. Yoshikane, "Applications of SDN-enabled optical transport network and cloud/edge computing technology," in *Proc. of OFC 2019*, pp. 1–3, Mar. 2019.

[5] J. Ren, G. Yu, Y. He, and G. Li, "Collaborative cloud and edge computing for latency minimization," *IEEE Trans. Veh. Technol.*, vol. 68, pp. 5031–5044, May 2019.

[6] B. Pan, F. Yan, X. Guo, and N. Calabretta, "Experimental assessment of automatic optical metro edge computing network for beyond 5G applications and network service composition," *J. Lightw. Technol.*, vol. 39, pp. 3004–3010, May 2021.

[7] Z. Zhu, W. Lu, L. Zhang, and N. Ansari, "Dynamic service provisioning in elastic optical networks with hybrid single-/multi-path routing," *J. Lightw. Technol.*, vol. 31, pp. 15–22, Jan. 2013.

[8] L. Gong *et al.*, "Efficient resource allocation for all-optical multicasting over spectrum-sliced elastic optical networks," *J. Opt. Commun. Netw.*, vol. 5, pp. 836–847, Aug. 2013.

[9] W. Shi, Z. Zhu, M. Zhang, and N. Ansari, "On the effect of bandwidth fragmentation on blocking probability in elastic optical networks," *IEEE Trans. Commun.*, vol. 61, pp. 2970–2978, Jul. 2013.

[10] Y. Yin *et al.*, "Spectral and spatial 2D fragmentation-aware routing and spectrum assignment algorithms in elastic optical networks," *J. Opt. Commun. Netw.*, vol. 5, pp. A100–A106, Oct. 2013.

[11] X. Chen *et al.*, "Deep-RMSA: A deep-reinforcement-learning routing, modulation and spectrum assignment agent for elastic optical networks," in *Proc. of OFC 2018*, pp. 1–3, Mar. 2018.

[12] D. Welch *et al.*, "Point-to-multipoint optical networks using coherent digital subcarriers," *J. Lightw. Technol.*, vol. 39, pp. 5232–5247, Aug. 2021.

[13] L. Gong and Z. Zhu, "Virtual optical network embedding (VONE) over elastic optical networks," *J. Lightw. Technol.*, vol. 32, pp. 450–460, Feb. 2014.

[14] J. Liu *et al.*, "On dynamic service function chain deployment and readjustment," *IEEE Trans. Netw. Serv. Manag.*, vol. 14, pp. 543–553, Sept. 2017.

[15] "Network functions virtualization (NFV)," Tech. Rep., Oct. 2014. [Online]. Available: https://portal.etsi.org/Portals/0/TBpages/NFV/Docs/NFV_White_Paper3.pdf.

[16] "Network functions virtualisation (NFV): use cases," Tech. Rep., Oct. 2013. [Online]. Available: http://www.etsi.org/deliver/etsi_gs/nfv/001_099/001/01.01.01_60/gs_nfv001v010101p.pdf.

[17] W. Fang *et al.*, "Joint spectrum and IT resource allocation for efficient vNF service chaining in inter-datacenter elastic optical networks," *IEEE Commun. Lett.*, vol. 20, pp. 1539–1542, Aug. 2016.

[18] D. Zheng, G. Shen, X. Cao, and B. Mukherjee, "Towards optimal parallelism-aware service chaining and embedding," *IEEE Trans. Netw. Serv. Manag.*, vol. 19, pp. 2063–2077, Sept. 2022.

[19] M. Ghaznavi *et al.*, "Fault tolerant service function chaining," in *Proc. of SIGCOMM 2020*, pp. 198–210, Jul. 2020.

[20] B. Li, W. Lu, and Z. Zhu, "Deep-NFVOrch: Leveraging deep reinforcement learning to achieve adaptive vNF service chaining in EON-DCIs," *J. Opt. Commun. Netw.*, vol. 12, pp. A18–A27, Jan. 2020.

