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The Effect of Competition among Brokers on the Quality and Price of Differentiated Internet Services

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Abstract

Price war, as an important factor in undercutting competitors and attracting customers, has spurred considerable work that analyzes such conflict situation. However, in most of these studies, quality of service (QoS), as an important decision-making criterion, has been neglected. Furthermore, with the rise of service-oriented architectures, where players may offer different levels of QoS for different prices, more studies are needed to examine the interaction among players within the service hierarchy. In this paper, we present a new approach to modeling price competition in (virtualized) service-oriented architectures, where there are multiple service levels. In our model, brokers, as the intermediaries between end-users and service providers, offer different QoS by adapting the service that they obtain from lower-level providers so as to match the demands of their clients to the services of providers. To maximize profit, players, *i.e.* providers and brokers, at each level compete in a Bertrand game while they offer different QoS. To maintain an oligopoly market, we then describe underlying dynamics which lead to a Bertrand game with price constraints at the providers' level. Numerical simulations demonstrate the behavior of brokers and providers and the effect of price competition on their market shares.

Keywords: Service-oriented architecture, Quality of Service (QoS), oligopolistic competition, service differentiation, Bertrand competition, price constraints.

I. INTRODUCTION

In today's highly competitive Internet service market, service providers, in order to survive, should offer their customers more flexibility in their quality-of-service (QoS) / price offerings to meet a variety of customer needs and application constraints. Clearly, any successful solution for a service provider to stay in the market, not only depends on supporting new and updated technologies, but also involves economic aspects. However, pricing the services of the network, even without considering quality differentiation, is a challenging problem that involves different issues. There have been many studies that attempted to address these issues with or without considering differentiated QoS. Pricing approaches include Paris Metro pricing [29], congestion pricing [7, 15], rate-reliability pricing [19], and fairness pricing [18]. On the other hand, with the rise of service-oriented architectures, such as computational clouds and recursive networks [36], and network virtualization such as CABO [10] and also with the increasing number of service brokerage companies such as Google in "Project Fi" [14], there is a need for more advanced solutions that manage the interactions among service providers at multiple levels. The ultimate goal in service-oriented architectures and network virtualization is to decouple the services offered by network providers from those of service providers which yield the layered structure of the network. Also, brokers as the intermediaries between clients and lower-level providers, play a key role in improving the efficiency of service-oriented structures by matching the demands of clients to the services of providers. They can downgrade or upgrade a service by sharing it among customers or by combining several services to satisfy customers' demand. For example, in "Project Fi"[14], Google offers a flat data rate of \$10 per gigabyte of data that is provided by either T-Mobile or Sprint, *i.e.*, Google selects the best network provider based on factors such as coverage and performance, thus adding flexibility and providing the best service to its customers. Furthermore, Project Fi customers can manage their costs based on their monthly needs. This

is in contrast to network providers, *e.g.*, T-mobile and Sprint, which offer their customers fixed data plans regulated by a static contract.

In this study we propose a multi-layer network market in which service brokers and service providers compete at different levels in an oligopoly to maximize their profit. In our settings, brokers can pay a cost to upgrade or downgrade the service that they buy from (lower-level) providers so as to offer a new service to the market (customers). The broker incurs costs when adapting a lower-level service as it expends resources to either enhance the service extended to its customers (*e.g.*, by employing delay-jitter reduction or capacity allocation techniques over a best-effort service) or degrade it (*e.g.*, by multiplexing client demands over a guaranteed service). We consider the competition among providers and among brokers separately, while brokers impose some preference constraints on (infrastructure, cloud or service) providers. We also consider conditions that may lead to a monopoly market and study how players act under such conditions. We model service quality differentiation after Hotelling's location model — [17], where firms compete and price their products in only one dimension, geographic location. In our model, brokers and (lower-level) providers compete and price their services based on the quality of the service that they offer. Our numerical results show that more service differentiation generally yields more profit for all players. However, besides quality differentiation, the cost that brokers undergo also plays an important role and they should forgo maximum differentiation to reduce the cost, which leads to higher profit. Also, as the number of brokers increases, the market gets more competitive and prices drop further.

Our contributions in this paper are as follows: we model a two-layered network market in which providers and brokers offer differentiated services and compete in a Bertrand game at each layer following the Hotelling's location model. We also analyze the actions of players under a monopoly setting. In Section II we review related work, and then in Section III, we develop a game-theoretic model by characterizing the competitive behavior of players with one another at each level of the service hierarchy. Section IV presents our analysis and numerical results when only the interaction of two brokers is captured in the model, while in Section IV-C we show how our model is useful to capture interactions among more brokers, dissecting two more case studies where we consider three and four brokers. Finally, in Section V we conclude the paper.

