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Research Article

Competition of Duopoly MVNOs for IoT Applications through Wireless Network Virtualization

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Network performance is of great importance for processing Internet of Things (IoT) applications in the fifth-generation (5G) communication system. With the increasing number of the devices, how network services should be provided with better performances is becoming a pressing issue. The static resource allocation of wireless networks is becoming a bottleneck for the emerging IoT applications. As a potential solution, network virtualization is considered a promising approach to enhancing the network performance and solving the bottleneck issue. In this paper, the problem of wireless network virtualization is investigated where one wireless infrastructure provider (WIP), mobile virtual network operators (MVNOs), and IoT devices coexist. In the system model under consideration, with the help of a software-defined network (SDN) controller, the WIP can divide and reconfigure its radio frequency bands to radio frequency slices. Then, two MVNOs, $MVNO_1$ and $MVNO_2$, can lease these frequency slices from the WIP and then provide IoT network services to IoT users under competition. We apply a two-stage Stackelberg game to investigate and analyze the relationship between the two MVNOs and IoT users, where $MVNO_1$ and $MVNO_2$ firstly try to maximize their profits by setting the optimal network service prices. Then, IoT users make decisions on which network service they should select according to the performances and prices of network services. Two competition cases between $MVNO_1$ and $MVNO_2$ are considered, namely, Stackelberg game (SG) where $MVNO_1$ is the leader whose price of network service is set firstly and $MVNO_2$ is the follower whose network service price is set later and noncooperative strategic game (NSG) under which the service prices of $MVNO_1$ and $MVNO_2$ are simultaneously set. Each IoT user decides whether and which MVNO to select on the basis of the network service prices and qualities. The numerical results are provided to show the effectiveness of our game model and the proposed solution method.

1. Introduction

With the technologies of the Internet of Things (IoT) growing rapidly, more and more IoT devices will be connected in the fifth-generation (5G) communication networks. It was predicted that smart objects would reach with the number 50 billion by 2020 [1]. In recent years, we have witnessed a wide adoption of IoT in many areas, such as health care, landslide detection, and environmental monitoring [2–4]. As shown in Figure 1, the number of connected things by the Internet had been over the population of people by the end of the year 2008 [5]. The radio frequency (RF) spectrum has become crowded due to the rapid increase in the number of IoT devices [7]. Furthermore, the demand from IoT devices for wireless data services is growing exponentially in recent years. From a recent report released by Cisco, in the year of 2021, the number of global mobile data traffic will reach 49 exabytes per month [8, 9], and part of these data traffic may be generated by unmanned aerial vehicle (UAV) [10]. The wireless spectrum is the scarce and precious radio resource in the 5G communication networks [11]. In general, the government statically allocates the licensed spectrum resource. Recent studies have shown that the static spectrum allocation scheme cannot handle the data generated by these smart devices [12, 13]. The paradox that IoT devices are in a great need for wireless network services and the spectrum has not been fully utilized indicates that the current static spectrum resource allocation policy has some shortcomings.

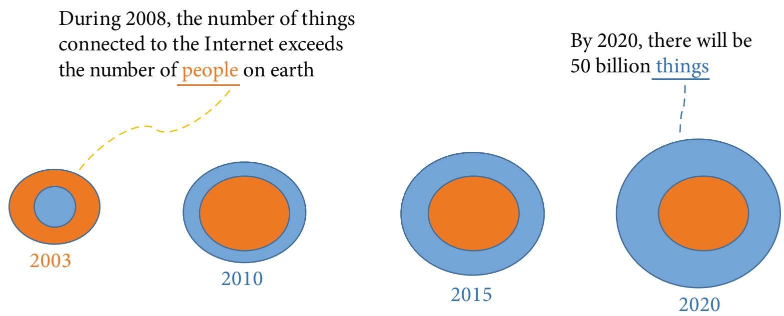

Figure 1: The prediction of the number of "things" [5, 6].

Traditionally, the Internet service providers adopted middleboxes to provide network services to users, which is inflexible and results in high Capital Expenses (CAPEX) and Operating Expenses (OPEX) [14]. Fortunately, a SDN and Network Function Virtualization (NFV) have appeared to address these problems. By using the technology of NFV, Virtual Network Functions (VNFs) can replace the middleboxes in traditional networks. The SDN is one of the most important technologies in the 5G commutation systems, and it is considered an emerging paradigm for applications in the IoT [15–18]. In the SDN, with the help of an OpenFlow protocol and SDN controller, the wireless infrastructure providers (WIPs) could programmatically divide and reconfigure their radio frequency bands to frequency slices, and the mobile virtual network operators (MVNOs) can lease these frequency slices from the WIPs in order to provide virtual network services in a fine-grained way [12, 16]. It should be pointed out that the WIP can also adopt NFV to provide virtual network services.

Today, MVNOs have received successful operations in many countries, such as the Google-Fi project. In Japan, IIJmio and LINE MOBILE are two MVNOs. They lease radio frequency slices from DOCOMO, which is one of the three WIPs in Japan, to provide network services. The market of global virtual operators is expected to grow with an annual rate of 7.4% and will reach 75.25 billion US $ by 2023 [19]. Although a lot of existing works have studied the network provision of MVNOs, many of them put more focus on the technical aspects, like energy-efficient spectrum allocation protocols for end users [20]. In this paper, we study from the economic perspective of wireless networks' network service provision. Besides, unlike the previous works that simply analyze homogeneous IoT users, in which all the IoT users are of the same valuation for the wireless network services, in our study, IoT users are divided into different types according to their different tastes for the wireless network service quality, which is more realistic than the previous works. For example, the IoT users might have stricter requirements for the latency in the applications of vehicular communications [17, 21] [22].

