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Multi-Provider and Multi-Domain Resource Orchestration in Network Functions Virtualization

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ABSTRACT Resource orchestration has a major impact on improving the performance of network services and reducing the system cost composed of both capital expenditures and operational expenses in network functions virtualization (NFV). In this paper, we consider the optimal resource orchestration problem in a multi-domain NFV system under the competition among multiple NFV service providers (NSPs). In particular, we analyze a game on an NFV platform where an NSP can reserve different types of resources, including the virtual computing, storage, and network resources, and the non-virtualized resources allocated by various NFV domains, for optimizing the utility in an individual manner. We also derive a necessary and sufficient condition for equilibrium under the competition among NSPs. We further investigate the equilibrium in a scenario of cooperation where NSPs build their own NFV infrastructure and join together to create a federation. Our numerical results illustrate the best response in resource reservation of a provider with respect to the strategy of other providers and the effect of the number of domains on the utility obtained by NSPs in the competition. Importantly, we demonstrate that an NSP is able to make a profit when the number of domains in an NFV infrastructure increases until a threshold, beyond which the utility of an NFV provider falls down, which is useful for designing a multi-domain NFV platform, especially in a multi-provider scenario. Another observation is that the best strategy of the NSPs in the competition is opposite to that in the scenario of cooperation, which is significant for the NSPs in the optimization of their utility.

INDEX TERMS NFV, resource orchestration, optimization, multi-provider, multi-domain.

I. INTRODUCTION

Telco provides network services by chaining network functions, aka middle-boxes, such as Firewall, Domain Name Services, Intrusion Detection Systems (IDS). For this traditional approach, network functions are strictly dependent on vendor-specific hardware and software. To meet the ever-increasing demands on new services, network providers must therefore continuously install, operate and perform maintenance on new physical equipments. It results in significant drawbacks on the service launching in terms of investment and operation cost, posing a hindrance on new services acceleration [1]. In this context, the emergence of Network Function Virtualization (NFV) introduces a new paradigm for designing, operating and maintaining network services in an agile and on-demand manner. The adoption of NFV is expected to bring a remarkable improvement in flexibility and scalability on resource utilization and cost efficiency.

In NFV, network functions (NFs) are moved from dedicated hardware to software running in virtualized containers (e.g., virtual machines) of commercial-of-the-shelf servers with advanced hypervisor platforms. The fundamental merit of this approach is that not only network functions can be implemented in a more cost-effective and vendor-independent manner, but also highly customized services can be easily composed by network operators. More specifically, a virtualized network function (VNF) can be instanced by any NFV service provider (NSP), and chained together to consolidate a service function chain (SFC). When different types of resources including the virtual computing, storage and network functions could be allocated dynamically across multiple resource domains and multiple NSPs, the resource reservation and orchestration strategy of a NSP has a tremendous impact on various NFV service quality metrics related to virtual network, virtual machine, as well as technology

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components offered 'as-a-Service' (e.g., Database-as-a-Service). In such a context, research on models and optimal resource orchestration in a multi-domain NFV platform is critical to maximize benefits of network virtualization. However, to the best of our knowledge, there has been no attempt thus far to systematically analyze the optimal resource reservation for a NSP in a multi-provider and multi-domain NFV scenario.

In a competitive context, the objective of a NSP is to optimize its profit by selecting a suitable strategy for resource reservation in different domains. When we consider the competitions between NSPs, the optimization process of a NSP is dynamic and the optimal strategy of NSPs is usually analyzed at equilibrium. More specifically, a decision of any NSP would have an impact on the strategies of the others while each NSP optimizes its decisions in an individual manner. As a consequence, a core analysis of the competition among NSPs for resource reservation is whether the system can lead to an equilibrium and under which assumptions. Several important questions raised in such a context are as follows: What is the impact of a resource reservation strategy of a NSP on the others? What is the optimal resource reservation strategy? What is the impact of the number of domains? Can a NSP profit from the diversity of resource domains? The first objective of this study is to answer these questions in order to better understand the benefits of network virtualization in a competitive NFV market of multiple NSPs.

NSPs would find it difficult to improve the flexibility and performance of network services as a consumer demand continues to require high bandwidth, low latency, and multi-technology. In response to these challenges, NSPs need to reserve resources out of the core network towards the network's edge that is close to consumers. The initial focus was to reduce routing costs and improve the quality of network services to their own subscribers. While this approach has helped, results have been limited. As the demand for network services continues to increase worldwide, a NSP would rather work with fewer individual NFV infrastructure (NFVI) providers for reserving resources. Given this situation, NSPs would join together to open NFV capabilities built from resources owned by all members, called NFV federation. The potential of this approach has been explored in cloud computing [2], Content Distribution Network (CDN) [3], and Information Centric Network (ICN) [4]. In our first objective, we consider the resource reservation problem of NFV service providers for maximizing the utility of individual NSPs under competition. In such a competitive context, the maximization of the sum of all NSPs' utility is not ensured due to selfish behavior of NSPs. Hence, the second objective of the study is to further address the problem of welfare maximization faced by a federation in a competitive context among NSPs.

The issue of resource orchestration in multiple domains is more challenging than that in a single domain, especially in a context of multiple NSPs. It comes from two main aspects. First, the operation of a multi-domain NFV system requires concurrently operational decisions in several domains providing different physical and virtual resources for satisfying a customer demand. Due to the diversity of input variables, modeling to optimize these decisions in a multi-domain system is more complex than that in a single domain system. Second, in a practical scenario of multiple providers, each NSP is only able to control its decision while assuming the strategies of other NSPs fixed. A NSP makes decisions so as to maximize its own utility, without coordination with other NSPs. In other words, the objective is not to maximize the utility function of a NSP over all the variables, but each utility function to each NSP as a function only of the variable they control. A natural approach is to use a game theoretic model for this class of problems. While a NSP would like to optimize its strategy for maximizing its utility at equilibrium, it is challenging to understand conditions for equilibrium and the impacts of various input factors on the utility of NSPs.

The major contributions of this paper are as follows:

- We propose a formal model that captures the competition among NSPs in a multi-domain NFV scenario, and helps us to analyze various impacts of resource reservation strategies at equilibrium.
- We propose a typical utility function assuming the fact that a NSP receives less returns for resource reservation when it already has a lot of resources, and a NSP is likely to behave selfishly for maximizing its utility. We analytically prove the existence of equilibrium in the competition among multiple NSPs, and investigate a necessary and sufficient condition for equilibrium under the competition. We also derive a resource allocation strategy leading to an equilibrium, under which a NSP is able to decide its optimal strategy on a domain without the knowledge of resource information from other domains.
- We formally formulate the problem of the NFV federation where NSPs build their own infrastructure and join together to create a federation. We analyze the best responses of NSPs and the federation in a scenario of cooperation of NSPs. We also investigate the optimal policy for the federation at equilibrium. Such a policy is important for maintaining the economy steady and acquiring economic augmentation.
- We complement our analysis with numerical results and provide useful insights on the impact of important factors on the resulting equilibrium. Particularly, we reveal the best response in resource reservation of a NSP with respect to the strategy of other NSPs and the federation, and the effect of number of domains on the utility obtained by NSPs in the competition. The result implies that many domains with a small amount of resources are not efficient for resource allocation and management in a NFV market with multiple NSPs, which is important for designing a NFV infrastructure, especially in a use case of multiple providers. Interestingly, we find that the best strategy of NSPs in competition is opposite to that in cooperation.