II. RELATED WORK

Game theory has been applied to a wide range of networking problems to capture the interaction of (selfish or cooperating) players seeking a maximum value for their (private) utility. The assumption is that every step (or move) toward the maximization of such utility impacts the utility of other players in the model (or game). Given the connectivity nature of a network of agents, a wide range of networking mechanisms have been modeled with game theory; from the physical ISO-OSI layer with transmission power utility games [5] or spectrum sharing [2, 35] to Medium Access Control [37] to routing and packet forwarding [4, 30], both in wireless [23] and wired [28] scenarios.

Aside from modeling multi-agent protocol behaviors and the various resource allocation mechanisms, markets and pricing equilibrium have further exemplified the synergy between game theory (and economics) and networked (cloud) systems [21, 31]. In particular, network economics has been a very active research area in which both pricing and market regulation strategies have been studied widely. However the exponential growth of Internet services in hierarchical (*i.e.*, multi-layer) markets requires a deeper study of new market features that will become available. One of the earliest work on layered networks, [13] identifies and discusses some difficult economic problems related to resale and complexity of competition among multiple owners of physical networks. The authors study some integrated and unintegrated telecommunication companies and the services that they offer to create differentiated products to cover their costs. The paper does not suggest any specific architecture or policies for pricing, but discusses the need for a full economic model that features oligopolistic competition among a few large companies that invest in the physical infrastructure as well as firms at the virtual network level.

Our work is inspired by Zhang *et al.* [39] and Nagurney and Wolf [27]. They propose an economic model for the interaction and competition among service providers, network providers and users. Both

studies develop a two-stage (Stackelberg) game, where service providers compete in a Cournot game, and network providers compete in a Bertrand game. Stackelberg games have also been proposed in other networking contexts, *e.g.*, in Wi-Fi scenarios [38]. In our framework, providers at all levels compete in Bertrand games (*i.e.*, competition on price). Although our work shares the same two-level game with [27, 39], Zhang *et al.* [39] study a market with two service providers and two network providers offering the same level of service quality. In [27] the authors consider a market with more than two providers for service and network, in which network providers offer different levels of service quality. In their model, the market is managed through the demand-price functions, which depend on both quality and quantity. Our model considers a market where at the providers' level, players can offer different qualities of service, while at the brokers' level, players can upgrade or downgrade the service to optimize their profit. Semret *et al.* [34] also consider a retail market where, for each network, three types of players interact: a service provider, a broker and end-users. However, their main contribution is a decentralized auction-based bandwidth pricing for differentiated Internet services; the authors show that Progressive Second Price (PSP) provides a stable pricing in a market where service providers receive most of the profits and the brokers' profit margin is small.

Pricing for single-level games has been studied even more extensively than two-level games. He and Walrand [16] consider a self-regulated service model, where market demand determines the service quality. In their model, there is a single Internet Service Provider (ISP) who offers two classes of service with different prices to manage congestion. The authors show that when the price does not match the service quality, the system may end up in an equilibrium similarly to the Prisoner's Dilemma game. Shetty *et al.* [35] also compare the revenue of a monopolist operator with and without service differentiation. They show that the revenue is higher when an operator offers two different services. Both Li *et al.* [20] and Fulp and Reeves [11] provide a traffic-sensitive pricing scheme for differentiated network services. The focus of [11] is on maximizing the profit of the service provider who buys a differentiated service connection from domain brokers and sells it to users; the focus of [20] instead is to provide economic incentives to users so as to maintain a given level of traffic load.

Different game-theoretic models for differentiated service markets of users and service providers have also been proposed [1, 22, 26]. In [26], the authors propose a game-theoretic model where service providers compete with duration-based contracts for differentiated service. Instead, [1] considers a joint price-quality market with a Stackelberg game where providers are leaders and users are followers. In their model, providers consider the migration of users when setting their price and quality. Finally, the authors in [22] study a congestion-prone market with usage-based pricing. They propose a model for users' preference over their value and sensitivity to congestion, and based on such model they characterize the market share and optimal price for providers.

Our model considers multi-layer differentiated service games where the service obtained from the lower level can be upgraded or downgraded, and hence can be sold to the higher level provider. In our analysis, we apply price constraints when players' optimal price would lead to losing market share, and we also give insights on how players should then update their price.

III. MODEL AND SOLUTION

In this section, we present our model and analysis of a two-level game configuration and focus on the competition among providers and brokers and what emerges as pricing of their services. Figure 1 illustrates the game-theoretic model: At the lower level, we have two service providers, while at the higher level, we have $m \geq 2$ service sellers or brokers that deal directly with users. Note that owning a network infrastructure is expensive, and only a few large companies can afford its cost. There are however many brokerage companies. Our model's goal is limited to analyzing and understanding the dynamics of a market in a formal economic setting. To this aim, we start by considering only two network / lower-level providers in a simple oligopoly market competition. The exclusion of more complex relationships that may exist in real markets keeps our model tractable while still producing interesting results and insights.

