Iaas: Cloud Providers for Multiple Souk Outlay Antagonism

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Abstract—cloud computing is the practice of using a network of remote servers hosted on the Internet to store, manage, and process data, rather than a local server or a personal computer.As an increasing number of infrastructure-as-a-service (IaaS) cloud providers start to provide cloud computing services,they form a competition market to compete for users of these services. Due to different resource capacities and service workloads,users may observe different finishing times for their cloud computing tasks and experience different levels of service qualities as a result. To compete for cloud users, it is critically important for each cloud service provider to select an "optimal" price that best corresponds to their service qualities, yet remaining attractive to cloud users. To achieve this goal, the underlying rationale and characteristics in this competition market need to be better understood. In this paper, we present an in-depth game theoretic study of such a competition market with multiple competing IaaS cloud providers. We characterize the nature of non-cooperative competition in an IaaS cloud market, with a goal of capturing how each IaaS cloud provider will select its optimal prices to compete with the others.Our analyses lead to sufficient conditions for the existence of a Nash equilibrium, and we characterize the equilibrium analytically in special cases. Based on our analyses, we propose iterative algorithms for IaaS cloud providers to compute equilibrium prices, which converge quickly in our study.

Key words—Cloud computing, infrastructure-as-a-service, market competition, cloud pricing

1 INTRODUCTION

cloud computing has recently emerged as a new paradigm for a cloud provider to host and deliver computing services to enterprises and consumers who use such services. One of the possible types of cloud services provided by today's cloud providers, such as Amazon EC2 and Rackspace, is referred to as infrastructure as a service (IaaS). With IaaS, each physical machine that a cloud provider hosts is virtualized using a hypervisor, such as Xen Server. Such virtualization makes it feasible for each physical machine to host multiple virtual machines (VMs), and computing resources are leased to cloud users in the form of these VMs. By migrating from traditional in-house server infrastructures to cloud computing, cloud users may trade a significant amount of up-front investment costs to the ongoing costs of using resources provisioned ondemand by IaaS cloud providers. In return, IaaS cloud providers are able to charge their users for using computing resources on a "pay-as-you-go" basis.With multiple IaaS cloud providers available to the cloud users, one of the ways they may differentiate themselves with is their pay-as-you-go prices of using VMs for an hour, and such prices reflect the quality of their services. For example, as of March 2013, for each VM with four CPU cores, Amazon EC2 charges $0:24 for an hour of usage (called large on-demand instance) [1], and GoGrid charges $0:32 [2], and Rackspace charges $0:48 [3]. Since a user's cloud service demand may be satisfied by any of these IaaS cloud providers, a rational user will choose the one that maximizes its own net reward, i.e., its utility obtained by choosing the IaaS cloud service minus its payment. The utility of a user is not only determined by the importance of the task (i.e., how much benefit the user can receive by finishing this task), but also closely related to the urgency of the task (i.e., how quickly it can be finished). Thesame task, such as running an online voice recognition algorithm, is able to generate more utility for a cloud user if it can be completed within a shorter period of time in the cloud. Since the diversity among IaaS cloud providers will lead to different net rewards, multiple IaaS providers form a market to compete for cloud users. Existing real-world measurement results [4] reveal that different IaaSproviders complete tasks with different completion times, and an IaaS provider can become less competitive with an inappropriate price setting. With different price settings, payments made to finish each benchmarking task are also different across different providers. As a consequence, the IaaS cloud providers are
presented with a question: How can each provider compute the optimal price to maximize its profit in such a competition market, in which demands from cloud users are sensitive to both the finishing time and the payment of completing a task?

It turns out that answering this question is nontrivial. On one hand, IaaS cloud providers may wish to increase the price to generate more profit. On the other hand, increasing the price too much in a competitive environment may risk losing potential cloud users, which then results in a reduced amount of profit. Further, although reducing the price should intuitively be an effective way to attract cloud users,these users may overwhelm the IaaS cloud provider due to an unreasonably low price, which then leads to longer finishing times on the tasks to be completed. As a consequence, the reduced utility will prohibit future users to choose this cloud provider.In this paper, we take the first step to study the price
competition in a cloud market formed by multiple IaaS cloud providers. More specifically, we present an in-depth analytical study on the monopoly, duopoly, and