This study investigates IoT network service selection from two MVNOs leasing radio frequency slices from the WIP and compete for the users of IoT devices, aiming to maximize their profits. The interaction of the MVNOs and IoT users is modelled as a Stackelberg game with two stages,

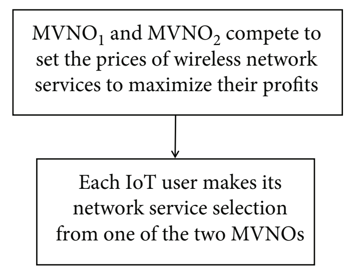

Figure 2: Two-level structure between MVNOs and IoT users.

where the two MVNOs set network service price strategies firstly aiming to get their maximized profits, and each IoT user will determine which MVNO it will select service from according to the network service prices and qualities, as Figure 2 illustrates. As far as the competition between the two MVNOs is considered, we analyze two cases: (1) Stackelberg game (SG) case where MVNO_1 acts firstly to set the network service price, and then, MVNO_2 sets the network service price, and (2) noncooperative strategic game (NSG), also called simultaneous-play game, under which the two MVNOs set the network service prices at the same time. The SG case means that an MVNO will enter an IoT network service market whose incumbent MVNO has better service quality, and the NSG case is that two MVNOs with different qualities of services offer network services at the same time.

The contributions that this study mainly made are summarized as follows:

(i) We study network service selection from two MVNOs, who lease radio frequency slices from WIP and compete to maximize their profits by providing network services. IoT users choose to buy services from one of the two MVNOs based on their offered IoT network service prices and qualities

(ii) The interaction of the two MVNOs and the IoT users is modelled by using the Stackelberg game with two stages, which can be analyzed and solved by leveraging the backward induction method

(iii) We studied and analyzed two competition cases between the two MVNOs, which are known as SG and NSG, respectively. A unique equilibrium for each case is proved to be obtained

(iv) Numerical results are provided to verify the analysis the system models proposed in this paper. Specifically, several parameters are considered to show their impacts on the profits, prices, and service demands of $MVNO_1$ and $MVNO_2$

The rest of this paper is structured as follows. The related work is reviewed and discussed in Section 2. The system model is introduced in Section 3. Service selection is analyzed in Section 3.1. We conduct numerical results and present our analysis results in Section 3.2. Section 4 gives the conclusions of this paper and shows several future research directions.

2. Related Work

Game theory-based techniques have been widely adopted for managing resources in wireless communication networks and cloud computing systems. In a femtocell communication system with two service providers, the authors explored the problem of spectrum sharing scheme decisions from the viewpoint of an entrant service provider [23]. As the IoT users exhibit different valuations for IoT data services, Li et al. investigated price and service selection in IoT data service market, where two service providers buy raw data from a data owner to provision data services to the end users [24]. As the increase in mobile data traffic may cause service quality, a mixed pricing model combined with usage-based and fixed free pricing is proposed in [25] to solve this problem. In [26], the authors studied opportunistic computation offloading in the cloud-enabled IOV by proposing a scheme based on a two-stage Stackelberg game. In [27], Li et al. studied pricing and service selection in mobile cloud architecture, under which the edge cloud and public cloud coexist. They also proposed a two-stage Stackelberg game-based approach to analyze the interactions of the service providers and the mobile users. In [28], the authors analyzed the prioritized sharing between a value MVNO and multiple MNOs. In [29], Wang et al. studied virtual resource management in the virtualized networks with ultradense small cells by using the hierarchical game.

The study of spectrum resource allocation for IoT and IoT service pricing has received a great deal of amount of attention in the past few years. In [30], Ejaz and Ibnkahla proposed a spectrum resource allocation scheme for IoT under the cognitive 5G communication systems. An optimization problem was formulated to solve the spectrum sensing and allocation problem. In [31], Ansere et al. studied energy-efficient spectrum allocation in the cognitive radio network systems. They proposed two dynamic spectrum algorithms to improve the efficiency of the network systems. In [1], a business model including WSNs, multiple service providers, and the end users was presented and analyzed by Guijarro et al. The service providers buy the sensed data from the owners of Wireless Sensor Networks (WSNs) and provide services to the end users in a competitive oligopoly IoT data service market. In [32], Ghosh and Sarkar studied IoT service provision in a monopoly IoT market that consists of IoT service provider (IoTSP), wireless service provider (WSP), and cloud service provider (CSP). Three kinds of interactions are analyzed among these providers. The authors in [33] studied how the MVNOs should make pricing decisions when others' inventory information is known or unknown. For the known case, they proposed an optimal pricing scheme for maximizing the revenue of each other. For the unknown case, a distributed coalition formation algorithm is developed to maximize each MVNO's revenue. In [34], a market-oriented model was proposed for IoT service delivery. A multileader multifollower Stackelberg game-based approach was proposed to study and analyze the relationship between the IoT service provider and users. In [35], the authors studied two service providers provisioning WSN-based services under competition.

Spectrum resource management in cognitive radio networks (CRNs) has been extensively studied by using game theory. The related works on price competitions in CRNs can be divided into two categories. The first category consists of a competition between the primary network operator who is the licensed spectrum owner and the secondary network operator who has no spectrum license. The second category is the competition between secondary operators who lease the spectrum from the spectrum holder to offer network services to secondary users. A spectrum sharing-method was proposed to set the appropriate price in [36] to maximize users' throughput and the profit of operators. Duan et al. studied price competition and spectrum leasing between two MVNOs in a secondary spectrum market [13]. They assumed that the two secondary operators set prices simultaneously to serve a number of SUs. Tran et al. first studied spectrum access control—based on price in a CRN, where two secondary operators use shared-use and exclusive-use DSA paradigms, respectively, to set prices simultaneously to provision services to delay-sensitive SUs via pricing strategies [37]. However, the costs of spectrum leasing are overlooked and channel quality is not thoroughly analyzed in these works. In [38], the authors studied duopoly service pricing competition in the secondary spectrum market, in which two MVNOs offer network services to the SUs under a competitive environment. However, they only considered one competition case.