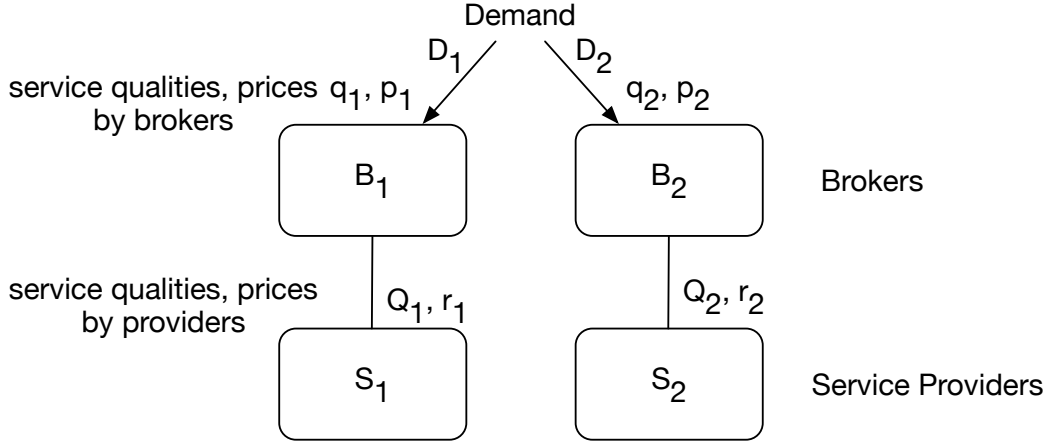


Fig. 1. Game-theoretic Model of a Two-level Competition among Brokers and Service Providers. At each level, brokers and service providers are in a Bertrand competition with each other. The set of strategies are the service prices and each player tries to maximize her revenue.

To model service quality differentiation, we adopt Hotelling's location model [6, 17] which introduced the idea of modeling difference between products as differences in a product's location in a product space. The idea is widely used for both location problems [24, 32, 33] and quality differentiation [8, 9, 25] in network studies. In Hotelling's model [17], there are two firms selling identical goods along a street. Customers are assumed to be uniformly distributed in the space, and the transport cost is a linear function of their distance to the selected firm. A consumer selects the firm that minimizes her cost of transportation to buy the product. Hotelling concluded that two firms would locate close to each other near the center. Later, D'Aspremont *et al.* [6] changed the utility function from linear to quadratic form, where firms choose to maximize their distance to the opposite player, and there is equilibrium for price competition. Brenner [3] extended the game with the quadratic cost function to more than two firms. He has shown that for more than two firms, the "principle of maximum differentiation" does not hold, and corner firms would benefit from moving marginally toward the market center. In our work, we model service quality differentiation after Hotelling's product differentiation, where customers have different preference for service quality that is modeled by their willingness to pay for that quality. We start by presenting our notation and some basic settings, then we discuss some analytical and numerical results.

A. Model Description

Let us consider a system with a continuum of customers, m service sellers (brokers), denoted by B_i , $i = 1, \dots, m$, and two service providers, S_j , $j = 1, 2$. We assume that customers have different preference for quality (utility) described by:

$$\theta q - p$$

where θ is the customer's marginal willingness to pay for quality q , and p is the price of service. There is a distribution of θ among customers. For simplicity, we assume that θ is uniformly distributed on an interval $\theta \in [\theta_{min}, \theta_{max}]$ and $\theta_{max} > 2\theta_{min}$. Customers seek a broker that maximizes their utility.

Both brokers and service providers can offer services with different qualities. The service quality offered by brokers is denoted by q_i and is in an interval $q \in [q_{min}, q_{max}]$, and the quality offered by service providers is denoted by Q_j . Also, we assume that brokers and service providers compete in an imperfectly competitive market. Furthermore, we assume that there is no supply constraint and so there are enough resources to meet each demand. We also assume that each broker buys just from one of the service providers that is more economical. Without loss of generality, we assume that B_1 buys from S_1

and B_m buys from S_2 (unless as we note in Section III-F, the market does not support this assumption) and other brokers choose the provider with the lower cost.

We assume that providers, and brokers, compete with each other in a Bertrand game. In a Bertrand game, players compete on the price based on their cost and other market information. We analyze the market at the Nash equilibrium point where the market is in steady state and no player intends to change her price.

B. Demand Distribution

Brokers first choose the quality of service that they will provide to customers, then they compete on prices. If the brokers choose the same quality, then the customers decide only based on the price, and this leads to a Bertrand competition with identical goods, whose prices should be set equal to costs, and no one makes profit. Thus the brokers should choose to offer different service qualities to make profits. Without loss of generality, we assume that $q_m > \dots > q_2 > q_1$, and also $Q_2 > Q_1$. Therefore, customers with a high willingness to pay for quality will buy from B_m , while customers with a low willingness will buy from B_1 .