oligopoly markets, in which multiple IaaS cloud providers are competing with one another. We use an M/M/1 queue to model correlations among the expected task finishing times,an IaaS cloud provider's resource capacity, and the request rates from cloud users. Since the pricing strategy of a cloud provider depends on its competitors, we take a gametheoretic perspective to study the strategic situation. To our knowledge, this is the first study that discusses the competition among IaaS cloud providers in the context of oligopoly market competition.In this paper, we take the first step to study the price competition in a cloud market formed by multiple IaaS cloud providers. More specifically, we present an in-depth analytical study on the monopoly, duopoly, and oligopoly markets, in which multiple IaaS cloud providers are competing with one another. We use an M/M/1 queue to model correlations among the expected task finishing times,an IaaS cloud provider's resource capacity, and the request rates from cloud users. Since the pricing strategy of a cloud provider depends on its competitors, we take a gametheoretic perspective to study the strategic situation. To our knowledge, this is the first study that discusses the competition among IaaS cloud providers in the context of oligopoly market competition.Our original contributions in this paper hinge upon the sufficient conditions we have derived for the existence of a Nash equilibrium in the market. By analyzing the Nash equilibrium, we make the following observations. First,when multiple IaaS cloud providers compete for users, the cloud provider with a larger resource capacity is able to charge a higher price and take more cloud users in equilibrium. However, its profit will not monotonically increase with larger resource capacities, due to increasing operating costs. As a result, though increasing the resource capacity is an effective way for a cloud provider to become more competitive in the market, it can only increase its expected profit to a certain extent. If we take service-level objectives, security measures, reputation and brand into consideration, increasing the capacity of a datacenter may become even less effective. Second, the equilibrium price is found to be sensitive to the importance as well as the urgency of tasks of cloud users: it decreases with the importance and increases with the urgency of tasks. This motivates the use of service-level objectives for cloud users to further specify the importance and urgency of their tasks.Third, the equilibrium prices are not always socially optimal. Finally, we propose iterative algorithms to find equilibrium prices in the duopoly and oligopoly markets,respectively, both of which are shown to be converging rapidly to the equilibrium.The remainder of this paper is organized as follows: We show the originality of our work in the context of related work in Section 2. In Section 3, we first formulate the competition market and present our model, and then begin our analysis with the monopoly problem, which serves as the baseline for our comparisons. In Section 4, we analyze the competition between two IaaS cloud providers with heterogeneous users, and propose an iterative algorithm to find equilibrium prices. We also study the corresponding social welfare problem. We extend our discussion to an oligopoly market in Section 4.2, and propose an algorithm to find Nash equilibrium prices for each cloud provider.Section 5 shows some characteristics of Nash equilibrium prices with extensive simulations. In Section 6, we conclude the paper with extensive discussions on other important factors that influence the pricing strategies in a cloud market.

2 RELATED WORK

Considerable performance differences across cloud providers have attracted a substantial amount of research attention.Hong et al. [5] and Tsakalozos et al. [6] applied dynamic programming and microeconomics, respectively,to achieve optimal resource allocation for cloud users in VM-based IaaS clouds, with full awareness of different prices harged by cloud providers.Existing papers were concerned with the problem of how optimal pricing in the cloud can be achieved. To find the optimal price for a caching service in the cloud, Kantere et al. [7] modeled the correlation between user demand and the price, and proposed a dynamic pricing scheme to maximize the cloud provider's profit. Teng and Magoules [8] and Mihailescu and Teo [9] studied optimal pricing with an auction mechanism, in which users had budgetary and deadline constraints. Our previous work [10] considered an exchange-based market for VMs, and proposed a solution based on Nash bargaining games. Xu and Li [11] used a revenue management framework to maximize a cloud provider's revenue with dynamic cloud pricing. Our work in this paper differs substantially from previous papers.First, all previous works considered the pricing of one provider alone, but our focus in this paper is how optimal pricing can be determined in a competitive environment with more than one cloud provider. Second, most previous models assume that the price is a certain function of user demand, which has not been validated in measurement studies. In contrast, we make the more realistic assumption that user demand at each cloud provider remains unknown, and is subject to a game-heoretic analysis in a duopoly or oligopoly cloud market. Price competition has been an active research topic in the context of economic markets with multiple service providers. Petri et all have studied the effects of risk in service-level agreements (SLAs) in service provider communities.Chen and Frank have presented an analysis of the equilibrium price in a monopoly market and they have also discussed equilibrium prices in a duopoly market with varying demand. Allon and Federgruen examined the scenario that multiple providers competed for users using different prices and time guarantees. The competition game among multiple resource providers was also considered in networking research. Anselmi et al. studied a congestion game with multiple links, each of which was under the control of a profit maximizing provider. In the context of processor sharing queues, they discussed the existence and efficiency of oligopolistic equilibria.Similar to these existing works, we are also interested in the existence of Nash equilibria in the cloud market with multiple IaaS cloud providers. Yet, the context of our study is price competition in a cloud computing environment,which has a different system model. In our model, each cloud user is associated with a different request rate as it is served by the cloud, and such heterogeneity in per-user request rates makes our analyses much more challenging.