Based on the above analysis of previous works on network service provision under competition, it can be obviously found that many of them only considered either one competition scenario or the revenues of MVNOs ignoring the operating costs, such as the leasing cost of a radio frequency slice. Although [39] studied two competition scenarios, the spectrum leasing costs and users' different valuations on network services are not considered.

The system model that this paper analyzed is mainly motivated by [12, 40, 41]. In [12], the authors studied the virtualization of the wireless network to create MVNOs who offer IoT network services to IoT users using the leased frequency slices from WIPs. They formulated a three-layer game where the interactions among WIPs, MVNOs, and IoT users are investigated. In [40], the authors proposed a spectrum access scheme based on price to solve the problem of duopoly competition in a secondary spectrum market, in which two MVNOs lease idle spectrums whose channel qualities are different from the

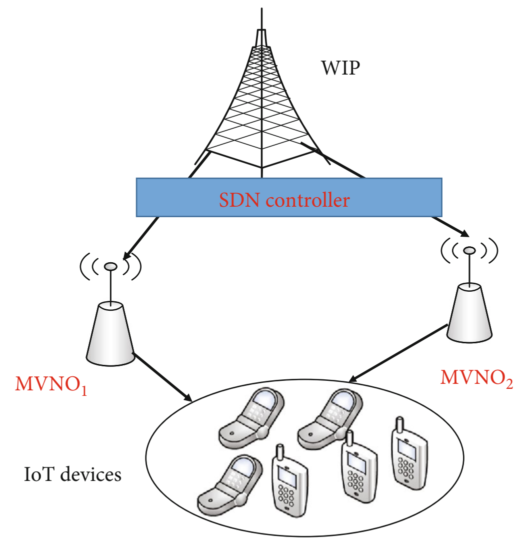

Figure 3: System model.

spectrum owner. In [41], Zhao et al. also studied the duopoly competition in a secondary spectrum market and analyzed the selection dynamics of SUs by using evolutionary game theory. Our study differs from the two previous works in the following aspects. First, the above works only considered one competition scenario, which is the simultaneous-play game scenario. Second, [40] assumed that the secondary users must choose network service from one of the operators, which is not valid in practice, as IoT users might refuse to subscribe to services from any of them if their obtained utilities are negative [37, 42]. Although [41] considered the practical case that some users might refuse to use networks services, the operating costs of the two MVNOs were not considered. Besides, different from [12] that considered a three-layer game among IPs, MVNOs, and IoT users, we mainly focus the two-layer game between two MVNOs and IoT users. Specifically, we analyzed two practical competition cases between the two MVNOs.

3. System Model

In this section, the system model is presented consisting of one WIP, two MVNOs, and a number of IoT users, as illustrated in Figure 3. Under the help of the SDN controller [12, 15–18], the WIP can divide and reconfigure its radio frequency band into slices. These radio frequency slices are of different qualities caused by different interference levels, as can be shown in Figure 4. The two MVNOs, denoted by MVNO_1 and MVNO_2, respectively, lease radio frequency slices from one WIP and provide network services to a number of IoTs. We assume that each IoT user has one device. Therefore, we use IoT users and IoT devices interchangeably throughout the paper. The system model of this paper is mainly inspired by [12] but is extended to consider two competition scenarios. Different from [12] that studied three-layer game among WIP, MVNOs, and IoT users, the only two-layer game between MVNOs and IoT users is considered in this study. We assume that each IoT user purchases one slice and has its preference when choosing network service.

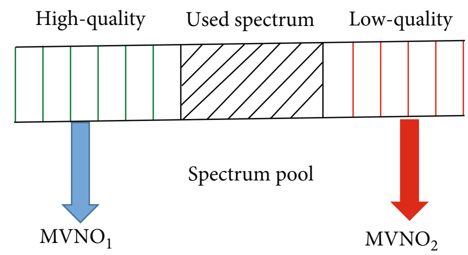

Figure 4: Radio frequency slices with two kinds of qualities.

We suppose that the slice with higher network quality denoted as C_1 is leased to MVNO_1, and the one with lower quality denoted as C_2 is leased to MVNO_2. The channel quality C_i is expressed as

$$C_i = B \log_2 \left(1 + \frac{\rho}{I_i} \right), \tag{1}$$

where B, ρ, and I_i, respectively, denote bandwidth, the received power of the SU, and the channel interference.

3.1. IoT Users' Model. To represent IoT users' different valuations of the network service, these users are divided into different types according to their tastes for the network service qualities. Suppose that the type of IoT user k is denoted by using the parameter α_k, whose value has uniform distribution in the range [0, 1] whose probability distribution function (PDF) is $f(\cdot)$ and cumulative distribution function (CDF) is $F(\cdot)$. One of the main reasons for the assumption of the uniform distribution is just for convenience. It should be noted that other forms of distribution can also be adopted without affecting our analysis results. The parameter of α_k reflects this IoT user's preference for network service quality, and a higher value of α_k means this IoT user has a higher preference for network service quality. For a type α_k IoT user that selects service from MVNO_i, its utility function is given as [12, 40, 41]

$$U_{i,k} = \alpha_k C_i - p_i, i = 1, 2, \tag{2}$$

where C_i and p_i denote the network service quality and price, respectively.