This paper is organized as follows. Section II reviews the related work. Section III discuss the background of multi-provider multi-domain NFV including a multi-provider multi-domain reference architecture and scenarios of competition and cooperation among NSPs. Section IV describes a game-theoretical model capturing the competition among multiple NSPs in different NFV domains. Section V presents the analytical results of resource reservation strategies at equilibrium under the competition. Section VI presents the model and analysis of welfare maximization in the NFV federation. In Section VII, we give the results of a numerical study. Finally, we conclude in Section VIII with a short summary and future work.

II. RELATED WORK

In this section, we will review the existing works on resource orchestration in NFV with multiple domains and multiple providers, and the federation of NFV service providers, respectively.

A. RESOURCE ORCHESTRATION IN NFV

NFV resource orchestration has been being investigated in several related aspects such as single-domain, multi-domain with different approaches. Some studies consider the VNF orchestration problem as a Virtual Network Embedding (VNE) problem [5]–[10]. The VNE problem deals with a mapping of virtual network resources on the underlying physical infrastructure, and the guarantee of the required performance. In [6], the authors propose a Mixed Integer Quadratically Constrained Program (MIQCP) to determine the placement of VNFs, then chaining them. In [5], a novel Mixed Integer Programming formulation is introduced for mapping nodes and links onto the network infrastructure. Another approach is to solve the NFV orchestration problem by considering both the VNF Placement and the VNF Routing [11].

A number of papers were published to study efficient heuristics for the orchestration problem [11]–[16]. In [11], Luizelli *et al.* report that the end-to-end delay of a service chain in NFV decreases up to 25% compared with traditional infrastructure. In [12], the authors define the VNF orchestration problem with the objective of finding the optimal size and location of VNFs with both cost and utilization constrains. They point out that a dynamic program heuristic can outperform the ILP model about 1.3 times for the large-size problem. In [13], the authors use game theory to deal with the problem of NFV placement and service chains. They show that their near-optimal solution is more cost-efficient than that in [12]. In [14], Elias *et al.* also take advantages of game theory for modeling and describing a dynamic strategy for resource orchestration. However, this work solely focuses on reducing the congestion in a virtual network. In [15], Pham and Pham propose an offline approximation algorithm to orchestrate resources for load balancing across multipath in NFV. In [16], they develop their work further to provide an optimization model and efficient algorithms for online load balancing.

While the orchestration in single domain has been adequately investigated, the multi-domain orchestration has still been under-explored due to its complexities. Most work in multi-domain orchestration has been carried out on architectural aspects. In [17], the authors present a multi-layer service orchestration system in a multi-domain network based on the ESCAPE framework, called UNIFY. Sonkoly et al. extend the work in [17] by introducing a novel SFC control plane that is capable of unifying any type of network infrastructures [18]. In [19], the authors propose an orchestration plane in a multi-domain architecture. Although this work is considered as the first complete framework for multi-domain orchestration, it lacks a definition of abstract model of resources. In [20], Francescon *et al.* propose the X-MANO framework that supports multi-domain orchestration by using the resource advertisement mechanism among the domain orchestrators. In the report on architecture options, ETSI also consider a use case related to multiple domains [21]. In [22], the authors introduce an optimal solution for building virtual networks over multiple domains without sharing information of infrastructure providers. In [23], Vaishnavi *et al.* provide an algorithm for embedding all the infrastructures of network service providers based on the abstract of physical resources in multi-domain. To the best of our knowledge, no research has been found that surveyed an optimal resource reservation strategy in a multi-domain NFV under the competition among multiple NSPs. Our work is designed to fill these gaps.

B. THE FEDERATION OF SERVICE PROVIDERS IN 5G NETWORKS

A rich body of literature is devoted to the federation of service providers in the Internet. Villegas et al. propose a model of federation between cloud providers (CP) at each layer of the cloud service stack [24]. Samaan presents the capacity sharing strategies for maximizing the revenue of the federation where the interactions among the CPs are modeled as a repeated game among selfish players [25]. For a survey on cloud federation architectures, we refer the reader to Assis and Bittencourt's paper [2]. The federation of service providers in CDN has been specified and implemented for improving the network performance and reducing the network operator's costs [26], [27]. Balachandran et al. analyze the benefits of the federation between telco and CDN for reducing the infrastructure costs [28]. Pham et al. study impacts of caching and pricing strategies in the interconnection of ICNs [4]. Zhang et al. propose a cooperative edge caching architecture for 5G networks where they take into account both caching and computing resources at the mobile network edge [29]. Ning et al. address the problem of resource allocation in 5G networks including vehicular edge computing, mobile cloud computing and mobile edge computing [30], [31]. However, they consider different scenarios whose elements are not likely to behave selfishly. So far, no research has been found that surveyed a systematic

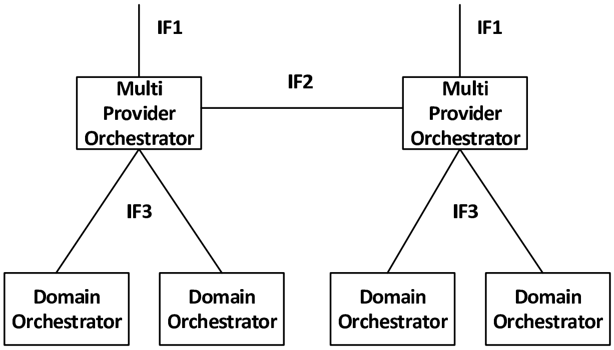

FIGURE 1. The multi-domain multi-provider reference architecture.

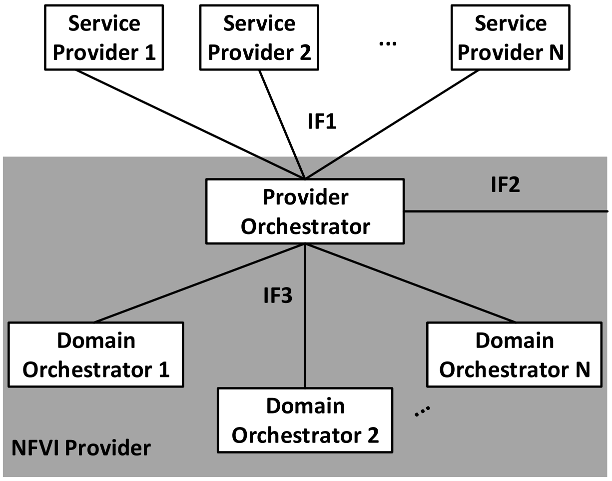

FIGURE 2. A scenario of competition among NFV service providers.

analysis of the federation among service providers in NFV with an appropriate model of federation among NSPs.