For simplicity, first let's assume that we have two brokers, B_1 and B_2 . We can characterize the demand for each broker by identifying the customers who are indifferent between the two differentiated qualities. The indifferent customers, denoted by θ^* , satisfy:

$$\theta^* q_1 - p_1 = \theta^* q_2 - p_2 \Leftrightarrow \theta^* = \frac{p_2 - p_1}{q_2 - q_1} \quad (1)$$

Having uniformly distributed θ , the demand for each broker, B_1 and B_2 , is given by:

$$\begin{aligned} D_1(p_1, p_2) &= \frac{\theta^* - \theta_{min}}{\Delta\theta} = \frac{1}{\Delta\theta} \left(\frac{p_2 - p_1}{q_2 - q_1} - \theta_{min} \right) \\ D_2(p_1, p_2) &= \frac{\theta_{max} - \theta^*}{\Delta\theta} = \frac{1}{\Delta\theta} \left(\theta_{max} - \frac{p_2 - p_1}{q_2 - q_1} \right) \end{aligned} \quad (2)$$

where $\Delta\theta \equiv \theta_{max} - \theta_{min}$.

For more than two brokers, we can generalize equation (1) to find indifferent customers θ_i^* between any two brokers B_i and B_{i+1} :

$$\theta_i^* q_i - p_i = \theta_i^* q_{i+1} - p_{i+1} \Leftrightarrow \theta_i^* = \frac{p_{i+1} - p_i}{q_{i+1} - q_i} \quad (3)$$

Consequently, the demand for each broker can be found by :

$$\begin{aligned} D_1(p_1, p_2, \dots, p_m) &= \frac{\theta_1^* - \theta_{min}}{\Delta\theta} \\ D_i(p_1, p_2, \dots, p_m) &= \frac{\theta_i^* - \theta_{i-1}^*}{\Delta\theta} \quad 1 < i < m \\ D_m(p_1, p_2, \dots, p_m) &= \frac{\theta_{max} - \theta_{m-1}^*}{\Delta\theta} \end{aligned} \quad (4)$$

Note that in the above equations D_i 's assume values in the interval $[0, 1]$. This means that if for broker B_i the demand D_i is negative, then B_i is "out of the market"; more precisely, we can rewrite the demand function as:

$$D_i = \min \left\{ \max \left\{ 0, \frac{\theta_i^* - \theta_{i-1}^*}{\Delta\theta} \right\}, 1 \right\} \quad for \ 1 \leq i \leq m \quad (5)$$

C. Brokers' Profits

Now that we have the demand distribution, we can calculate broker i 's profit, assuming that converting Q_j to q_i (whether to upgrade or downgrade the service) has a marginal cost c_i :

$$\Pi_i = p_i D_i - \frac{q_i D_i}{Q_j} r_j - c_i D_i (Q_j - q_i)^2 \quad (6)$$

where r_j is the price of service that broker B_i pays to service provider S_j and $\frac{q_i D_i}{Q_j}$ is the amount of service that B_i needs to buy to supply its own market. We assume here that the cost to the broker, c_i , for converting the service quality it gets (Q_j) to that it offers its customers (q_i), is proportional to the square of the difference in quality, $(Q_j - q_i)$. Intuitively, the cost increases more rapidly as the service quality increases, or alternatively, there is a diminishing return in service quality as more resources are allocated and cost increases. We henceforth, for simplicity, assume that $c_i = c$.

As we mentioned earlier, we assume that the broker with lowest quality (B_1) buys from the lower quality provider (S_1) and the highest quality broker (B_m) buys from the higher quality provider (S_2). This is the only valid assumption to have an oligopoly market at the level of service providers. For simplicity, again let's assume that we have two Brokers. If B_1 prefers to buy from S_2 , then the cost of buying from S_2 must be less than the cost of buying from S_1 :

$$\frac{q_1}{Q_2} r_2 + c(q_1 - Q_2)^2 < \frac{q_1}{Q_1} r_1 + c(q_1 - Q_1)^2$$

Given $(q_1 - Q_2)^2 > (q_1 - Q_1)^2$, we have $\frac{r_2}{Q_2} < \frac{r_1}{Q_1}$. Thus, given $\frac{r_2}{Q_2} < \frac{r_1}{Q_1}$, and also $(q_2 - Q_2)^2 < (q_2 - Q_1)^2$, we deduce that it is less costly for broker B_2 to buy from S_2 as well, which results in a monopoly market at the level of service providers. The same logic applies if B_2 prefers to buy from S_1 , and also for general case with m brokers.