3 MODEL FORMULATION AND MONOPOLY ANALYSIS.

To begin with, we present our system model in the context of IaaS cloud providers, and establish important results with respect to monopoly pricing, which, while being the most elementary in our analyses, provides us with a solid understanding toward our main analytical results that follow.

3.1 System Model.

In this paper, we are concerned with a market with multiple IaaS cloud providers, who are competing for cloud users.Each cloud provider is modeled by an M/M/1 queue,serving a common pool of potential cloud users with one “super” server, which combines the resource capacity of multiple physical servers that the provider manages. When it comes to analyzing the response time exhibited when processing requests as afunction of the computational capacity and the request arrival rate, the M/M/1 queuing model has been adopted by a number of existing papers in the literature that analyzed datacenter operations. The resource capacity of each cloud provider i is represented by its service rate is used to denote the operating cost at cloud provider i, which is assumed to be a function of its resource capacity. For users who would liketo choose the cloud service, the IaaS cloud provider will charge a fixed per-time-unit usage price for each type of resources consumed to finish their tasks.All operational IaaScloud providers support on-demand pricing for users to use cloud computing resources. Ondemand pricing allows users to pay for the amount of resources consumed to complete their tasks with no longterm commitments. With this pricing scheme, cloud providers charge users based on the amount of resources consumed to complete their tasks. As a result, we use to denote the fixed usage price per resource unit—for example, a unit of CPU time when using a virtual machine—at an IaaS provider i for a type of resource r. As we will focus on the price competition among multiple IaaS providers for a given type of resource, the indices r will be dropped for simplicity.The arrival of requests from cloud users is assumed to follow a Poisson process, an assumption that is commonly used in competition models in the economic literature. A cloud user j makes a choice to be served by a specific cloud provider. Yet, it also maintains a reservation value v (assumed to be the same across all users), and if by using the cloud service its net reward falls below v, user j can refuse to use any cloud service, and choose to finish its task locally. As shown in Fig. 1, a user j has a task with requests for resources that it wishes to finish in the cloud. The rate at which these requests are generated when running the task at a cloud provider is denoted by. The market share of a cloud provider i is denoted by fi, which equals the sum of request rates of all users who choose cloud provider i. Each cloud user only selects one of the IaaS cloud providers, i.e., it does not split its requests by routing them to multiple IaaS providers simultaneously. Since the cloud provider i is modeled as an M/M/1 queue with a service rate _i, based on queuing theory the expected finishing time experienced by a request from one of the cloud users (called response time in the queuing theory literature), including both the time waiting in the

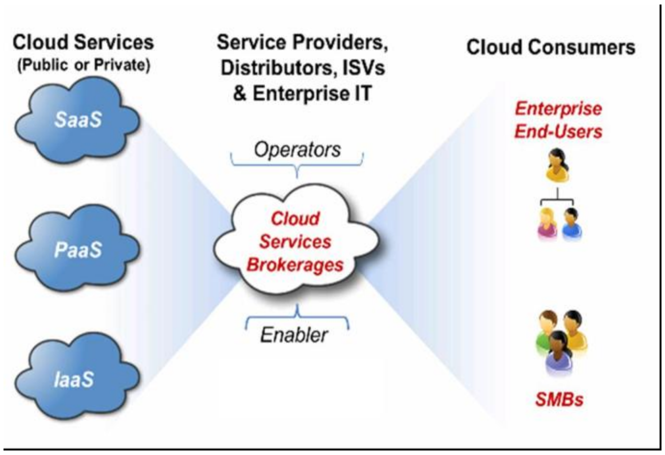

Fig. 1. Our model of competition in an oligopoly cloud market with multiple IaaS cloud providers