3.2. MVNOs' Model. Assume that there are two network service operators, denoted as MVNO_1 and MVNO_2, competing to attract a standard number of IoT users. The objective of the MVNOs is to set optimal network service prices p_1 and p_2, respectively, to maximize their profits. For an MVNO_i, $i = \{1, 2\}$, its profit is denoted as the revenue it can obtain minus the cost of leasing radio frequency slices from the WIP, which is given as

$$\pi_i = (p_i - \mu_i), i = 1, 2, \tag{3}$$

where μ_i and D_i are the operating cost including radio frequency slice leasing cost and user demands of MVNO_i, respectively.

Table 1: Summary of notations.

Notation	Description
i	$i \in \{1, 2\}$, which is a MVNO set
k	Subscript of a mobile user
p_i	The network service price of $MVNO_i$, for $i = 1, 2$
D_i	The demands of IoT users for services from $MVNO_i$
C_i	The network service quality of $MVNO_i$
p_i^s	The equilibrium price of $MVNO_i$ in SG scenario
p_i^n	The equilibrium price of $MVNO_i$ in NSG scenario
π_i^s	The profit of $MVNO_i$ in SG scenario
π_i^n	The profit of $MVNO_i$ in NSG scenario
α_k	IoT user k's preference for network service quality
$f(\cdot)$	PDF of IoT users' type
$F(\cdot)$	CDF of IoT users' preference parameter
μ_i	The operating cost of $MVNO_i$
α_i	The marginal IoT type
$\alpha^{\sim}$	The marginal type
$U_{i,k}$	The utility that type α_k IoT user gets from $MVNO_i$

For ease of analysis, we summarize the notations of this paper in Table 1.

4. Price and Service Selection

In this section, we analyze price and service selection in a wireless network service market where two MVNOs compete for IoT users through the set of optimal prices of their network services to have maximized profits. The relationship between MOVNOs and IoT users can be characterized by using the Stackelberg game with two stages, and it is solved by making use of the technique of backward induction [43, 44]. We first analyze the network service selection of IoT users in stage II and then analyze how the network service prices are determined in stage I.

For the service selection and price from the two MVNOs, we consider two cases: (1) the Stackelberg game (SG) case where one MVNO sets network service price firstly and the other one sets later and (2) noncooperative strategic game (NSG) [43, 45], also known as simultaneous-play game, where the network service prices are simultaneously set by the two MVNOs. The SG case means that an entrant MVNO who plans to offer network service competes with an incumbent MVNO whose quality of network service is better, and the NSG case means that two MVNOs whose network service prices and qualities are different compete simultaneously.

4.1. IoT Users' Demand Decision. Based on the prices and service qualities of the two MVNOs, each of the IoT users will make a network service demand decision to buy network service from one of the two MVNOs or neither. We denote the demands of IoT users for network services from $MVNO_1$ and $MVNO_2$ as $D_1(p_1, p_2)$ and $D_2(p_1, p_2)$, respectively. Two critical types of IoT users denoted as α_1 and α_2 are considered, such that

$$U_{1,k} = \alpha_1 C_1 - p_1 = 0, \tag{4}$$

$$U_{2,k} = \alpha_2 C_2 - p_2 = 0. \tag{5}$$

From Equations (4) and (5), we get

$$\alpha_1 = \frac{p_1}{C_1}, \tag{6}$$

$$\alpha_2 = \frac{p_2}{C_2}. \tag{7}$$

We also denote an indifferent IoT user by $\alpha\sim$ such that $U_{1,k} = U_{2,k}$; that is,

$$\alpha \sim C_1 - p_1 = \alpha \sim C_2 - p_2. \tag{8}$$

Then, from Equation (8), $\alpha\sim$ is calculated as

$$\alpha \sim = \frac{p_1 - p_2}{C_1 - C_2}. \tag{9}$$

IoT users are assumed to be self-interested, which means that they choose service access from $MVNO_i$ $(i = 1, 2)$ if their utilities are not only positive but also higher than the other one. Therefore, the following results can be obtained.

Proposition 1. *An IoT user with type α_k will choose network services according to the following conditions:*

(i) It chooses service from $MVNO_1$ if $U_{1,k}(\alpha_k, p_1) > U_{2,k}(\alpha_k, p_2)$ and $U_{1,k}(\alpha_k, p_1) > 0$, requiring $\alpha_k < \alpha^{\sim}$ and $\alpha_k < \alpha_1$

(ii) It chooses service from $MVNO_2$ if $U_{2,k}(\alpha_k, p_2) > U_{1,k}(\alpha_k, p_1)$, and $U_{2,k}(\alpha_k, p_2) > 0$, requiring $\alpha^{\sim} < \alpha_k < \alpha_2$

(iii) It chooses no service if $U_{1,k}(\alpha_k, p_1) < 0$ and $U_{2,k}(\alpha_k, p_2) < 0$, requiring $\alpha_k > \alpha_1$ and $\alpha_k > \alpha_2$

According to the results of Proposition 1, the service demand decisions of IoT users from $MVNO_1$ and $MVNO_2$ are, respectively, given as

$$D_1 = F_1(\alpha) = \int_{\max\{\alpha_1, \alpha\sim\}}^{1} f(\alpha) d\alpha, \tag{10}$$

$$D_2 = F_2(\alpha) = \int_{\alpha_2}^{\alpha\sim} f(\alpha) d\alpha. \tag{11}$$

From Equations (10) and (11), the following proposition can be obtained.

