Price Competition in a Duopoly IaaS Cloud Market

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***Abstract*—Pricing cloud resources plays an important role in leading to the success of cloud computing. Cloud services are priced at different levels in infrastructure-as-a-service (IaaS) cloud market. For example, Amazon EC2 offers its cloud resources with three pricing schemes, the subscription model, pay-as-you-go model and spot pricing model. With more and more IaaS cloud service providers (CSPs) beginning to provide cloud services, they form a competitive market to compete for cloud users. Therefore, how to set optimal prices in order to maximize their revenue in a competitive IaaS cloud computing market while at the same time meeting the cloud users' demand satisfaction is a problem that CSPs should consider. Towards this end, in this paper, we study subscription pricing competition in a duopoly IaaS cloud computing market. First, we analyze whether or not the cloud users choose to use cloud service. Then, we present a game theoretic analysis of a cloud market with two CSPs competing non-cooperatively for cloud users.**

Keywords—cloud computing; IaaS; cloud service provider

I. INTRODUCTION

In recent years, cloud computing has attracted significant attention not only from industry but also from academia, and the use of cloud computing is increasing rapidly in many organizations. Cloud Computing can be defined in various ways [1] and a popular definition of cloud computing proposed by Buyya et al. [2] is:

"a cloud is a type of parallel and distributed system consisting of a collection of interconnected and virtualized computers that are dynamically provisioned and presented as one or more unified computing resources based on service-level agreements established through negotiation between the service provider and the consumers."

Today's cloud service providers (CSPs), such as Amazon EC2 and Windows Azure, deliver Infrastructure as a Service (IaaS) to cloud users. In the cloud computing environment, IaaS CSPs bundle their physical resources, such as CPU, memory and disk, into distinct types of virtual machines (VMs), according to their sizes and features, and offer them as services to the general public. Amazon EC2 is a public CSP, which has hosted several types of spot instances (e.g. small, medium, large and extra large) based on the capacities of CPU, memory and disk, etc. [3], configurations of some spot instances are shown in TABLE I. Cloud users purchase units of computing time on VMs to run their jobs.

The most common pricing mechanism used by IaaS CSPs is pay-as-you-go model, where users are charged with a fixed price per unit resource per unit time. This fixed pricing scheme may result in unused resources [4], especially, when the users' demand is stochastic. Besides the pay-as-you-go model, there are two additional pricing models in IaaS cloud market, i.e., the subscription pricing model and the spot pricing model [5], [6]. The former pricing scheme allows a cloud user to reserve some unit of cloud resource for a certain period of time by paying a one-time subscription fee at a discount. The cloud user can use the reserved cloud resource at any time during the subscription period. In the latter pricing scheme, cloud users should submit bids per hour to the CSP, who determines the spot prices. Cloud users can get access to the cloud resource as long as their bids are higher than the spot prices, and they are rejected otherwise.

With more and more IaaS CSPs beginning to provide cloud services, these CSPs form a competitive market to compete for cloud users. On the one hand, CSPs want to charge more from the cloud users in order to get more revenue. On the other hand, if the prices of cloud resources are set too high in a competitive environment, CSPs may have the risk of losing cloud users in the long run. Therefore, how to set the

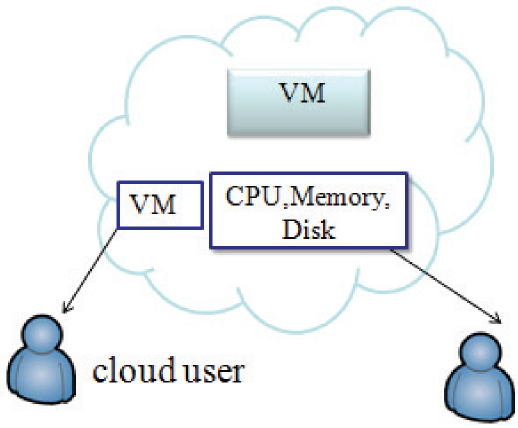

Fig. 1. IaaS cloud market.