A few studies have attempted to investigate the impacts of federation on profit maximization in NFV [32]–[34]. Valcarenghi et al. propose a framework for the federation of 5G services including multi-access edge computing, NFV, and network slicing [32]. Boubendir et al. present an architecture relying on a brokering layer that allows the federation of resources provided by service providers [34]. A closely related study to ours is the one conducted by Gazit *et al.* [33] who study the problem of cooperation and competition in next-generation SDN/NFV core networks. However, the model does not take into account the dynamics of several parameters such as the capacity of providers during the process of cooperation and competition. Different from these studies on the federation of service providers, our work tackles the problem of profit maximization of both individual NSPs and the federation where each of them is able to adjust its strategies dynamically.

III. ILLUSTRATIONS OF COMPETITION AND FEDERATION IN NFV

A network can be composed of multiple domains classified by their characteristics such as technology, geography, scalability, vendor lock-in, and policy. Such a multiple domain network is used by an organization that comprises multiple locations, departments, or business functions. In a multiple domain network, a service is deployed at many administrative domains for the support of user mobility and an integrated enterprise application over different geographic locations. The quality of services needs to be assured in the collaboration among various infrastructure and service providers such as cloud computing and NFV services.

NFV naturally introduces a separation of network functions from location. As a result, NFV allows infrastructure providers to build an effective NFVI to deliver VNF as a service (VNFaaS). Typical network services such as Firewall, NAT, and IDS that are recognized as SFC can spread over multiple providers as well as multiple domains.

The IRTF NFV research group proposes a multi-domain multi-provider reference architecture for NFV networks as shown in Fig. 1 [35]. In the model, a tenant sends a service request to the Multi-Provider Orchestrator (MPO) via interface IF1 that is an interface used for requesting network services from the service orchestrator (see ETSI GS-NFV IFA 013 [36]). MPO exchanges information with others by using interface IF2 that is an interface used for the service and resource federation between the domains (see ETSI GS-NFV IFA 013 [36] and ETSI GS-NFV IFA 005 [37]). IF2 is the key element to allow multi-provider operation. The connection between Multi Provider Orchestrators and Domain Orchestrators is provided by interface IF3 concentrated on abstracting the implementation details to support orchestration (see GS-NFV IFA 005 [37] and ETSI GS-NFV IFA 006 [38]).

To date, the IRTF reference architecture for multi-domain multi-provider only focuses on orchestrating network resources. However, in a multi-domain multi-provider framework, how to get a maximum profit is one of the biggest concerns of a provider. In this paper, we discuss two scenarios including competition and federation among NFV service providers.

Fig. 2 illustrates the first scenario. Due to some reasons such as geography and technology, service providers sometime have to rent NFV infrastructure from other operator to implement their services. Therefore, there will be a competition among service providers for taking advantages of resource utilization so that they could maximize their revenue. A free market might lead to an ‘‘inefficient’’ operation in which none of service providers could get their optimal utility. In this work, we study the best response of NSPs in a competitive game among them, and the condition under which the competition can lead to an equilibrium.

Fig. 3 depicts a scenario of federation among NFV service providers. By sharing resources among particular providers, the paradigm of an NFV federation derives benefits from the use of shared resources close to the customers. In addition, by virtue of being part of this federation, service providers can make some profits by selling their unused

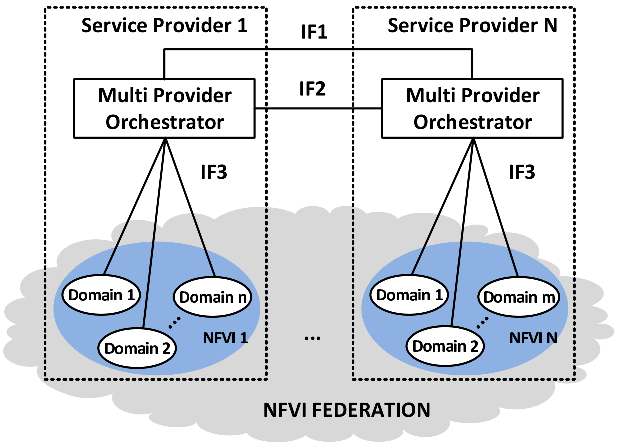

FIGURE 3. **A scenario of NFV federation.**

resources. In this paper, we consider the problem of welfare maximization of the NFV federation under the competition among NFV service providers.

IV. A GAME-THEORETICAL MODEL OF THE COMPETITION AMONG NFV SERVICE PROVIDERS

Network Functions Virtualization is based on virtualization technologies such as those widely used in cloud computing. A NFV framework includes three components that are VNF, NFVI and a NFV management and orchestration system (MANO) [39]. The quality of NFV services provided by a NSP is related to speed, accuracy and reliability. Different phases of resource orchestration and management use different service quality metrics collected from a monitoring and analytic module in MANO. For the phase of virtual network establishment (VN establishment), the resource reservation of a provider has a major impact on the provisioning latency, diversity compliance and provisioning reliability of a virtual network. In a competitive context among NSPs, we focus on reserving resources as part of feasibility step, prior to instantiation, which could apply to different types of resources including the virtual computing, storage and network resources as well as the non-virtualized resources. We assume that NFVI is composed of J domains. We denote a set of domains by $\mathbb{D}$. Suppose that M_j is the total utility of infrastructure domain j, and let x_{ij} denote the amount of resources that provider i requests to domain j. We denote by α_{ij} the utility that provider i can receive when reserving one unit of resources from domain j. The following condition has to be guaranteed

$$\sum_i x_{ij}\alpha_{ij} \leqslant M_j. \tag{1}$$

Suppose there are N service providers that consume resources from NFVI for satisfying customer demands. We denote by $\mathbb{P}$ a set of NSPs. By convention, if $\sum_i x_{ij}\alpha_{ij} > M_j$ we take $x_{ij} = M_j/\left(N\alpha_{ij}\right)$. After the phase of resource reservation, a provider receives an equal share of the utility remaining in each domain as a level of resource redundancy for ensuring service quality in case of a node or link failure and unavailability in NFVI. The payoff function of a NSP i is given by

$$U_i(S) = \ln\left(\sum_j x_{ij}\alpha_{ij}\right) + \sum_j \ln\left(\frac{M_j - \sum_k x_{kj}\alpha_{kj}}{N}\right), \tag{2}$$

where we measure the utility of a NSP with respect to resource reservation. This is a common utility function that exploits the fact that the provider receives less returns for resource reservation when he already has a lot of resources [40]. We will use the terms payoff and utility interchangeably throughout this paper.