Proposition 2. *For network service prices (p_1, p_2), a unique pair of equilibrium demands $D^e{}_1$ and $D^e{}_2$ exist at $MVNO_1$ and $MVNO_2$, respectively:*

(1) If $\alpha_2 > \alpha_1$, then $\alpha_1 > \alpha\sim$ and $\alpha_2 > \alpha\sim$. We have $F_1(\alpha) = 0$ and $F_2(\alpha_2) = F(\alpha_2)$

(2) If $\alpha_1 > \alpha_2$, then $\alpha\sim > \alpha_1$ and $\alpha\sim > \alpha_2$. We have $F_1(\alpha) = 1 - F(\alpha\sim)$ and $F_2(\alpha_2) = F(\alpha_2) - F(\alpha\sim)$

(3) This corresponds to the case that $MVNO_1$ and $MVNO_2$ coexist to offer network services. Therefore, the demands for network services from $MVNO_1$ and $MVNO_2$ in equilibrium are, respectively, given as

$$D_1 = 1 - F_1(\alpha) = 1 - \frac{p_1 - p_2}{C_1 - C_2}, \tag{12}$$

$$D_2 = F_2(\alpha\sim) - F_2(\alpha) = \frac{p_1 - p_2}{C_1 - C_2} - \frac{p_2}{C_2}. \tag{13}$$

4.2. Two Competition Cases. After the network service demands of IoT users are given, the two MVNOs will compete to get their maximized profits through setting optimal network service prices. Therefore, the profits of the two MVNOs can be, respectively, expressed as

$$\pi_1 = (p_1 - \mu_1)D_1(p_1, p_2) = (p_1 - \mu_1)\left(1 - \frac{p_1 - p_2}{C_1 - C_2}\right), \tag{14}$$

$$\pi_2 = (p_2 - \mu_2)D_2(p_1, p_2) = (p_2 - \mu_2)\left(\frac{p_1 - p_2}{C_1 - C_2} - \frac{p_2}{C_2}\right). \tag{15}$$

The competition of the two MVNOs can be modelled and analyzed by using the one-shot game, which is formulated as follows:

Players: $MVNO_1$ and $MVNO_2$

Strategies: prices $p_i > 0$, $i = 1, 2$

Payoff: profits π_i, $i = 1, 2$

4.3. Stackelberg Game (SG) Case. In this case, the competition of the two MVNOs is modelled and analyzed by using the Stackelberg game (SG), where $MVNO_1$ is the leader, whereas $MVNO_2$ is the follower. $MVNO_1$ moves firstly to set the optimal network service price to get the maximized profit by anticipating the choice on p_2 of $MVNO_2$.

The problem that maximizes the profit of $MVNO_1$ is expressed as follows.

Problem 3.

$$\max\ \pi_1 = (p_1 - \mu_1)D_1(p_1, p_2), \quad p_1 \geq 0 \tag{16}$$

where $D_1(p_1, p_2)$ is given by Equation (10).

After getting $MVNO_1$'s price p_1, $MVNO_2$ tries to solve the following profit optimization problem to get its price p_2.

Problem 4.

$$\max\ \pi_2 = (p_2 - \mu_2)D_2(p_1, p_2), \quad p_2 \geq 0, \tag{17}$$

where $D_2(p_1, p_2)$ is given in Equation (11).

From solving Problem 3 and Problem 4 sequentially, Proposition 5 is obtained, and the proof is shown in Appendix A.

Proposition 5. *A unique pair of the price $(p^s{}_1, p^s{}_2)$ is obtained in equilibrium in the SG case.*

According to the results of Proposition 5, Corollary 6 can be obtained.

Corollary 6. *In the SG case, the profits that $MVNO_1$ and $MVONO_2$ get are, respectively, expressed as*

$$\pi_1^s = (p_1^s - \mu_1)D_1^s, \tag{18}$$

$$\pi_2^s = (p_2^s - \mu_1)D_2^s. \tag{19}$$

4.4. Noncooperative Strategic Game (NSG) Case. Noncooperative strategic game (NSG), which is also known as simultaneous-play game [46], is the case that $MVNO_1$ and $MVNO_2$ simultaneously set their service prices in order to get their maximized profits.

The problem that tries to solve the maximized profit of $MVNO_1$ is expressed as follows.

Problem 7.

$$\max\ \pi_1 = (p_1 - \mu_1)D_1(p_1, p_2), \quad p_1 \geq 0, \tag{20}$$

where $D_1(p_1, p_2)$ is shown in Equation (10).

The problem that tries to solve the maximized profit of $MVNO_2$ is expressed as follows.

Problem 8.

$$\max\ \pi_2 = (p_2 - \mu_2)D_2(p_1, p_2), \quad p_2 \geq 0, \tag{21}$$

where $D_2(p_1, p_2)$ is shown in Equation (11).

From solving Problem 7 and Problem 8 jointly, the following results are obtained; the proof is given in Appendix B.

Proposition 9. *In the NSG case, a unique price pair $(p_1{}^n, p_2{}^n)$ exists in equilibrium.*

According to Proposition 9, Corollary 10 is obtained.

$$\pi_1^n = (p_1^n - \mu_1) D_1^n, \quad (22)$$

$$\pi_2^n = (p_2^n - \mu_1) D_2^n. \quad (23)$$

Corollary 10. *In SG case, the profits that $MVNO_1$ and $MVONO_2$ get are, respectively, expressed as*

5. Numerical Results

This section provides numerical results to verify the analysis presented in the prior sections. We consider an IoT environment with two MVNOs who lease radio frequency slices from a WIP and provision network services to a number of IoT users under two competition cases. Specifically, we analyze the sensitivity of network service prices and profits in equilibrium with respect to different parameters, like the quality of slice and cost coefficient. We assume $\mu_i = \beta C_i$, for $i = 1, 2$, where β is the cost coefficient. Unless otherwise specified, the set of parameter values is mainly referred to as [12, 40] $\beta = 0.2, 0.1 \leq C_2 \leq C_1 \leq 3$ (bps). We use the tool of MATLAB to develop the simulation environment.