TABLE I. CONFIGURATION OF SOME AMAZON EC2 INSTANCES

Instance Types	Processor Arch (bit)	Compute Unit	Storage (GB)	Memory (GiB)
m3.xlarge	64	4	80 SSD	15
m3.2xlarge	64	8	160SSD	30
c3.large	64	2	32SSD	3.75
c3.xlarge	64	4	80SSD	7.5
c3.2xlarge	64	8	160SSD	15

optimal prices to make revenue maximized while attracting more cloud users is an intractable problem that CSPs should consider. Furthermore, computing resources, such as CPU cycles and disk, are inherently *perishable*: they are of no value if they are not utilized in time [7]. From the cloud users' perspective, since they can run their jobs on different providers' VMs, a rational cloud user will choose the cloud service that can maximize the net reward, which is his/her utility minus the payment. Even for the similar type of VM, different CSPs have different prices. For example, as of February of 2014, Amazon EC2 [6], GoGrid [8], and Rackspace [9] charged different prices with respect to the VM with 4 CPU cores.

In this paper, we study subscription pricing competition in a duopoly IaaS cloud computing market. We present a game theoretic analysis of a cloud market with two CSPs competing non-cooperatively for cloud users.

The rest of the paper is structured as follows. Section II reviews the related works; the system model is described in section III. In section IV, we turn to analyze the duopoly competitive cloud market using game theory.

II. RELATED WORKS

In this section, we present the related works and motivations of our study. Our study is mainly motivated by two streams of works.

A. Cloud Computing

The widespread use of cloud resources is making the efficient utilization and revenue management in cloud computing environments increasingly important. Some studies about pricing have appeared in cloud computing environment recently. The authors in [10] presented a study of cloud resources. The work of [11] proposed a statistical model for the spot prices of EC2. Reference [12] studied fair competition of cloud resource with a computationally efficient pricing mechanism. A pricing algorithm was proposed in [13] to maximize the social welfare by regulating admission and performing resource allocation.

B. Pricing

A plethora of works exist on pricing in communication networks and Internet. Since Kelly's pioneering work [14], there have been numerous works adopting pricing schemes to carry out studies on resource allocation and revenue management problems in wireless communication networks. The work in [15] applied time-constrained pricing to study Internet service provider's revenue maximization. The work of [16] studied the problem of distributed resource allocation and revenue maximization between different Internet service providers. Price competition is a hot research topic in the economic markets where there exist multiple service providers. Focusing on a femtocell communication market, the authors in [17] studied the problem of network service providers' long-term decision whether to enter the femtocell communication market and what kind of spectrum sharing technology to choose to get the maximized profit. Chen et al. analyzed the equilibrium price in a duopoly competitive market with varying demand in the economic context [18].

To the best of our knowledge, pricing competition in a cloud computing market is relatively less explored. An exception is the work of [19] where Li et al. studied the price competition in a cloud market with multiple IaaS cloud providers based on pay-as-you-go pricing model.

III. MODEL FORMULATION

We consider a cloud computing market with two CSPs, denoted by CSP 1 and CSP 2, respectively, and each of them has a capacity μ_i serving a common potential pool of Λ (the market size) cloud users. Each CSP sets its price of cloud services p_i per unit time, $i=1,2$. The potential cloud users are assumed to have full knowledge of R_i (the reward of the CSP i 's service) per unit time, the capacity μ_i, the price p_i per unit time, the cloud users' reservation value v (assumed to be the same across all users) and if his/her net reward falls below v by using the cloud service, cloud users will refuse to use either cloud service and choose to finish their tasks locally [19]. For a cloud user k, the quality of service (QoS) of his/her valuation for cloud service is denoted by θ_k, which reflects his/her preference for cloud service.

As in [20], two further assumptions are made. First, all cloud users choose only one CSP. Second, a cloud user pays a price per unit time for the right to use the CSP i 's cloud service, so the prices are subscription-based rather than usage-based.