In a competitive context, each NSP can have different resource reservation strategies depending on the strategies of other providers and its evaluation of customer demands. We denote the resource reservation strategy space of provider i by $P_i = \left\{x_{ij} : j \in \mathbb{D}\right\}$. We define $\mathbb{S} = \times P_i$ where $i \in \mathbb{P}$ to be the strategy space of the competitive game among NSPs, which is the Cartesian product of the strategy sets of all providers. Let S be an arbitrary member of the strategy set $\mathbb{S}$. We define $\mathbb{U} = \{U_i : i \in \mathbb{P}\}$ to be the set of the payoff functions of NSPs. For convenience, we summarize our notations in Table 1.

The optimization process of NSP i is stated as follows:

$$\begin{aligned} &\text{Maximize } U_i(S),\\ &\text{Subject to: } 0 \leqslant x_{ij} \leqslant \frac{M_j}{\alpha_{ij}} \quad \forall j \in \mathbb{D},\\ &\qquad\qquad \sum_i x_{ij}\alpha_{ij} \leqslant M_j \quad \forall j \in \mathbb{D}. \end{aligned}$$

Note that NSP i only controls its resource variables, i.e., x_{ij} where $j \in \mathbb{D}$. All NSPs simultaneously choose an appropriate strategy for optimizing its utility, and the combination of strategies chosen by them establishes the utility of each NSP. We formulate the competition among NSPs as a normal-form game with the set of players $\mathbb{P}$, the set of strategies $\mathbb{S}$, and the set of the payoff functions $\mathbb{U}$.

Let's consider a simple scenario including NSP 1, NSP 2, and two resource domains for a detail presentation of NSP's optimization process in selecting its strategy. For explaining the optimization process, we use another notation $b_{ij}^{(t)}$ denoting a specific value of resources that provider i requests to domain j at iteration step t. The strategy of NSP 1 and NSP 2 are $P_1 = \{(x_{11}, x_{12})\}$ and $P_2 = \{(x_{21}, x_{22})\}$, respectively. The utility functions of NSP 1 and NSP 2 are $U_1(x_{11}, x_{12}, x_{21}, x_{22})$ and $U_2(x_{11}, x_{12}, x_{21}, x_{22})$, respectively. At $t = 0$, the strategy of NSP 1 is $\left(b_{11}^{(0)}, b_{12}^{(0)}\right)$ and the strategy of NSP 2 is $\left(b_{21}^{(0)}, b_{22}^{(0)}\right)$.

The strategies of NSP 1 and NSP 2 optimized simultaneously at $t = 1$ are as follows:

$$\begin{aligned} \left(b_{11}^{(1)}, b_{12}^{(1)}\right) &= \mathrm{ArgMax}_{(x_{11},x_{12})} U_1\left(x_{11}, x_{12}, b_{21}^{(0)}, b_{22}^{(0)}\right),\\ \left(b_{21}^{(1)}, b_{22}^{(1)}\right) &= \mathrm{ArgMax}_{(x_{21},x_{22})} U_2\left(b_{11}^{(0)}, b_{12}^{(0)}, x_{21}, x_{22}\right). \end{aligned}$$

TABLE 1. Summary of notations.

Notation	Meaning
$\mathbb{P}$	The set of NSPs
$\mathbb{D}$	The set of resource domains in NFVI
N	The number of NSPs
J	The number of domains in NFVI
M_j	The total utility of domain j
x_{ij}	The amount of resources that NSP i requests to domain j
α_{ij}	The utility that NSP i can receive when reserving one unit of resources from domain j
P_i	The resource reservation strategy space of NSP i, $P_i = \{x_{ij} : j \in \mathbb{D}\}$
q_i	The throughput of NFV services that NSP i supplies customers
q_{-i}	The throughput of NFV services that all NSPs other than given NSP i supply customers
Q_i	The service strategy space of NSP i, $Q_i = \{q_i \in [0, \bar{q}_i]\}$, where $\bar{q}_i$ is the maximum amount of the total throughput of NFV services that NSP i supplies customers.
q^{σ}	The total amount of throughput of NFV services that all NSPs supply customers
q^f	The charge of the federation for the resource orchestration among NSPs
Q^f	The charge strategy space of the federation, $Q^f = \left\{q^f \in \left[q_1^f, q_2^f\right]\right\}$, where q_1^f and q_2^f are the minimum and maximum amount of charge respectively.
$\mathbb{S}$	The strategy space in the competition among NSPs, $\mathbb{S} = \prod\limits_{i \in \mathbb{P}} P_i$
$\mathbb{S}_2$	The strategy space in the federation of NSPs, $\mathbb{S}_2 = Q^f \times \prod\limits_{i \in \mathbb{P}} Q_i$
S	A member of the strategy set $\mathbb{S}$
S_2	A member of the strategy set $\mathbb{S}_2$
$U_i(S)$	The payoff to NSP i if the NSPs select strategy S
$U_{2i}(S_2)$	The payoff to NSP i if the players select strategy S_2
$U_f(S_2)$	The payoff to the federation if the players choose strategy S_2
$\mathbb{U}$	The set of the payoff functions of NSPs in the competition without a federation, $\mathbb{U} = \{U_i : i \in \mathbb{P}\}$
$\mathbb{U}_2$	The set of the payoff functions of NSPs in the competition with a federation, $\mathbb{U}_2 = \{U_{2i} : i \in \mathbb{P}\}$
$\varphi(.)$	The price function of NFV services with respect to the total throughput of NFV services that all NSPs are able to process
c	The marginal cost that a NSP incurs when providing a throughput unit of NFV services

The strategies of NSP 1 and NSP 2 optimized simultaneously at $t = 2$ are as follows:

$$\left(b_{11}^{(2)}, b_{12}^{(2)}\right) = \mathrm{ArgMax}_{(x_{11},x_{12})} U_1\left(x_{11}, x_{12}, b_{21}^{(1)}, b_{22}^{(1)}\right),$$
$$\left(b_{21}^{(2)}, b_{22}^{(2)}\right) = \mathrm{ArgMax}_{(x_{21},x_{22})} U_2\left(b_{11}^{(1)}, b_{12}^{(1)}, x_{21}, x_{22}\right).$$

This process continues to iterate. It may settle down to a steady state, called a Nash equilibrium, at which no NSP can gain by unilaterally deviating from its own strategy.

V. ANALYSIS OF RESOURCE RESERVATION UNDER THE COMPETITION

In this section, we present analytical results for a competition scenario among NSPs in a multi-domain use case of NFV. We first prove the existence of equilibrium at which the resource reservation can be studied to see if there is a possibility for the provider to set up an optimal resource reservation strategy. We then derive a necessary and sufficient condition for equilibrium under the competition of resource reservation. We also show that a NSP is profitable when the number of domains in NFVI increases until a threshold, beyond which the utility of the NSP falls down.