3.2 An Analysis of Monopoly Pricing

We are now ready to present our analytical results on monopoly pricing, which serve as preliminaries and a basis for later comparisons. In this section, we consider a single cloud provider modeled by an M/M/1 queue, with a service rate _ and an operating cost .A rational cloud user j will seek to maximize its expected net reward by finishing the task, i.e., its utility obtained by choosing the cloud service minus its total payment. Since cloud users are charged based on how much resource they consume, cloud user j’s total payment. Now that there is only one cloud provider in the market, this implies that the cloud user will choose to use the cloud service if v and refuse to use it otherwise. In equilibrium,

4 PRICE COMPETITION AMONG MULTIPLE IAAS CLOUD PROVIDERS.

4.1 The Duopoly Case

As a starting point, we first consider the case of a duopoly cloud market, in which two IaaS cloud providers compete with each other, with a similar game theoretic analysis as the monopoly case. In this context, we derive the relationship between the equilibrium prices for each cloud provider, and analyze the comparative statics of Nash equilibrium prices. We first discuss how decisions are made by cloud users in this market. All cloud users act in a selfish fashion so as to maximize their own expected net reward. The optimal choice of cloud user j is to choose the cloud provider i from which it obtains a maximized net reward, or to refuse to use the cloud service if its net reward failed to exceed its reservation value. That is, a cloud user j will choose a cloud provider i (or the option of choosing neither cloud provider) that achieves

4.1.1 Nash Equilibrium in a Duopoly Market

Let be the expected profit of cloud provider i. Each cloud provider i seeks to maximize by choosing its usage price hich clearly depends on the reaction of the other cloud provider and that of all cloud users. Let denote the expected profit of cloud provider i if it chooses a price pi given the other cloud provider k's price and A pair of prices is said to be a Nash equilibrium if it satisfies:In a Nash equilibrium, any cloud provider cannot increase the expected profit by changing its price unilaterally.That is equivalent to say, the Nash equilibrium price is the optimal price a cloud provider can achieve in a market when cloud providers do not cooperate with each other. In the equilibrium, the expected profits of both cloud providers are maximized, and the market is balanced dynamically. In our subsequent analysis, we aim to prove whether such equilibrium exists in the duopoly market, and how can each cloud provider achieve the equilibrium price if it exists.The equilibrium prices can be found by a standard procedure of identifying the best response function of each cloud provider. Let be cloud provider i's optimal price given the usage price pk selected by cloud provider k.

A Nash equilibrium in this duopoly competition market is then a pair of prices ðp1; p2Þ such that and an intersecting point of two best response functions. Take cloud provider 1 as an example. The best response function F1 can be found by assuming that cloud provider 2's price p2 is given and by solving cloud provider 1's problem as follows where Pij is the total payment user j makes to cloud provider i. Both constraints (10) and (11) come from optimizing cloud users' net rewards. Constraint (10) indicates that for any user to choose cloud provider 1, it should be offered at least the same expected net reward as its reservation value of the task.If this constraint does not hold, the cloud user would prefer to finish its task locally rather than using the cloud service.Constraint (11) states that in equilibrium, the expected net rewards that a cloud user can derive from different cloud providers should be the same, which prohibits any cloud user from switching cloud providers.Similarly, the optimal price of cloud provider 2 can be found by solving its corresponding problem, under the assumption that the price of cloud provider 1, p1, is given Each cloud provider will update its prices with respect to the reaction of its competitor and all cloud users, until an equilibrium point is reached, i.e., when neither cloud provider can gain a higher expected profit by changing its own price unilaterally.When cloud users are charged based on their usage of resources, the problem of finding cloud provider 1's best response function (9) is equivalent to By considering the best response problems of both cloud providers together, we derive the necessary condition for the existence of a Nash equilibrium. Any equilibrium must satisfy the following constraints, referred to as the firstorder necessary condition for the existence of a Nash equilibrium, as summarized in Lemma 1.

4.1.2 Nash Equilibrium in a Duopoly Market with Homogeneous Cloud Providers

In the homogeneous case that two cloud providers have the same resource capacity, the next theorem establishes the result that a unique Nash equilibrium exists in the duopoly converges to the same price for both cloud providers. It can be derived by solving the optimization problem in Theorem 1.