5.1. Impact of Slice Quality. First, we analyze how the quality of radio frequency slice impacts the network service prices, IoT user demands, and profits of the two MVNOs in equilibrium under the two competition cases.

Figure 5 shows the impact of slice quality C_1 on the network prices of $MVNO_1$ in equilibrium under the two competition cases, where C_2 is fixed as 0.3. Figure 6 shows the impact of slice quality C_2 on network prices of $MVNO_2$ in equilibrium under two competition cases, where C_1 is fixed as 3. The cost efficient β is set as 0.2 in the two figures. From Figures 5 and 6, it can be observed that, in equilibrium, the network service prices that $MVNO_1$ and $MVNO_2$ get are higher in the NSG competition case than those in the SG competition case. Figures 5 and 6 suggest that MVNOs can achieve higher network service prices with respect to their qualities of leased frequency slice increasing. From the two figures, it can also be observed that $MVNO_1$ can get higher network prices than $MVNO_2$ in equilibrium under the two competition cases due to its leased quality of frequency slice which is higher.

Figures 7 and 8, respectively, show the profits of $MVNO_1$ and $MVNO_2$ versus slice qualities C_1 and C_2 in the SG scenario. We set β as 0.2 in the two figures, $C_2 = 0.3$ in Figure 7 and $C_1 = 3$ in Figure 8. From Figure 7, it can be found that the profits of $MVNO_1$ and $MVNO_2$ will increase if the better slice quality of $MVNO_1 C_1$ is leased from WIP. It can be found from this figure that the obtained profit of $MVNO_2$ is larger than that of $MVNO_1$. This is because $MVNO_1$ has a higher operating cost. From Figure 8, it can be observed that the profit of $MVNO_1$ increases while the profit of $MVNO_2$ first increases then decreases with respect to the increase in radio frequency quality C_2 increasing.

Figures 9 and 10 show, respectively, the profits that $MVNO_1$ and $MVNO_2$ obtain versus the slice qualities C_1 and C_2 in NSG case. We set β as 0.2 in the two figures, $C_2 =$ 0.3 in Figure 9 and $C_1 = 3$ in Figure 10. Figure 9 shows that the profits of $MVNO_1$ and $MVNO_2$ decrease with the slice quality of $MVNO_1$ increasing. Although the slice quality of $MVNO_1$ increases, the profit of this MVNO decreases, due to the reason that less IoT users choose $MVNO_1$ for the higher network price, which can be observed from Figure 5. From Figure 10, it can be observed that the profit of $MVNO_2$ increases if it leases better slice quality from the WIP, as more

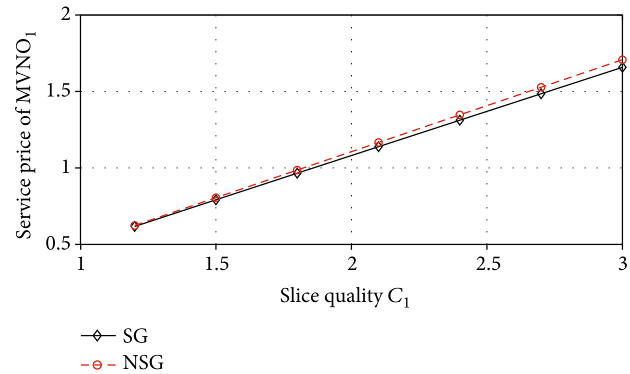

FIGURE 5: The equilibrium network price of $MVNO_1$ versus slice quality C_1 in two cases.

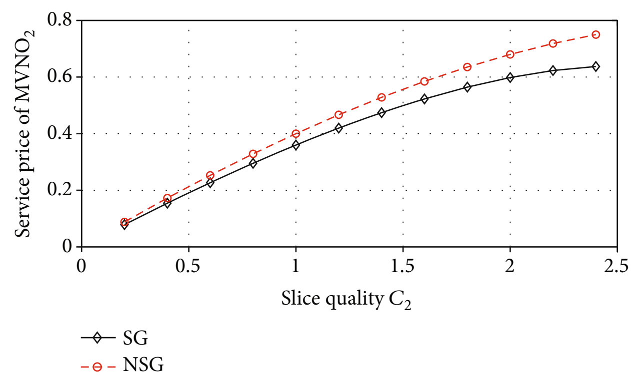

FIGURE 6: The equilibrium network price of $MVNO_2$ versus slice quality C_2 in two cases.

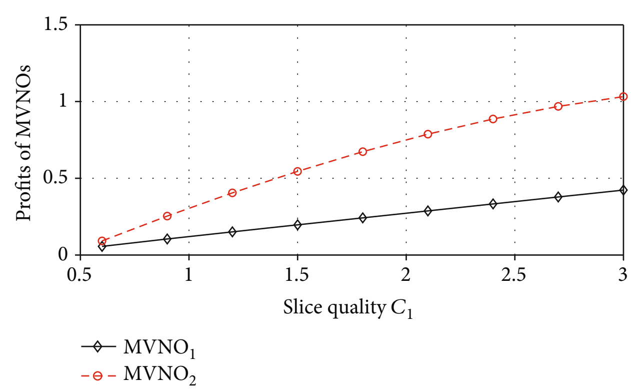

FIGURE 7: The profits of $MVNO_1$ and $MVNO_2$ versus slice quality C_1 in the SG case.