[21] Z. Lv and W. Xiu, "Interaction of edge-cloud computing based on SDN and NFV for next generation IoT," *IEEE Internet Things J.*, vol. 7, pp. 5706–5712, Oct. 2019.

[22] B. Li and Z. Zhu, "GNN-based hierarchical deep reinforcement learning for NFV-Oriented online resource orchestration in elastic optical DCIs," *J. Lightw. Technol.*, vol. 40, pp. 935–946, Feb. 2022.

[23] C. Song *et al.*, "Hierarchical edge cloud enabling network slicing for 5G optical fronthaul," *J. Opt. Commun. Netw.*, vol. 11, pp. B60–B70, Apr. 2019.

[24] R. Muñoz *et al.*, "Integration of IoT, transport SDN, and edge/cloud computing for dynamic distribution of IoT analytics and efficient use of network resources," *J. Lightw. Technol.*, vol. 36, pp. 1420–1428, Jan. 2018.

[25] F. Foukalas and A. Tziouvaras, "QoE-aware edge computing through service function chaining," *IEEE Internet Comput.*, vol. 26, pp. 53–60, Mar./Apr. 2022.

[26] A. Baktir, A. Ozgovde, and C. Ersoy, "How can edge computing benefit from software-defined networking: A survey, use cases, and future directions," *IEEE Commun. Surveys Tuts.*, vol. 19, pp. 2359–2391, Fourth Quarter 2017.

[27] P. Ray and N. Kumar, "SDN/NFV architectures for edge-cloud oriented IoT: A systematic review," *Comput. Commun.*, vol. 169, pp. 129–153, Jan. 2021.

[28] X. Chen *et al.*, "Incentive-driven bidding strategy for brokers to compete for service provisioning tasks in multi-domain SD-EONs," *J. Lightw. Technol.*, vol. 34, pp. 3867–3876, Aug. 2016.

[29] L. Sun, X. Chen, and Z. Zhu, "Multi-broker based service provisioning in multi-domain SD-EONs: Why and how should the brokers cooperate with each other?" *J. Lightw. Technol.*, vol. 35, pp. 3722–3733, Sept. 2017.

[30] Z. Zhu *et al.*, "Demonstration of cooperative resource allocation in an OpenFlow-controlled multidomain and multinational SD-EON testbed," *J. Lightw. Technol.*, vol. 33, pp. 1508–1514, Apr. 2015.

[31] S. Li *et al.*, "Protocol oblivious forwarding (POF): Software-defined networking with enhanced programmability," *IEEE Netw.*, vol. 31, pp. 58–66, Mar./Apr. 2017.

[32] S. Li, B. Li, and Z. Zhu, "To cooperate or not to cooperate: Service function chaining in multi-domain edge-cloud elastic optical networks," in *Proc. of OFC 2022*, pp. 1–3, Mar. 2022.

[33] Z. Han *et al.*, *Game Theory in Wireless and Communication Networks: Theory, Models, and Applications*. Cambridge University Press, 2012.

[34] R. Mijumbi *et al.*, "Network function virtualization: State-of-the-art and research challenges," *IEEE Commun. Surveys Tuts.*, vol. 18, pp. 236–262, First Quarter 2016.

[35] M. Xia *et al.*, "Network function placement for NFV chaining in packet/optical datacenters," *J. Lightw. Technol.*, vol. 33, pp. 1565–1570, Apr. 2015.

[36] M. Zeng, W. Fang, and Z. Zhu, "Orchestrating tree-type VNF forwarding graphs in inter-DC elastic optical networks," *J. Lightw. Technol.*, vol. 34, pp. 3330–3341, Jul. 2016.

[37] D. Zheng *et al.*, "Network service chaining and embedding with provable bounds," *IEEE Internet Things J.*, vol. 8, pp. 7140–7151, May 2021.

[38] J. Cisneros, S. Yangui, S. Hernandez, and K. Drira, "A survey on distributed NFV multi-domain orchestration from an algorithmic functional perspective," *IEEE Commun. Mag.*, vol. 60, pp. 60–65, Aug. 2022.