Proof. When the two cloud providers are equivalent to each other in service rate, i.e., the two cloud providers are indifferent to the cloud users, which implies that the equilibrium solution is symmetric. According to Theorem 1, we have

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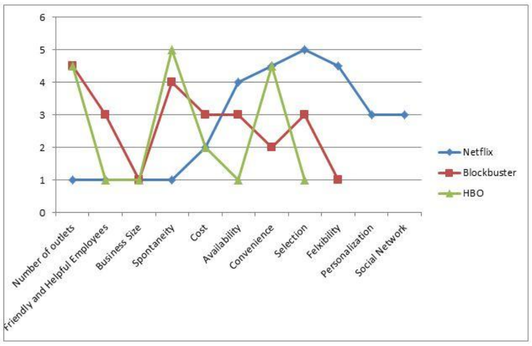

Fig. 2. The convergence of usage prices.

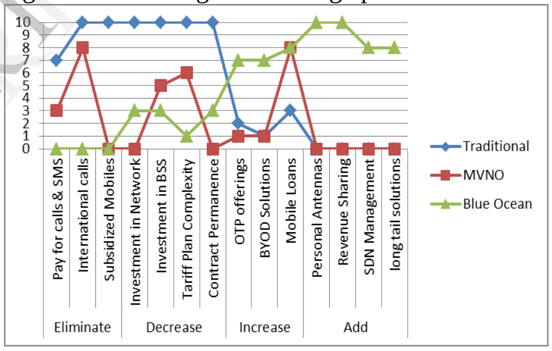

Fig. 3. The convergence of market shares.

The comparative statics of the equilibrium price are illustrated in Fig. 4. As we can see, they conform with most of our intuitions. A cloud provider will raise the usage price with an increase in the users' benefit factor r and its resource capacity _, and reduce the price in response to an increase in the waiting cost factor c and the reservation value v. Since the benefit factor r reflects the importance of the task and the waiting cost factor c represents its urgency, this implies that the more important the task is, the more the cloud provider will charge the user; the more urgent users view the task, the less the cloud provider "dares" to charge to win the "deal" from users. The rationale is that if the cloud provider knows that the task is important to the user, i.e., the user will gain substantial benefit by completing the task, the cloud provider will infer that the user is willing to pay more to finish the task, and hence ask for more. Yet if the task is urgent, the cloud provider will tend to ask less to make up for its limited resource capacity.In addition, if the cloud provider is able to increase its resource capacity _ by investing in new servers or by upgrading its current facilities, it will be able to ask more for the improved service quality. In the figure, we can see that when the resource capacity is small, the demand will be relatively strong compared to the resource capacity, which results in a noncompetitive environment in the market.Increasing the resource capacity slightly results in a rapid increase of usage price. Finally, in cases when users have a higher reservation value v and thus may refuse to use the cloud service with a higher probability, cloud providers will have to reduce their prices to attract users.The market size _ will affect the usage price in a more complicated way. When the resource capacity is large enough, i.e., the cloud provider will raise the price when the market size increases, until it reaches a certain threshold, for example,4:6 in the figure. If the market size continues to increase, users will overwhelm the cloud providers and may experience longer task finishing times.Cloud providers will reduce the price to compensate for the increased waiting costs. However, if the resource capacity is small, i.e., the market is again in a noncompetitive environment, which results in the fact that price increases with a larger market size.

4.1.3 Social Welfare Problem in the Duopoly Market

We have previously analyzed the Nash equilibrium prices in a competition market with two cloud providers. In equilibrium, each cloud provider's price is determined by its best response function to the other cloud provider's price. In other words, prices are optimized for cloud providers only, with no direct implication that all cloud providers and users will reach an outcome that is socially optimal. A choice of prices one by each cloud provider is socially optimal if it maximizes the sum of payoffs to all participants. In the cloud market, it implies a set of equilibrium prices at which the payoffs of both cloud providers and cloud users are maximized. A cloud user j's payoff for being served by cloud provider i is its expected net rewards with a request rate of and a usage price pi, a cloud provider i's payoff in this market equals its expected profit, which is. Therefore, the social welfare is In the social welfare problem, prices are simply an internal transfer of wealth and hence are not considered as objective variables. Our interest is how cloud users are distributed between two cloud providers to maximize social welfare. Though we hope that the duopoly equilibrium prices are also socially optimal, our analysis shows it is not always the case.