Theorem 1: Given the resource prices of NFVI, there exists an equilibrium in the competition between NFV service providers

Proof: By differentiating $U_i(S)$ with respect to x_{ir} where $i \in \mathbb{P}$ and $r \in \mathbb{D}$, we obtain

$$\frac{\partial U_i(S)}{\partial x_{ir}} = \frac{1}{\sum_j x_{ij}\alpha_{ij}} - \frac{N}{M_r - \sum_k x_{kr}\alpha_{kr}}, \tag{3}$$

and so

$$\frac{\partial^2 U_i(S)}{(\partial x_{ir})^2} = \frac{-\alpha_{ir}}{\left(\sum_j x_{ij}\alpha_{ij}\right)^2} + \frac{-\alpha_{ir}N}{\left(M_r - \sum_k x_{kr}\alpha_{kr}\right)^2}. \tag{4}$$

Since $\partial^2 U_i(S) \big/ (\partial x_{ir})^2 < 0$, $U_i(S)$ is concave. The strategy set of all NSPs are nonempty compact convex subsets of a Euclidian space, and the utility function $U_i(S)$ of the providers is continuous and concave on their strategy sets. Hence, there exists a pure Nash equilibrium, which demonstrates Theorem 1. ■

Theorem 2: A resource allocation strategy solves the competition between NFV service providers at equilibrium if and only if

$$\sum_j x_{ij}\alpha_{ij} = \frac{\sum_j M_j}{N(J+1)}, \tag{5}$$

where $i \in \mathbb{P}, j \in \mathbb{D}$.

Proof: From (3) and the fact that $\partial U_i(S) \big/ \partial x_{ir} = 0$ at equilibrium, we find

$$N\sum_j x_{ij}\alpha_{ij} = M_r - \sum_k x_{kr}\alpha_{kr}. \tag{6}$$

Adding (6) for all r, we get the following equation for each provider i

$$NJ\sum_j x_{ij}\alpha_{ij} = \sum_j M_j - \sum_{kj} x_{kj}\alpha_{kj}. \tag{7}$$

After adding (7) for all providers and doing some manipulations, we find

$$\sum_{ij} x_{ij}\alpha_{ij} = \frac{\sum_{ij} M_j}{J+1}. \tag{8}$$

Substituting (8) into (7), we obtain

$$\sum\nolimits_j x_{ij}\alpha_{ij} = \frac{\sum_j M_j}{N\,(J+1)}, \tag{9}$$

which proves Theorem 2. ■

Theorem 2 implies that a NSP can have a variety of resource reservation strategies that can lead the system to equilibrium at which no provider can profitably deviate. The following simple derivation of the theorem shows an optimal strategy for a NSP.

Corollary 1: There is an equilibrium under which the NFV service providers is able to decide their optimal strategy on a domain without the knowledge of resource information from other domains:

$$x^*_{ij} = \frac{M_j}{\alpha_{ij} N\,(J+1)}, \tag{10}$$

where $i \in \mathbb{P}, j \in \mathbb{D}$.

Proof: It is straightforward to show that $\left\{x^*_{ij}\right\}$ solves (5), which proves the claim by Corollary 1. ■

Theorem 3: Given the resource prices of NFVI, at equilibrium, NSPs are able to gain their utility when the number of domains in NFVI increases if

$$\sum\nolimits_j M_j \geqslant N\,(J+1)\,, \tag{11}$$

where $J \in \mathbb{D}$.

Proof: Substituting (5) into (6), we obtain

$$\sum\nolimits_k x_{kr}\alpha_{kr} = M_r - \frac{\sum_j M_j}{J+1}. \tag{12}$$

Substituting (5) and (12) into (2), we find

$$U_i(S) = (J+1)\ln\left(\frac{\sum_j M_j}{N\,(J+1)}\right).$$

By differentiating the payoff function $U_i\,(S)$ with respect to the number of domains J, we obtain

$$\frac{\partial U_i(S)}{\partial J} = \ln\left(\frac{\sum_j M_j}{N\,(J+1)}\right) + \frac{N}{\sum_j M_j}.$$

It is simple to show that $\partial U_i(S)\big/\partial J > 0$ if $\sum_j M_j \geqslant N\,(J+1)$. Thus, the utility function $U_i\,(S)$ is increasing with respect to J, which demonstrates Theorem 3. ■

VI. WELFARE MAXIMIZATION OF NFV FEDERATION

The objective of the federation is to maximize the sum of NSPs' utility and its utility by regulating a charge. A NSP wants to maximize its benefits by adjusting the total throughput of NFV services that it provides. In the first stage, the federation decides to an amount of charge. In the second stage, NSPs simultaneously choose a number of service throughput that they are able to process.

We denote the service strategy space of provider i by $Q_i = \{q_i \in [0, \bar{q}_i]\}$ where $\bar{q}_i$ is the maximum amount of the total throughput of NFV services that provider i supplies customers. Let $Q^f = \left\{q^f \in \left[q^f_1, q^f_2\right]\right\}$ denote the charge strategy space of the federation where q^f_1 and q^f_2 are the minimum and maximum amount of charge respectively. The strategy space $\mathbb{S}_2$ is the Cartesian product of the strategy sets of the federation and all NSPs,

$$S_2 = Q^f \times \prod_{i\in P} Q_i. \tag{13}$$

Let S_2 be an arbitrary member of the strategy set $\mathbb{S}_2$. We define $\mathbb{U}_2 = \{U_{2i} : i \in \mathbb{P}\}$ to be the set of the payoff functions of NSPs.

The optimization process of the federation is stated as follows:

$$\begin{aligned}&\text{Maximize}_{q^f\in Q^f}\ U_f(S_2),\\ &\text{Subject to } q_i \text{ is decided by NSP } i.\end{aligned}$$

The service strategy $S^*_2 = \left(q^f \in Q^f, q^*_i \in Q_i\right)$ solves the following optimization problems for all providers $i \in P$:

$$\text{Maximize}_{q_i\in Q_i}\ U_{2i}(S^*_2\backslash q^*_i, q_i).$$

We consider a simple example of NFV federation including NSP 1 and NSP 2. The utility functions of NSP 1, NSP 2, and the federation are $U_{21}(q^f, q_1, q_2)$, $U_{22}(q^f, q_1, q_2)$ and $U_f(q^f, q_1, q_2)$, respectively. First, the federation gives its charge q^f. Then, NSP 1 and NSP 2 are competitive for maximizing its utility. The optimization process of NSP 1 and NSP 2 in NFV federation is similar to that in a scenario of competition. After the optimization process, suppose the optimal strategy of NSP 1 and NSP 2 at equilibrium are a^*_1 and a^*_2 respectively, the federation can optimize its utility function (i.e., $U_f(q^f, a^*_1, a^*_2)$).