IV. PRICE COMPETITION BETWEEN TWO CLOUD SERVICE PROVIDERS

In this section, we consider a duopoly cloud market. Suppose two IaaS CSPs compete non-cooperatively with each other. The objective of each CSP is to maximize its expected revenue per unit time. Each CSP chooses and posts its price p_i, $i=1,2$, and charges all its cloud users with the same price. For each CSP the problem is to choose a price per unit time to maximize its revenue. The revenue of the CSPs is denoted as $\pi_i = p_i \lambda_i$.

All cloud users act in a selfish manner so as to maximize their net payoff. Following [17], we assume that each cloud user can only choose one CSP in one unit time. A cloud user k 's surplus from using the cloud service of provider i is modelled as

$$U_i = R_i - p_i - \theta_k \, \mathrm{w}(\lambda_i), i = 1,2 \tag{1}$$

For a cloud user k , the optimal choice is to choose the cloud provider i from which he/she can obtain the maximized net payoff, or he/she will refuse to use the cloud service if the net payoff obtained failed below his/her reservation value.

A. Nash Equilibrium in a Duopoly Cloud Market

Let π_i be the expected revenue of CSP i per unit time. The objective of each CSP i is to seek to maximize its revenue by choosing its price p_i , which is obviously dependent on the reaction of the other CSP and that of all the cloud users. Let $\pi_i(p_1, p_2)$ denote the expected revenue of CSP i if it chooses a price p_i given the other CSP's price p_{-i} . A pair of prices is Nash equilibrium if it satisfies

$$\pi_1(p_1^*, p_2^*) \geq \pi_1(p_1, p_2^*), \forall p_1 \geq 0 \tag{2}$$

$$\pi_2(p_1^*, p_2^*) \geq \pi_2(p_1^*, p_2), \forall p_2 \geq 0 \tag{3}$$

In equilibrium, the expected revenue of both CSPs is maximized and the cloud market is balanced dynamically. In the Nash equilibrium, neither of the two CSPs can change its price to increase its expected revenue unilaterally. That is equivalent to say, the Nash equilibrium price is the optimal price that a CSP can achieve in a cloud market when the two CSPs do not cooperate with each other. The equilibrium prices can be solved by a standard procedure of identifying the best response function of each CSP. Let $p_i = F_i(p_{-i})$ be the CSP i 's optimal price given the posted price p_{-i} of the other CSP. A Nash equilibrium in this duopoly IaaS cloud market is then a pair of prices (p_1, p_2) such that $p_1 = F_1(p_2)$ and $p_2 = F_2(p_1)$, i.e., an intersecting point of the two best response functions. Take CSP 1 as an example. The best response function F_1 can be found under the assumption that the price of CSP 2, p_2, is given.

$$\max_{p_1 \geq 0} \quad \pi_1 = p_1 \lambda_1, \tag{4}$$

$$\text{s.t.} \;\; R_1 - p_1 - \theta_k \frac{\lambda_1}{\mu_1} \geq v, \tag{5}$$

$$R_1 - p_1 - \theta_k \frac{\lambda_1}{\mu_1} = R_2 - p_2 - \theta_k \frac{\lambda_2}{\mu_2}, \tag{6}$$

$$\lambda_1 + \lambda_2 \leq \Lambda, 0 \leq \lambda_1 < \mu_1 \tag{7}$$

Similarly, the optimal price of CSP 2 can be found by solving its corresponding problem, under the assumption that the price of CSP 1, p_1, is given.

$$\max_{p_2 \geq 0} \quad \pi_2 = p_2 \lambda_2, \tag{8}$$

$$\text{s.t.} \;\; R_2 - p_2 - \theta_k \frac{\lambda_2}{\mu_2} \geq v, \tag{9}$$

$$R_2 - p_2 - \theta_k \frac{\lambda_2}{\mu_2} = R_1 - p_1 - \theta_k \frac{\lambda_1}{\mu_1}, \tag{10}$$

$$\lambda_1 + \lambda_2 \leq \Lambda, 0 \leq \lambda_2 < \mu_2. \tag{11}$$

B. Homogeneous Cloud Service Providers

Consider the special case where there are two identical CSPs in an IaaS cloud market, i.e., $R_1 = R_2 \equiv R$, $\mu_1 = \mu_2 \equiv \mu$.