Now that we have the profit function for brokers, we can find the optimal price for them. In the first stage, given the service prices r_j , and service qualities Q_j , the brokers compete in a Bertrand game with differentiated goods. We present the results for case $m = 2$, but all of results can be calculated for general cases with more than two brokers. Plugging Equation (2) into Equation (6), and solving $\partial \Pi_i / \partial p_i = 0$ for achieving Nash equilibrium, leads to:

$$p_1 = \frac{1}{3}((q_2 - q_1)(\theta_{max} - 2\theta_{min}) + \frac{2q_1 r_1}{Q_1} + \frac{q_2 r_2}{Q_2} + 2c(q_1 - Q_1)^2 + c(q_2 - Q_2)^2) \quad (7)$$

$$p_2 = \frac{1}{3}((q_2 - q_1)(2\theta_{max} - \theta_{min}) + \frac{q_1 r_1}{Q_1} + \frac{2q_2 r_2}{Q_2} + c(q_1 - Q_1)^2 + 2c(q_2 - Q_2)^2) \quad (8)$$

Now we have the brokers' prices, p_1 and p_2 , as a function of the brokers' and providers' service qualities, and providers' prices r_j 's. The next step is to plug them into D_i 's to make demand function as a function of r_j 's :

$$D_1 = \frac{1}{3\Delta\theta}(\theta_{max} - 2\theta_{min}) + \frac{\frac{q_2 r_2}{Q_2} - \frac{q_1 r_1}{Q_1} - c(q_1 - Q_1)^2 + c(q_2 - Q_2)^2}{3\Delta\theta(q_2 - q_1)} \quad (9)$$

$$D_2 = \frac{1}{3\Delta\theta}(2\theta_{max} - \theta_{min}) + \frac{\frac{q_1 r_1}{Q_1} - \frac{q_2 r_2}{Q_2} + c(q_1 - Q_1)^2 - c(q_2 - Q_2)^2}{3\Delta\theta(q_2 - q_1)} \quad (10)$$

Now, D_1 and D_2 are dependent on service providers' prices r_j 's, which shows the interaction between the two layers. Providers' prices are part of the cost for brokers and in turn affect the price of brokers and consequently the demands of both brokers and providers. In the next subsection we show how to find the optimal r_j 's.

D. Providers' Profits

At this stage, we have the total demand served by (service sold by) each broker. To have an imperfectly competitive market at the level of service providers, the combination of their price and quality should be such that each broker prefers a different service provider. Assuming B_1 prefers S_1 and B_2 prefers S_2 , the following inequalities should hold for B_1 and B_2 , respectively:

$$\begin{aligned} \frac{q_1}{Q_1}r_1 + c(q_1 - Q_1)^2 &< \frac{q_1}{Q_2}r_2 + c(q_1 - Q_2)^2 \\ \frac{q_2}{Q_2}r_2 + c(q_2 - Q_2)^2 &< \frac{q_2}{Q_1}r_1 + c(q_2 - Q_1)^2 \end{aligned} \quad (11)$$

These constraints ensure that broker B_1 chooses provider S_1 and B_2 chooses S_1 , as the cost is lower than that of getting service from the other provider. Later we will discuss the situation when one of these constraints is violated.

For general case, we assume that the k first brokers choose provider S_1 and from broker B_{k+1} to broker B_m choose S_2 . Constraint (11) should be hold for B_k and B_{k+1} instead of B_1 and B_2 .

In this stage of the game, service providers compete in another Bertrand game. The profit of each provider is defined as:

$$\begin{aligned} U_1 &= \sum_{i=1}^k \frac{D_i q_i}{Q_1} (r_1 - f_1) - eQ_1^2 \\ U_2 &= \sum_{i=k+1}^n \frac{D_i q_i}{Q_2} (r_2 - f_2) - eQ_2^2 \end{aligned} \quad (12)$$

where eQ_j^2 is the cost of providing quality Q_j , r_j is the service price and f_i represents some general cost (fee). After plugging Equations (9) and (10) into the providers' profit, we obtain quadratic equations in r_j . To obtain the optimal solution (Nash equilibrium), we solve $\partial U_j / \partial r_j = 0$ which for two brokers yields:

$$\begin{aligned} r_1 &= \frac{2f_1}{3} + \frac{f_2 q_2 Q_1}{3q_1 Q_2} + \frac{Q_1}{3q_1} \times [c(q_2 - Q_2)^2 - c(q_1 - Q_1)^2 - (q_1 - q_2)(4\theta_{max} - 5\theta_{min})] \\ r_2 &= \frac{2f_2}{3} + \frac{f_1 q_1 Q_2}{3q_2 Q_1} + \frac{Q_2}{3q_2} \times [c(q_1 - Q_1)^2 - c(q_2 - Q_2)^2 - (q_1 - q_2)(5\theta_{max} - 4\theta_{min})] \end{aligned}$$

By substituting r_j 's in Equations (7) and (8), we get the final values for p_i 's only as functions of user preferences and service qualities:

$$\begin{aligned} p_1 &= \frac{1}{9} (5c(q_1 - Q_1)^2 + 4c(q_2 - Q_2)^2) + \frac{4f_2 q_2 Q_1 + 5f_1 q_1 Q_2}{9Q_1 Q_2} + \frac{1}{9} (q_2 - q_1)(16\theta_{max} - 20\theta_{min}) \\ p_2 &= \frac{1}{9} (4c(q_1 - Q_1)^2 + 5c(q_2 - Q_2)^2) + \frac{5f_2 q_2 Q_1 + 4f_1 q_1 Q_2}{9Q_1 Q_2} + \frac{1}{9} (q_2 - q_1)(20\theta_{max} - 16\theta_{min}) \end{aligned}$$