Let q^σ be the total throughput of NFV services that all NSPs supply customers,

$$q^\sigma = \sum\nolimits_{i\in P} q_i. \tag{14}$$

We define $\varphi\,(.)$ to be the function of price with respect to the total throughput of NFV services that all providers are able to produce. Suppose a NSP incurs a marginal cost c when providing a throughput unit of NFV services. We refer to all NSPs other than given NSP i as "NSP i's opponents" and denote them by "$-i$". The utility function of NSP i is

$$U_{2i}(q^f, q_i, q_{-i}) = \left(\varphi(q^\sigma) - c - q^f\right) q_i. \tag{15}$$

The objective function of the federation is

$$U_f(S_2) = \sum\nolimits_i U_{2i}(q^{f\,,} q_i, q_{-i}) + q_i q^f. \tag{16}$$

Substitute (15) into (16) to get

$$U_f(S_2) = q^\sigma\,\left(\varphi(q^\sigma) - c\right). \tag{17}$$

Theorem 4: Given the resource prices of NFVI, at equilibrium, the optimal policy for the federation is to select a unit charge equal to

$$q^f = \frac{1-N}{N} q^\sigma \frac{d\varphi}{dq^\sigma}. \tag{18}$$

Proof: From (17), the utility of the federation is maximized if we can archive

$$q^{\sigma} = q^{\sigma *} = \text{ArgMax}_{q^{\sigma}} U_f(S_2). \tag{19}$$

Some tedious manipulation yields

$$\varphi(q^{\sigma *}) - c = -q^{\sigma *}\varphi'(q^{\sigma *}). \tag{20}$$

We are now in a position to show that $q^{\sigma *}$ is the results of competition among NSPs with the charge q^f.

Assuming U_{2i} is concave, q_i is selected so that

$$\frac{\partial U_{2i}}{\partial q_i} = 0. \tag{21}$$

We find

$$\frac{\partial U_{2i}}{\partial q_i} = \varphi\left(q_i + \sum\nolimits_{j \neq i} q_j\right) - c - q^f + \frac{\partial \varphi\left(q_i + \sum_{j \neq i} q_j\right)}{\partial q_i} q_i. \tag{22}$$

$q_i = q^{\sigma *}/N$ is an equilibrium point if

$$\left(\varphi(q^{\sigma *}) - c - q^f\right) + \varphi'(q^{\sigma *})\frac{q^{\sigma *}}{N} = 0. \tag{23}$$

From (23), we obtain

$$q^f = \varphi(q^{\sigma *}) - c + \varphi'(q^{\sigma *})\frac{q^{\sigma *}}{N}. \tag{24}$$

Substituting (20) into (24) gives

$$q^f = \frac{1-N}{N} q^{\sigma *}\varphi'(q^{\sigma *}), \tag{25}$$

which demonstrates Theorem 4. ■

Theorem 4 implies that when a NSP increases its shared resources, it decreases price not just for itself but for all other NSPs as well. The charge by the federation makes NSPs pay the social cost of the marginal unit of the shared resources (i.e., parameter c in Eq. (17)).

VII. NUMERICAL RESULTS

We present some numerical results to illustrate our analysis of resource reservation strategy in a multi-domain NFV use case under the competition among multiple NSPs. Despite the fact that we do not incorporate a lot of parameters into our models, our aim is not a comprehensive numerical study over the complete parameter space. Instead, we give some numerical results for parametric instances to observe general trends of the NFV system under the competition and cooperation. Particularly, we show the best response in resource reservation of a NSP with respect to the strategy of other NSPs, the effect of number of domains on the utility obtained by NSPs in the competition, the best response of NSPs in service supply in a scenario of cooperation, and the convergence of strategies to equilibrium.

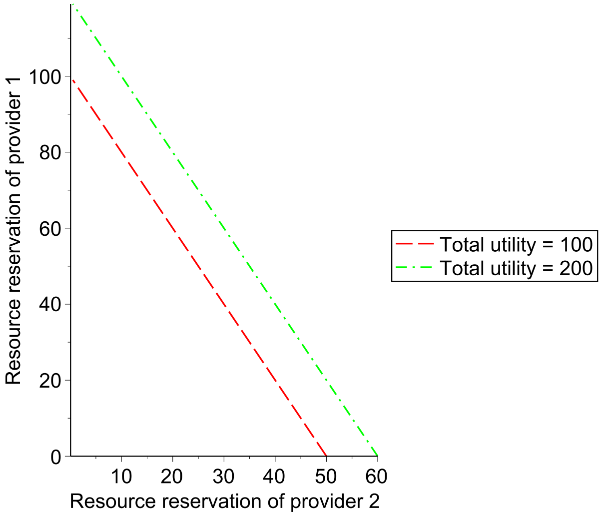

FIGURE 4. The best response of a NFV service provider in resource reservation.

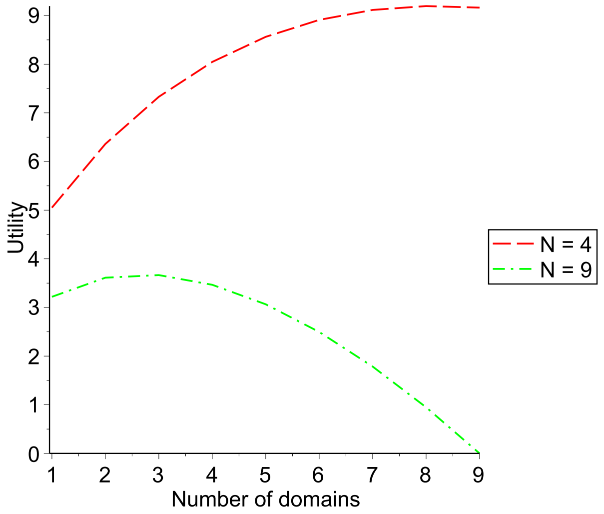

FIGURE 5. The impact of number of domains on the utility at equilibrium.

A. THE IMPACT OF COMPETITION ON THE UTILITY

We consider an NFV model where NSPs are competitive to maximize their utility. The number of NSPs varies between $N = 2$ and $N = 9$. The number of domains varies between $J = 1$ and $J = 9$. The total utility provided by NFVI is 100, and the utility provided by a domain is similar. The utility that a provider can receive when reserving one resource unit from a domain is given by $\alpha_{ij} = 1$. In our numerical analysis, all parameters are set to their values above unless explicitly specified. Note that it is the strategy of NSPs that affects the relative differences of utility between NSPs rather than the number of NSPs and the number of domains.