[39] P. Iovanna *et al.*, "Main challenges on WAN due to NFV and SDN: multi-layer and multi-domain network virtualization and routing," in *Proc. of ONDM 2015*, pp. 1–6, May 2015.

[40] R. Vilalta *et al.*, "The SDN/NFV cloud computing platform and transport network of the ADRENALINE testbed," in *Proc. of NetSoft 2015*, pp. 1–5, Apr. 2015.

[41] T. Taleb, I. Afolabi, K. Samdanis, and F. Yousaf, "On multi-domain network slicing orchestration architecture and federated resource control," *IEEE Netw.*, vol. 33, pp. 242–252, Sept./Oct. 2019.

[42] R. Vilalta *et al.*, "Experimental demonstration of the BlueSPACE's NFV MANO framework for the control of SDM/WDM-enabled fronthaul and packet-based transport networks by extending the TAPI," in *Proc. of ECOC 2018*, pp. 1–3, Sept. 2018.

[43] J. Baranda *et al.*, "Orchestration of end-to-end network services in the 5G-crosshaul multi-domain multi-technology transport network," *IEEE Commun. Mag.*, vol. 56, pp. 184–191, Jul. 2018.

[44] Y. Wang, P. Lu, W. Lu, and Z. Zhu, "Cost-efficient virtual network function graph (vNFG) provisioning in multidomain elastic optical networks," *J. Lightw. Technol.*, vol. 35, pp. 2712–2723, May 2017.

[45] B. Yan *et al.*, "Service function path provisioning with topology aggregation in multi-domain optical networks," *IEEE/ACM Trans. Netw.*, vol. 28, pp. 2755–2767, Dec. 2020.

[46] N. Toumi, M. Bagaa, and A. Ksentini, "On using deep reinforcement learning for multi-domain SFC placement," in *Proc. of GLOBECOM 2021*, pp. 1–6, Dec. 2021.

[47] T. Pham and H. Chu, "Multi-provider and multi-domain resource orchestration in network functions virtualization," *IEEE Access*, vol. 7, pp. 86 920–86 931, 2019.

[48] M. Dieye, W. Jaafar, H. Elbiaze, and R. Glitho, "Market driven multidomain network service orchestration in 5G networks," *IEEE J. Sel. Areas Commun.*, vol. 38, pp. 1417–1431, Jul. 2020.

[49] J. Zhu, B. Zhao, and Z. Zhu, "Leveraging game theory to achieve efficient attack-aware service provisioning in EONs," *J. Lightw. Technol.*

[50] L. Gong, X. Zhou, W. Lu, and Z. Zhu, "A two-population based evolutionary approach for optimizing routing, modulation and spectrum assignments (RMSA) in O-OFDM networks," *IEEE Commun. Lett.*, vol. 16, pp. 1520–1523, Sept. 2012.

[51] Z. Zhu *et al.*, "OpenFlow-assisted online defragmentation in single-/multi-domain software-defined elastic optical networks," *J. Opt. Commun. Netw.*, vol. 7, pp. A7–A15, Jan. 2015.

[52] T. Başar and G. Olsder, *Dynamic Noncooperative Game Theory*. SIAM, 1998.

[53] J. Nash, "The bargaining problem," *Econometrica*, vol. 18, pp. 155–162, Apr. 1950.

[54] H. Kuhn and A. Tucker, *Contributions to the Theory of Games*. Princeton University Press, 1953.

[55] D. Fudenberg and J. Tirole, *Game Theory*. MIT press, 1991.

[56] M. Osborne and A. Rubinstein, *A Course in Game Theory*. MIT press, 1994.

[57] M. Savi *et al.*, "Impact of processing-resource sharing on the placement of chained virtual network functions," *IEEE Trans. on Cloud Comput.*, vol. 9, pp. 1479–1492, Oct.-Dec. 2021.

[58] Amazon Web Services. [Online]. Available: https://aws.amazon.com/cn/.