We obtain the final values for D_i 's from Equations (9) and (10):

$$\begin{aligned} D_1 &= \frac{1}{9\Delta\theta} (4\theta_{max} - 5\theta_{min}) + \frac{c(q_1 - Q_1)^2 - c(q_2 - Q_2)^2}{9\Delta\theta(q_1 - q_2)} + \frac{-f_2 q_2 Q_1 + Q_2 f_1 q_1}{9\Delta\theta(q_1 - q_2)Q_1 Q_2} \\ D_2 &= \frac{1}{9\Delta\theta} (5\theta_{max} - 4\theta_{min}) + \frac{c(q_2 - Q_2)^2 - c(q_1 - Q_1)^2}{9\Delta\theta(q_1 - q_2)} + \frac{f_2 q_2 Q_1 - Q_2 f_1 q_1}{9\Delta\theta(q_1 - q_2)Q_1 Q_2} \end{aligned}$$

E. Positive Utility

In the previous setting we assumed that customers buy service from either B_1 or B_2 , even if their utility is negative. Here we solve a game with only positive utility customers, *i.e.*, customers whose value of $\theta q - p$ is positive. Therefore, customers with zero utility provide a lower bound on θ (we call it θ_0), which can be found by solving $\theta_0 q_1 - p_1 = 0$. Thus θ_{min} is replaced by $\frac{p_1}{q_1}$:

$$D_1(p_1, \dots, p_m) = \frac{\theta_1^* - \theta_0}{\Delta\theta} = \frac{1}{\Delta\theta} \left(\frac{p_2 - p_1}{q_2 - q_1} - \frac{p_1}{q_1} \right) \quad (13)$$

As in our previous setting, this is a two-stage Bertrand game, and the Nash equilibrium for each game is found by replacing the D_i 's into the profit functions and solving $\partial\Pi_i/\partial p_i = 0$ and $\partial U_i/\partial r_i = 0$. We discuss the difference between this positive utility game and the previous (unconstrained utility) game later in Section IV.

F. Game with Constraints

At the lower level of service providers, the constraints (11) are not considered while calculating the equilibrium points. Therefore, in some situations, one of the constraints might be violated. Let us assume that after finding r_1 's, the constraint for B_1 is violated, *i.e.*, $\frac{q_1}{Q_1} r_1 + c(q_1 - Q_1)^2 \geq \frac{q_1}{Q_2} r_2 + c(q_1 - Q_2)^2$. This means that, under this condition, for broker B_1 , it incurs more cost to buy service from provider S_1 than provider S_2 ; so if provider S_1 does not change its price, B_1 will get service from S_2 , and this situation leads to a monopoly market at the providers' level.

To find an optimal point that also meets the constraints (11), provider S_1 should set its price such that $r_1 < \frac{Q_1}{q_1} \left(\frac{q_1}{Q_2} r_2 + c(q_1 - Q_2)^2 - c(q_1 - Q_1)^2 \right)$. In response, provider S_2 updates its price by plugging r_1 into $\partial U_2/\partial r_2 = 0$ which leads to $r_2 = f(r_1)$, *i.e.*, r_2 as a function of r_1 . Thus, S_1 can replace the r_2 with $f(r_1)$ in its inequality to calculate an optimal price that satisfies the constraint:

$$r_1 = \frac{Q_1}{q_1} \left(\frac{q_1}{Q_2} f(r_1) + c(q_1 - Q_2)^2 - c(q_1 - Q_1)^2 \right) - \epsilon \quad \epsilon > 0$$

In this stage of the game, S_1 should find a positive value for ϵ that maximizes its profit. By substituting r_1 and r_2 as functions of ϵ , U_1 is a decreasing quadratic function of ϵ . Solving $\partial U_1/\partial \epsilon = 0$ results in optimal ϵ . If $\epsilon < 0$, it can be replaced with a small positive number close to zero. Since U_1 is decreasing with respect to ϵ , any other positive value larger than the chosen ϵ leads to less profit. Clearly, the new set of prices for the service providers is an equilibrium point for the game, since it maximizes the revenue of both providers while meeting the constraints so each service provider does not lose its market (*i.e.*, one of the two brokers stays as its customer); therefore neither of the service providers has an incentive to change its price independently.

IV. NUMERICAL ANALYSIS

In this section we present some numerical results to illustrate the effect of choosing different qualities of service by brokers. We consider settings with two, three and four brokers. We also study the positive game model for two brokers. We show in detail how the best strategy for any broker is to choose a quality level that maximizes quality differentiation with other brokers. Also, when there are more brokers, the higher competition leads to more reasonable prices and a lower probability of a monopoly market.