Fig. 4 reveals the best response of a NSP when another NSP changes its resource reservation strategy for maximizing its utility in a scenario of two NSPs. We observed that the best responses of a NSP for different values of the total utility provided by NFVI are similar. It is surprised at finding out

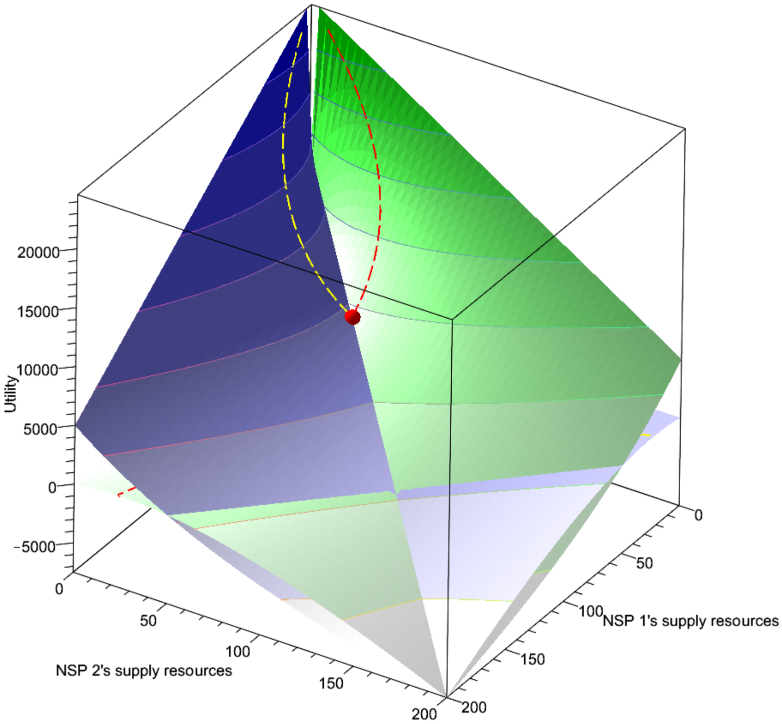

FIGURE 6. **The equilibrium in cooperation: The red point is the Nash equilibrium. The yellow and red curves are the best responses of NSP 1 and NSP 2, respectively.**

that the decrease in resource reservation of NSP 1 is observed upon the increase in resource reservation of NSP 2 rather than the increase. This result identifies a circumstance under which decreasing investment leads to more profit due to the share of resources between providers in the second phase as a level of resource redundancy and the strategic interaction of providers. Of course, how this game between NFV service providers and NFV infrastructure would progress in a real NFV scenario depends on a variety of techno-economic factors, which are beyond the scope of this paper.

We next study the impact of the number of domains on the utility maximization at equilibrium. The results in Fig. 5 illustrate the analysis in Theorem 3 that a NSP is able to make a profit when the number of domains in NFVI increases up to a threshold. For example, when the number of domains is larger than three, the utility of a NSP falls down in a scenario of nine providers. It is due to the fact that with a fix amount of total resources of NFVI the increase in the number of domains reduces an amount of resources in a domain. The result implies that many domains with a small amount of resources are not efficient for resource allocation and management in a NFV market with multiple NFV service providers, which is important for designing a NFV infrastructure, especially in a use case of multiple providers scenarios.

B. THE IMPACT OF FEDERATION ON THE UTILITY

We consider scenarios of two NSPs and four NSPs who build their own NFVI and join together to create a federation. The federation decides on a charge (i.e., q^f) for the resource orchestration among NSPs. NSP i controls an amount of throughput supply resources (i.e., q_i) shared with other NSPs in the federation. The customers of a NSP receive the benefits of federated NFV including the performance improvement and the lower cost of NFV services. The price that a customer pays a NSP is measured in cost per an unit of throughput, and is not under the control of NSPs or the federation. To characterize a price function that represents the effect of supply on prices, we use the following price function with parameter c_1 as follows:

$$\varphi(q^\sigma) = \frac{c_1}{q^\sigma}. \tag{26}$$

Note that this price function is suitable because it reflects the general rule of decreasing prices in response to an increase in the supply. In our evaluation below, we set $c_1 = 50000$, the marginal cost $c = 100$ unless explicitly specified.

Fig. 6 shows the equilibrium in competition with a federation created by two NSPs, at which the utility of NSPs and the welfare of the federation are maximized. The results illustrate the convergence to the equilibrium under a context of competition and cooperation, where the federation controls its charge for maintaining the sharing infrastructure and NSPs adjusts their supply resources in the federation for maximizing their utility.

Fig. 7 plots the best response of a NSP when another NSP changes its resource reservation strategy for maximizing its utility. We observe that the best response of NSPs in

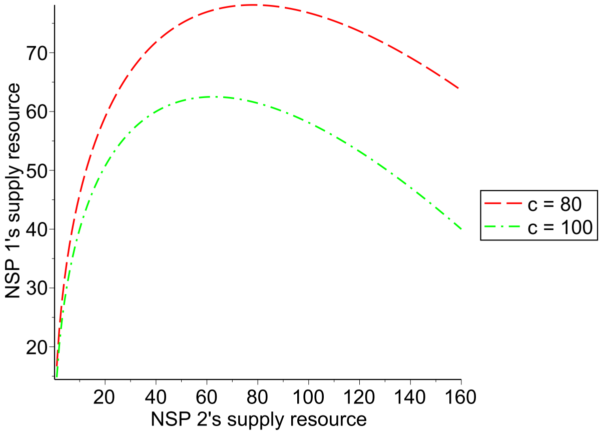

FIGURE 7. The best response of a NSP in cooperation with respect to the strategy of another NSP.

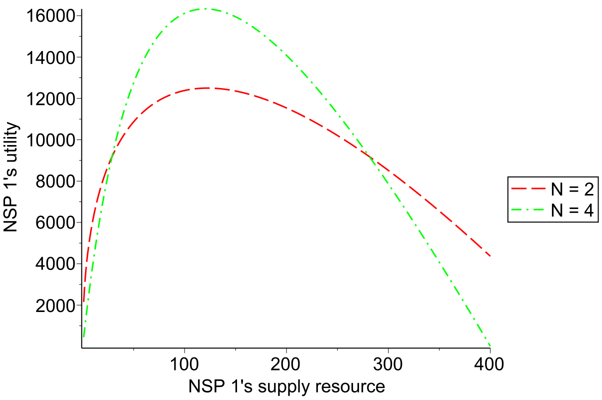

FIGURE 8. The utility of a NSP with respect to its strategy in cooperation where other NSPs use their best responses and the federation gives the price at equilibrium.

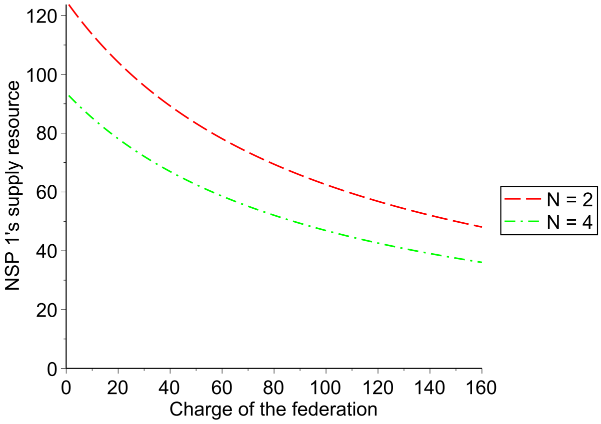

FIGURE 9. The best response of a NSP with respect to the strategy of the federation in cooperation where all NSPs use their best responses.