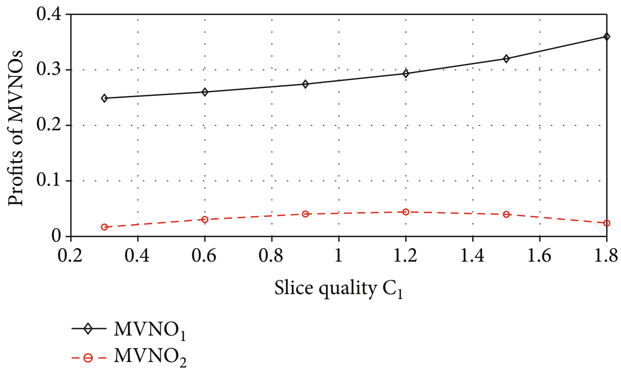

Figure 8: The profits of $MVNO_1$ and $MVNO_2$ versus slice quality C_2 in the SG case.

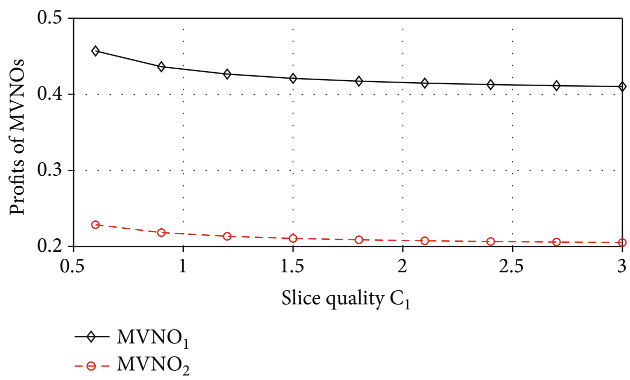

Figure 9: The profits of $MVNO_1$ and $MVNO_2$ versus slice quality C_1 in the NSG case.

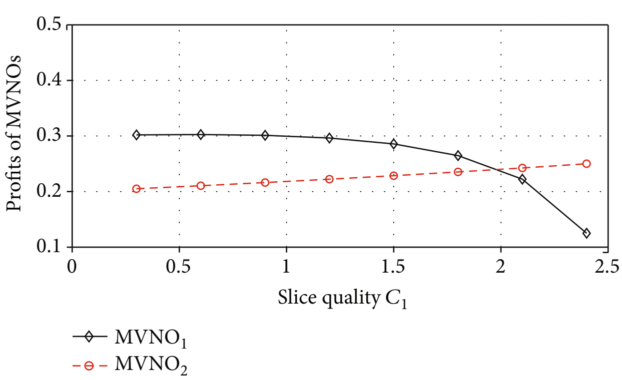

Figure 10: The profits of $MVNO_1$ and $MVNO_2$ versus slice quality C_2 in the NSG case.

IoT users will choose the service from $MVNO_2$, which can be found in Figure 6.

5.2. Impact of Operating Cost. This part analyzes how the operating cost impacts the network service prices and profits of $MVNO_1$ and $MVNO_2$ in equilibrium under the two competition cases. Figures 11 and 12 show the profits of the two MVNOs versus cost coefficient β, respectively, under the SG and NSG cases with $C1 = 2$ and $C_2 = 0.7$. Figure 11

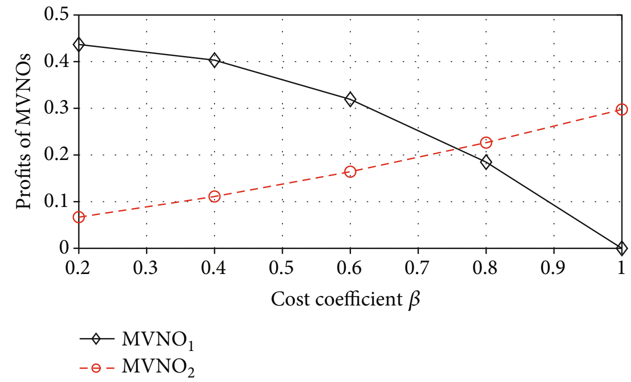

Figure 11: The profits of $MVNO_1$ and $MVNO_2$ versus cost coefficient β in the SG case.

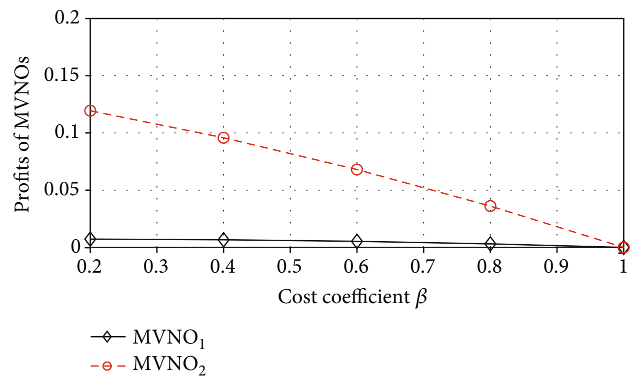

Figure 12: The profits of $MVNO_1$ and $MVNO_2$ versus cost coefficient β in the NSG case.

illustrates that with the cost coefficient β increasing, unlike $MVNO_2$ whose profit increases, the profit of $MVNO_1$ under the SG case decreases indicating that $MVNO_2$ benefits more from this competition case when the cost coefficient β increases. The profit of $MVNO_2$ will be larger than that of $MVNO_1$ with the increase of β. Figure 12 indicates that, in the NSG case, the profits of the $MVNO_1$ and $MVNO_2$ decrease with respect to the increasing cost coefficient β. A higher value of cost coefficient means that the two MVNOs should afford more operating costs.