Due to space constraints, we provide a detailed proof in our supplementary technical report.Though the conclusion that the social welfare maximizing solution is not the same as the market shares in equilibrium is not a surprise, it is not intuitive either. More importantly, a Price of Anarchy of 0 can be achieved in a homogeneous duopoly, which means that the social welfare maximizer also reflects the equilibrium market share.

4.2 The General Case.

Based on our game theoretical analysis of price competition in the monopoly and duopoly cloud markets, we now proceed to consider the general case when multiple cloud providers are competing with one another. Our analyses will show that a unique Nash equilibrium exists in an oligopoly cloud market. We will also present an iterative algorithm to compute the equilibrium prices based on our analyses.

4.2.1 Cloud Provider 's Problem in an Oligopoly Market

From our previous analysis in the duopoly market, we can see that the market share of each cloud provider is not only affected by the cloud provider's own price, but also the other cloud provider's pricing choice, which are both variables to be determined. In a market with multiple cloud providers, the usage prices will influence each cloud provider's market share in a highly complicated way, and due to this reason we are not able to get the exact analytical presentation. As an alternative, We apply the multiplicative competitive interaction (MCI) model to capture the relationship between usage prices and market shares in an oligopoly market. Proposed by Bell etal.the MCI model is widely used in economic competition markets. To be specific, the market share of each cloud provider in a market with N cloud providers is assumed to take the following form where ti represents the expected finishing time of a unit request experienced at cloud provider i, including both the waiting time in the queue and the service time. The numerator , with a; b _ 0, represents the attraction of cloud provider i, which corresponds to how cloud users feel toward its service given its usage price, expected finishing time, and other competitive factors, for example,API, load balancing, and reputation. The parameter a and b are referred to as the price attraction factor and the finishing time attraction factor, respectively. The parameter Li > 0 represents the combined effects of other competitive factors, with a larger Li reflecting a higher degree of attraction to cloud users. Cloud provider i's market share is given by its relative attraction to all cloud providers in the market. In subsequent analyses, we choose a ¼ b ¼ 1for simplicity.

Based on queuing theory, the expected finishing time t of a single request, including both the waiting time and the service time, equals in an M/M/1 queue. Note that in a cloud environment, for a given resource capacity at cloud provider i, the expected finishing time is a function of its market share fi, which is determined by the cloud provider's usage price. As a consequence, if we use to denote the combined attraction of cloud provider i's competitors, the market share of cloud provider .Expressed as a function of usage prices, the market share of cloud provider i, fi, is in a much more complicated form than that in typical economic papers in the literature discussing price competition, and this makes our subsequent analyses substantially more challenging.Again, the objective of cloud provider i is to find the best response function that maximize its expected profit, taking into consideration the usage prices set by other cloud providers. Mathematically, the problem faced by cloud provider i can be formulated as the following

4.2.2 Nash Equilibrium in an Oligopoly Market

In an oligopoly market with N cloud providers, the N-tuple price vector is called a Nash equilibrium if for each cloud provider is the best response to price chosen by all other firms j 6¼ i. In other words, the Nash equilibrium implies that no single cloud provider can benefit by deviating from this equilibrium point unilaterally.By solving problem,cloud provider i is able to compute its optimal price pi based on the combined attraction of its competitors, which in turn can be computed using the current prices of other cloud providers j 6¼ i. With the idea of solving this problem in an iterative fashion, we have designed the following iterative algorithm, Algorithm 2, to compute the Nash equilibrium price for each cloud rovider.