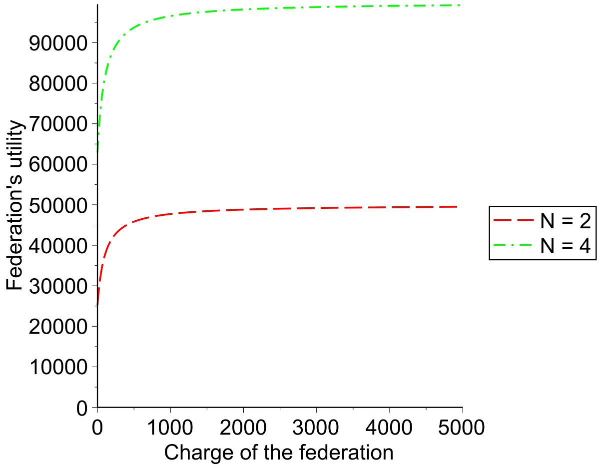

FIGURE 10. The utility of the federation.

cooperation is different from that in competition without a federation. Particularly, a NSP decreases its resource reservation in response to the increase in resource reservation of another NSP in competition without a federated infrastructure (Fig. 4). On the contrary, Fig. 7 shows that NSP 1 increases its supply resources until a threshold when NSP 2 expands its shared resources for optimizing its utility in cooperation. This occurs because the profit of a NSP rises when it increases its shared resources. However, when the supply resource is excessive, the profit decreases because the price is reduced to a very low level, as shown in Fig. 8. In brief, a NSP needs to adjust its strategy in different contexts for maximizing its utility.

We next study the best strategy of a NSP in response to a variation in the charge of the federation. As shown in Fig. 9, we obtained the similar best response of a NSP for different number of providers. The results suggest that NSP 1 should decrease its shared resources if the charge of the federation increases. It is due to the fact that as a NSP would like to grow its utility, it will reduce its shared resources to restrain the decrease in the prices when the federation increases its charge. The result illustrates the analysis demonstrated by Theorem 4 that at equilibrium the change in the prices (i.e., φ) and the change in the charge of the federation are opposites.

Fig. 10 plots the utility of the federation as a function of its charge. The federation receives higher utility in a scenario of a large number of providers. However, for different number of NSPs, the impact of the change of the federation on the utility is similar. The results show that the utility of the federation increases rapidly at the beginning, and then it increases slowly when its prices are on the rise. It implies that for optimizing the social welfare under competition among NSPs the federation could not continue to increase its charge. This occurs because the social welfare is influenced by both the factors that the federation controls (i.e., the charge) and other factors that the NSPs control (i.e., the shared resources).

C. THE CONVERGENCE OF STRATEGIES TO EQUILIBRIUM

We study the rate of convergence to equilibrium when the number of NSPs varies. Fig. 11 and Fig. 12 present results

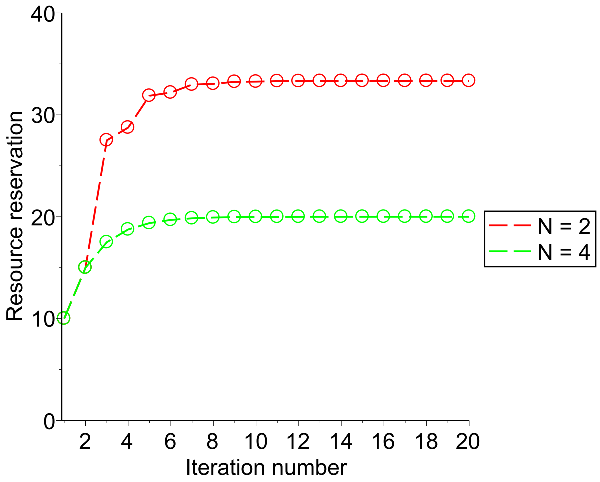

FIGURE 11. Convergence to equilibrium in a scenario of competition without a federation.

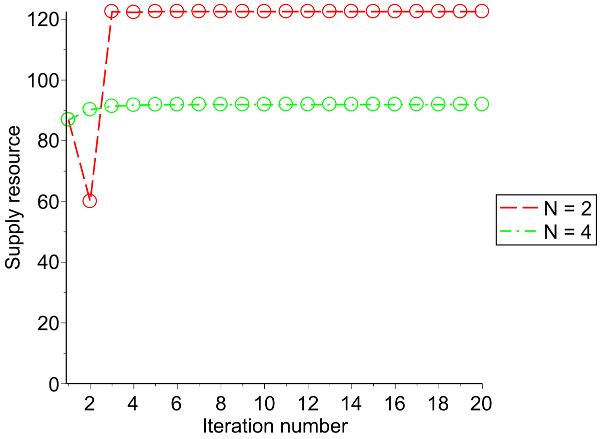

FIGURE 12. Convergence to equilibrium in a scenario of cooperation.

in a scenario of competition without a federation, and in that of cooperation for $N = 2$ and $N = 4$. The basic unit of the x axis is one iteration. We observed that the strategies of NSPs converge almost instantaneously to the Nash equilibrium. Specifically, the number of time steps taken to reach the equilibrium is less than 10 steps in all scenarios. The results also show that the rate of convergence grows slowly when the number of NSPs increases. In other words, in a NFV market including multiple domains and multiple providers, a NSP is able to quickly reach an equilibrium state at which no NSP can gain by unilaterally deviating from its own strategy.

VIII. CONCLUSIONS

In this paper, we have modeled and addressed the optimal resource orchestration in a multi-domain NFV platform under the competition among multiple NSPs with and without a federation, which are crucial for the realization of a platform of multi-domain multi-provider NFVs. We proved the existence of equilibrium in these scenarios under certain assumptions. In a scenario of competition without a federation, we investigated a resource reservation strategy for NSPs to decide their optimal strategy on a domain without the knowledge of resource information from other domains. Interestingly, we find that the utility at equilibrium under the competition is not improved by increasing the number of domains beyond a threshold. We further analyzed the best response of NSPs in a scenario of cooperation. The results show that the system under cooperation can lead to an equilibrium at which all NSPs and the federation have no incentive to change their strategy. In addition, our analytical and numerical results provide useful suggestions for NSPs to maximize their utility in the competition and cooperation.

Possible extensions of our results include an analysis taking into account specific consumer demand-response models (e.g., demand-sensitivities to network service performance), the competition among multiple NSPs where side payments play a more significant role, or an analysis of a cooperative context where NSPs form coalitions for sharing utilities. Resource orchestration in NFV continues to be an exciting area of research. Some of the open issues related our work are dynamic resource sharing for fault tolerance of virtualized network functions, and a prediction model across users and infrastructure to efficiently allocate resources.

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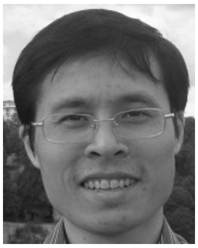

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