6. Conclusions and Future Works

This paper has studied a two-layer game in an IoT network service environment aiming to get the maximized MVNOs' profits by taking IoT users' heterogeneous tastes for the service qualities into account. We investigated and analyzed network service pricing competition of $MVNO_1$ and $MVNO_2$ by using NSG and SG, respectively, and a unique equilibrium is obtained in each game case. The numerical results show that, in equilibrium, $MVNO_1$ and $MVNO_2$ can charge their network services with higher prices if they leased better slice qualities from the WIP, and they charge higher network service prices in the SG case than in the NSG case. The numerical results also indicated that IoT users are not prone to pay to use network services even if the two MVNOs provide network services with better slice qualities. We got the conclusion that with the increase in operating cost, the profit of $MVNO_1$ decreased in the two competition cases while the profit of $MVNO_2$ increases in the SG case and decreases in the NSG case.

Several research directions still remained to be further studied as future works. First, the duopoly competition scenario can be extended to the oligopoly one where multiple MVNOs exist provisioning network services. For the oligopoly case where there are more than two MVNOs, we can apply the model in [47]. Second, we can investigate and analyze the three-layer game by incorporating the interaction between the WIP and the two MVNOs. Third, the MVNOs can improve their profits through price differentiation, i.e., charging network service with different prices according to the different types of IoT users.

Appendix

A. Proof of Proposition 5

Given the network service price of $MVNO_1$, by setting the first derivative of π_2 concerning p_2 to zero,

$$\frac{\partial \pi_2}{\partial p_2} = \frac{C_1 p_1 - 2C_1 p_2 + C_1 \mu_2}{C_2(C_1 - C_2)} = 0. \quad (A.1)$$

From Equation (A.1), p_2 is calculated as

$$p_2 = \frac{C_2 p_1 + C_1 \mu_2}{2C_1}. \quad (A.2)$$

After substituting Equation (A.1) into Equation (14), π_1 is calculated as

$$\pi_1 = (p_1 - \mu_1)\left[1 - \frac{2C_1 p_1 - C_2 p_1 - C_1 \mu_2}{2C_1(C_1 - C_2)}\right]. \quad (A.3)$$

Equation (A.3) is convex; therefore, by setting the derivative of π_2 with respect to p_2 to zero,

$$\frac{\partial \pi_1}{\partial p_1} = 1 - \frac{4C_1 p_1 - 2C_2 p_1 - C_1 \mu_2 + C_2 \mu_1}{2C_1(C_1 - C_2)} = 0. \quad (A.4)$$

From Equation (A.4), the best response of $MVNO_1$ is

$$p_1^s = \frac{2C_1(C_1 - C_2) + 2\mu_1 C_1 + C_1 \mu_2 - C_2 \mu_1}{2(2C_1 - C_2)}. \quad (A.5)$$

By substituting Equation (A.5) into Equation (A.2), the best response of $MVNO_2$ is

$$p_2^s = \frac{C_2[2C_1(C_1 - C_2) + 2\mu_1 C_1 + C_1 \mu_2 - C_2 \mu_1]}{4C_1(2C_1 - C_2)} + \frac{\mu_2}{2}. \quad (A.6)$$

Accordingly, by, respectively, substituting Equations (A.5) and (A.6) into Equations (12) and (13), the service demands from $MVNO_1$ and $MVNO_2$ in the SG case are denoted, respectively, as

$$D_1^s = \frac{2C_1(C_1 - C_2) - 2\mu_1 C_1 + C_1 \mu_2 + C_2 \mu_1}{4C_1(C_1 - C_2)}, \quad (A.7)$$

$$D_2^s = \frac{2C_1(C_1 - C_2) - 2\mu_1 C_1 + C_1 \mu_2 + C_2 \mu_1}{4(2C_1 - C_2)(C_1 - C_2)}. \quad (A.8)$$

B. Proof of Proposition 9

The objective function for Problem 3 is easily proved as convex; hence, by setting the derivative of π_1 with respect to p_1 to zero,

$$\frac{\partial \pi_1}{\partial p_1} = 1 - \frac{2p_1 - p_2 - \mu_1}{C_1 - C_2} = 0. \quad (B.1)$$

From Equation (B.1), p_1 is calculated as

$$p_1 = \frac{C_1 - C_2 + p_2 + \mu_1}{2}. \quad (B.2)$$

Similarly, by setting the derivative of π_2 with respect to p_2 to zero,

$$\frac{\partial \pi_2}{\partial p_2} = \frac{C_1 p_1 - 2C_1 p_2 + C_1 \mu_2}{C_2(C_1 - C_2)} = 0. \quad (B.3)$$

From Equation (B.2), p_2 is calculated as

$$p_2 = \frac{p_1 C_2 + C_1 \mu_2}{2C_1}. \quad (B.4)$$

By solving Equations (B.2) and (B.4), the optimal service prices of $MVNO_1$ and $MVNO_2$ are, respectively, denoted as

$$p_1^n = \frac{2C_1(C_1 - C_2) + C_1(2\mu_1 + \mu_2)}{4C_1 - C_2}, \quad (B.5)$$

$$p_2^n = \frac{C_1 C_2 - C_2^2 + C_2 \mu_1 + 2\mu_2 C_1}{4C_1 - C_2}. \quad (B.6)$$

Accordingly, by, respectively, substituting Equations (B.5) and (B.6) into Equations (12) and (13), the service demands from $MVNO_1$ and $MVNO_2$ in NSG case are, respectively, denoted as

$$D_1^n = \frac{2C_1(C_1 - C_2) - 2\mu_1 C_1 + C_1 \mu_2 + C_2 \mu_1}{(4C_1 - C_2)(C_1 - C_2)}, \quad (B.7)$$

$$D_2^n = \frac{C_1[\mu_2(C_2 - 2C_1) + C_2(\mu_1 + C_1 - C_2)]}{C_2(4C_1 - C_2)(C_1 - C_2)}. \quad (B.8)$$

Data Availability

The data and programme of this study can be available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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