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Algorithm  2. Compute the Nash equilibrium price for cloud  provideri in an oligopoly market.
1: (Initialization). Each cloud provider i sets the usage price to be a very small value pi ¼ _0.
2: (Iterative step).
3: for cloud provider 1 to N do
4: Each cloud provider i computes the optimal price pi by solving problem (23) using the current values pj of other cloud providers j 6¼ i, and updates the price pi.
5: end for
6: (Convergence criterion). Repeat the iterative step until price pi differs from its previous value by less than some predetermined value
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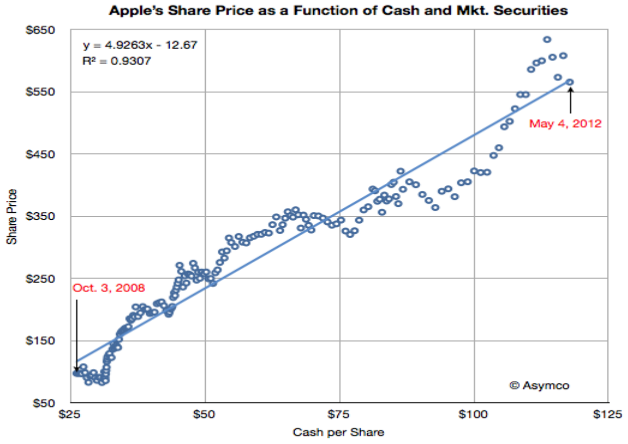
In subsequent analyses, we are going to show that a unique Nash equilibrium exists in a price competition market with multiple cloud providers, and the above iterative algorithm always converges to this equilibrium solution. This is fairly significant, in that if the required information in Algorithm 2 is available, we now have an algorithmic tool to compute the unique Nash equilibrium.We first present a necessary result that is useful to derive the key results in Lemma 3.



Apple		Google	
Today's close	$ 633.68	Today's close	$ 632.32
Change	+9.37 +1.50%	Change	-2.83 -0.45%
Day low	Day high	Day low	Day high
$623.40	$634.66	$628.57	$636.43
Open: 626.98		Open: 632.24	
52 week low	52 week high	52 week low	52 week high
$310.50	$634.66	$473.02	$670.25
Market cap	$582.09B	Market cap	$206.51B

Fig. 4. Effects of resource capacities on a cloud user's equilibrium priceand its market share.

By comparing with results in Theorem 2, we can see that the Nash equilibrium in an oligopoly market is in the general form of that in a duopoly market. All cloud providers in the market will charge the same price that has the form of the monopoly price p_, with each of them taking 1=N of the market. In other words, each cloud provider will behave independently and operate exactly the same as a monopolist, when all of them have the same resource capacity. The comparative statics of the homogeneous Nash equilibrium price in an oligopoly market is the same as what was shown in Corollary.

5 EVALUATION

We now present our evaluation results based on simulations,on how the Nash equilibrium is influenced by both cloud providers and cloud users. From the cloud providers'perspective, we study the effects of resource capacities on equilibrium prices. On the cloud users' side, we show how the task importance and urgency can influence the equilibrium prices of the cloud service. The design of our simulator is based on a time-slotted synchronous model,with all events generated and processed in their respective time slots. Our simulator is developed in the MATLAB environment.

5.1 Analyzing the Nash Equilibrium in a Duopoly Market

We begin our evaluation with two cloud providers competing in the market. Since the proposed algorithm is shown to be able to find the Nash equilibrium prices within a small number of iterations, the equilibrium prices in each simulated scenario are obtained by Algorithm 1. Our simulation results have further validated our analytical results in Section 4.We assume that there are 20 cloud users in the market,i.e., M ¼ 20. Except otherwise specified, the resource capacity of each cloud provider is set to be _1 ¼ 2 and _2 ¼ 4; the operating costs _1ð_1Þ and _2ð_2Þ are set to be 0 to focus only on the price competition; the reservation value v is set to be 1; the benefit factor r is set to be 5; and the waiting cost factor c is set to be 1 for all cloud users.User j's request rate _j for the cloud service is uniformly random in as the total request rate has to be smaller than the total service rate to avoid an unlimited queuing delay.Effects of resource capacities on equilibrium prices. We first study how a cloud provider's resource capacity ,will affect the Nash equilibrium prices. In this scenario, _1 is set to be 2, _2 > _1 and their ratio is assumed to range from 1 to 4. Fig. 4 shows how the Nash equilibrium price and the market share of cloud provider 2 react when its server capacity increases, while that of cloud provider 1 remains the same. As we can see, both the usage price and the market share increase with the resource capacity. To further understand the impact of resource capacities on both cloud providers, we compute the ratio of Nash equilibrium prices as well as the ratio of market shares of the two cloud providers. Our results in Fig. 7 show that, when resource capacities change while other characteristics remain constant,the comparative advantage of cloud provider 2 to cloud provider 1 on both price and the market share also increases, which further proves the importance of the resource capacity.