A. Two Brokers

For the two brokers case, we consider a setting where $\theta_{max} = 1.5$, $\theta_{min} = 0.2$, $c = 0.1$, and $f_i = .01265 \times Q_i^{1.5}$. The service quality of the providers are set to $Q_1 = 20$ and $Q_2 = 45$. For the brokers, q_2 varies between 30 and 60, and we set q_1 to different values such that it is less than, equal to, or larger than Q_1 to see how the market changes under different conditions.

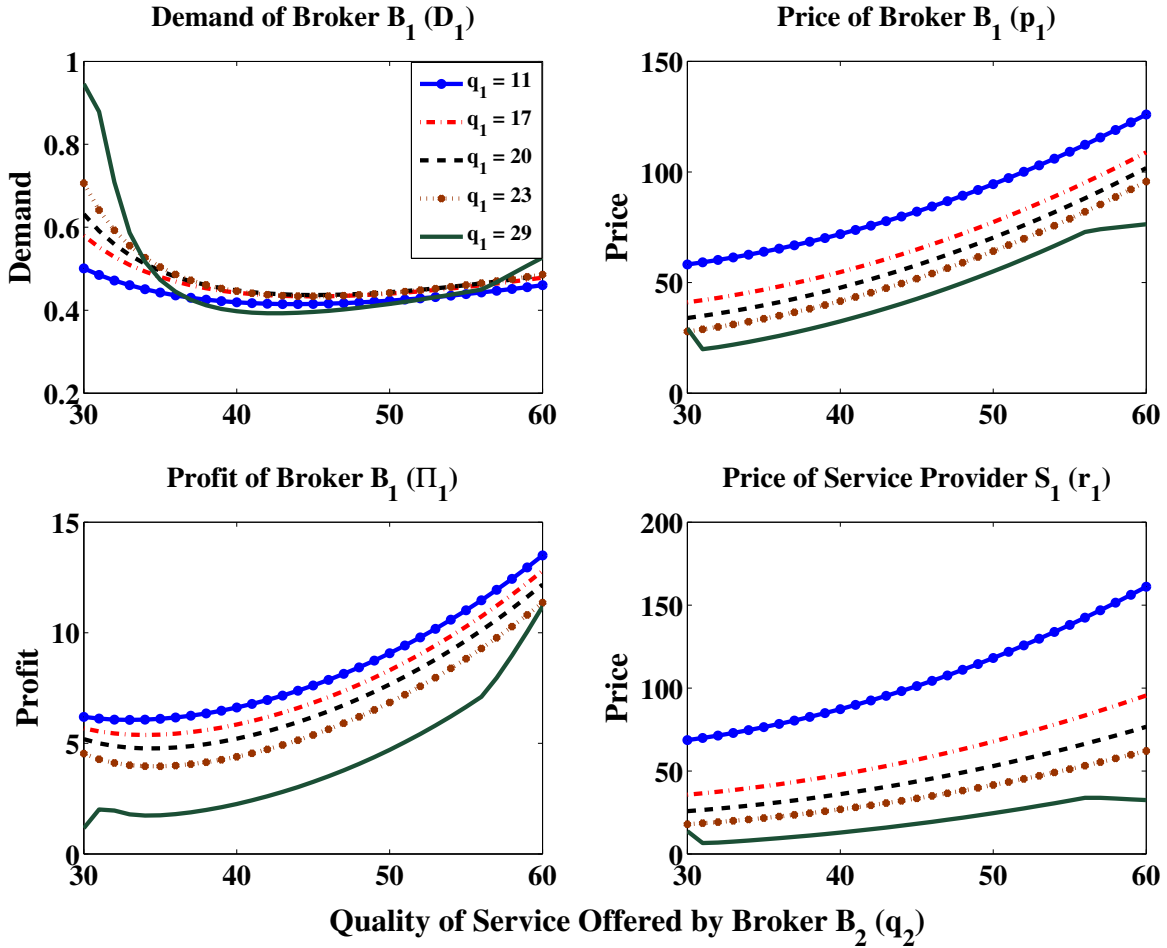


Fig. 2. Price, profit and demand distribution for broker B_1 , and price of its provider S_1 , for $Q_1 = 20$, $Q_2 = 45$, $30 \leq q_2 \leq 60$, as the service quality offered by brokers changes.

Examining a first set of plots shown in Figures 2 and 3, we note that the total demand constitutes the whole market. So, when the demand for one broker/provider side decreases, the demand for the other side increases and vice versa. But this is not the case for prices and profits – they increase or decrease together. Furthermore, observing the behavior for different values of q_1 , we see from the brokers' and providers' price plots, when broker B_1 downgrades the lower-level service obtained from its provider S_1 (*i.e.*, $q_1 < Q_1$), all brokers and providers can offer their service at higher prices and make more profit. Similarly, by comparing the behavior for higher values of q_2 , where $q_2 > Q_2$, with that for lower values where $q_2 < Q_2$, we observe that a better strategy for broker B_2 is to upgrade the lower-level service that it obtains from S_2 (*i.e.*, $q_2 > Q_2$). This happens because upgrading q_2 or downgrading q_1 leads to a larger gap between q_1 and q_2 , therefore the two sets of broker and provider can offer more differentiated services at higher prices. In fact it follows the maximum differentiation principle. In this setting, since we have the minimum number of brokers to compete, it's more likely that monopoly situations happen. For example, for $q_1 = 29$, the market exhibits abnormal behavior when the gap between q_1 and q_2 is small, while the gap between providers' qualities and brokers' qualities is large. Specifically, the market approaches a monopoly where S_2 and B_2 have a small market share when broker B_2 is downgrading the service obtained from its service provider S_2 , *i.e.*, $q_2 < Q_2$. Observing the results when the values of q_2 are close to 30, we note that here, although the providers' game is a monopoly at some points where S_2 's price $r_2 = 0$, the brokers' game is not, and B_2 can have a small share of the market D_2 while it gets service from provider S_1 . This is because when the gap between q_1 and q_2 is not significant, most