It turns out that the Nash equilibrium will have two forms according to whether the two CSPs can take the whole market or not. Let $\bar{\Lambda} = \dfrac{\mu(R - v)}{\theta_k}$.

1) Non-competitive scenario

We first consider the ample demand scenario that is the cloud users have more demand than the two CSPs can handle. Therefore, each of the two CSPs behaves like a monopoly and charges cloud users with monopoly prices.

Theorem 1. Suppose that $\Lambda > \bar{\Lambda}$, there is a unique equilibrium such that each CSP charges its own monopoly price

$$p_1^* = p_2^* = \frac{R - v}{2} \tag{12}$$

and the corresponding actual market shares are

$$\lambda_1^* = \lambda_2^* = \frac{\mu(R - p^* - v)}{\theta_k} \tag{13}$$

From Theorem 1 we can find that equilibrium price p_i^* is the first-order optimal price for a monopoly CSP. Hence, CSPs are indifferent to the cloud users, namely, each CSP behaves independently and they operate themselves as the monopolists. Note that in this scenario, the net rewards of cloud users are equal to their reservation value.

Corollary 1. If $\Lambda > \bar{\Lambda}$, then the comparative statics of the equilibrium are as follows:

$$\frac{\partial p^*}{\partial R} = \frac{1}{2} > 0 \tag{14}$$

$$\frac{\partial p^*}{\partial v} = -\frac{1}{2} < 0 \quad (15)$$

2) Competitive scenario

Each CSP will engage in competition when Λ decreases, so they will form a competitive market.

Theorem 2. Suppose that $\Lambda \leq \bar{\Lambda}$, and then any pair of the Nash equilibrium prices (p_1, p_2) must satisfy

$$\frac{(R - p_1^* - v)\mu}{\theta_k} + \frac{(R - p_2^* - v)\mu}{\theta_k} = \Lambda \quad (16)$$

and the corresponding market share of CSPs is

$$\lambda_i^* = \frac{(R - p_i^* - v)\mu}{\theta_k},\ i = 1,2 \quad (17)$$

In particular,

$$p_1^* = p_2^* = R - v - \theta_k \frac{\Lambda}{2\mu} \quad (18)$$

is an equilibrium with the corresponding market share of each CSP is

$$\lambda_1^* = \lambda_2^* = \frac{\Lambda}{2} \quad (19)$$

Corollary 2. If $\Lambda > \bar{\Lambda}$, then the comparative statics of the equilibrium are as follows:

$$\frac{\partial p^*}{\partial R} = 1 > 0 \quad (20)$$

$$\frac{\partial p^*}{\partial v} = -1 < 0 \quad (21)$$

$$\frac{\partial p^*}{\partial \theta_k} = -\frac{\Lambda}{2\mu} < 0 \quad (22)$$

$$\frac{\partial p^*}{\partial \Lambda} = -\frac{\theta_k}{2\mu} < 0 \quad (23)$$

$$\frac{\partial p^*}{\partial \mu} = \frac{\theta_k \Lambda}{\mu^2} > 0 \quad (24)$$

From theorem 1 and theorem 2, we can see that when reduced to homogeneous scenario, i.e., the two CSPs have the same capacities, both CSPs will charge the same price, and they have the same market share. The two CSPs are indifferent to cloud users, which imply that the equilibrium solutions of the homogeneous scenario are symmetric.

V. CONCLUSIONS

In this paper, we studied price competition in a duopoly IaaS cloud market. We characterized the existence of Nash equilibrium and analyzed the comparative statics. In future works, we will focus on the numerical analysis of the effects of resource capacities on equilibrium prices and expected revenues in monopoly cloud market and duopoly cloud market.

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