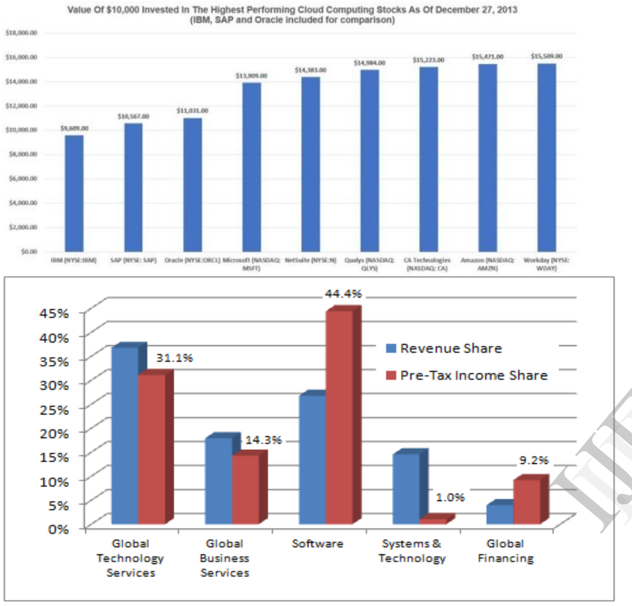


Fig. 5. Effects of resource capacities on the ratio of equilibrium prices And market shares.

toward the service of a cloud provider, including alternative influential factors such as whether the application programming interface (API) is secure and easy to use, how load balancing is to be performed, as well as the reputationand brand of the cloud provider. As the final experiment in this section, we are interested in investigating the combinedeffects of these alternative factors. We use two cloud providers as an example, with resource capacities 1 ¼ 150 and _2 ¼ 500. Fig. 6 shows when the ratio of varies from 0.1 to 1, how relative differences of their usage prices,their market shares, and their expected profits change accordingly. As the ratio becomes smaller, it represents the fact that the provider with a larger capacity has become less attractive to cloud users due to the combined effects of the alternative factors. As we can observe from the figure, being less attractive to cloud users does not affect the usage prices, as the two cloud providers have the same prices over the entire range of ratios (i.e., the relative difference remains zero). That said, as the provider with a larger capacity has become less attractive due to alternative factors, both its market share and its expected profit decrease significantly, to the point that they can be smaller than its competitor with a third of the capacity. This implies that if a cloud provider wishes to keep its competitive edge, it needs to become more attractive with respect to alternative quality factors, such as its reputation and brand. We will discuss more implications in our concluding remarks.

6 DISCUSSIONS AND CONCLUDING REMARKS

In this paper, we have studied the problem of price competition in a market with multiple IaaS cloud providers.In particular, we have focused on answering the question When multiple IaaS providers face a common pool of potential users, how should each one of them choose the optimal price that maximizes its own profit? Intuitively, if prices are set to be too high, cloud users will choose alternative cloud providers; but if they are too low, the overwhelming demand for resources from a large number of cloud users may increase the task finishing times, therefore negatively affecting the performance of cloud applications and the utility of cloud users. By modeling each provider as an M/M/1 queue, we analyze this problem using a game theoretic technique in monopoly, duopoly and oligopoly markets. We have derived the sufficient condition for the existence of a Nash equilibrium and propose two iterative algorithms for each provider to find its equilibrium price in the duopoly and oligopoly market,respectively. Our algorithms represent a first step toward designing practical mechanisms to price resources in operational IaaS cloud providers, and are shown to converge quickly.One important question that is closely related to our analyses and evaluation remains: What an IaaS cloud provider, either an established one or a new player making its market debut, should do to attract new customers and to stay competitive? By analyzing the Nash equilibrium in an oligopoly market where multiple IaaS providers compete,our evaluation have pointed to some intriguing observations that are worth discussing.At a first glance on our evaluation results, to become more competitive in the market and to gain a larger market share, a cloud provider may initially choose to increase its resource capacity. Yet, the total cost of ownership (TCO),including capital expenses (CAPEX) and operating expenses (OPEX), escalates as cloud providers add to their resource capacities. Such escalating costs may become an important contributing factor that leads to much smaller marginal gains, or even marginal losses, in profits at the IaaS cloud providers.

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