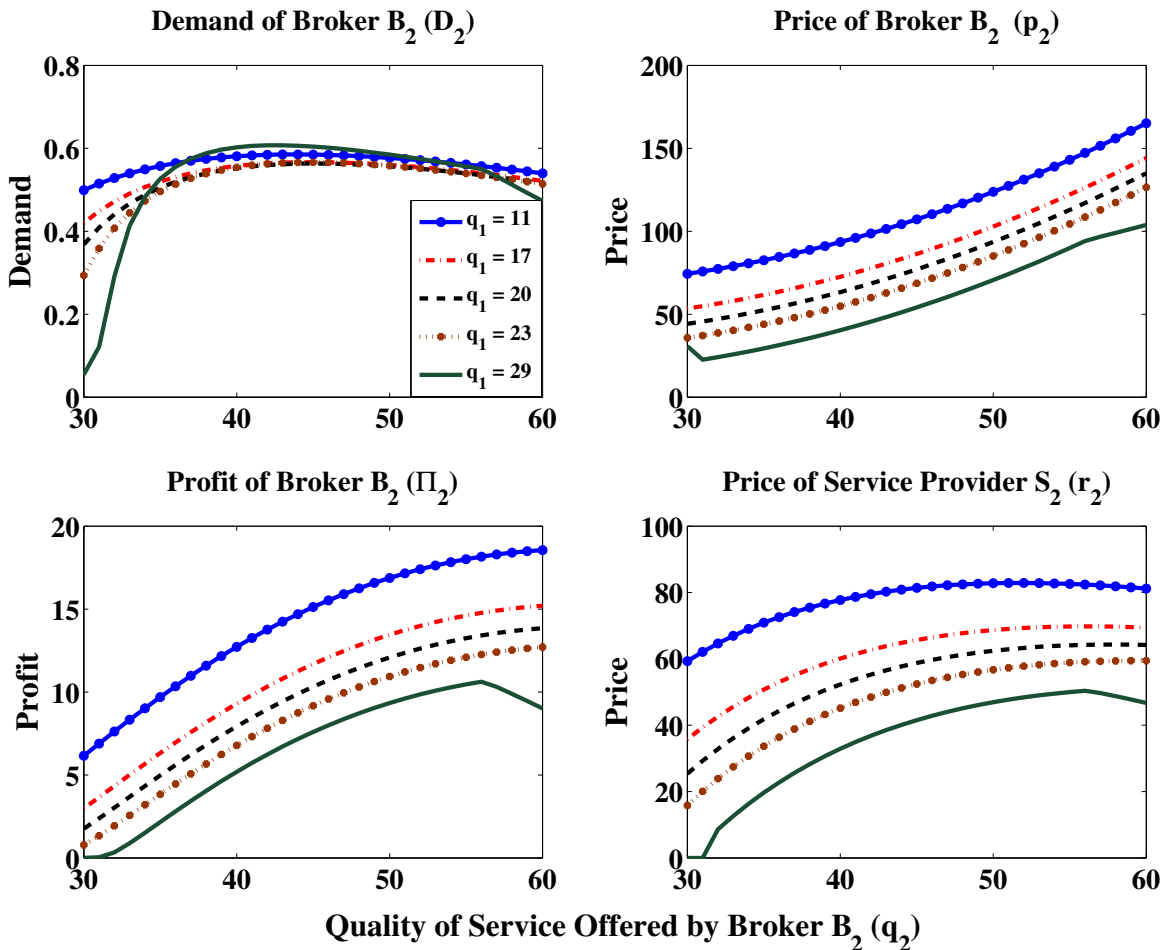


Fig. 3. Price, profit and demand distribution for broker B_2 , and price of its provider S_2 , for $Q_1 = 20$, $Q_2 = 45$, $30 \leq q_2 \leq 60$, as the service quality offered by brokers changes.

of the customers prefer the cheaper service provided by broker B_1 . When the market is a monopoly, the provider or broker who remains in the market can increase its price to a value such that the other competitor cannot enter the market even if it lowers its price to equal its cost, thus there is no way for the competitor to make profit and is prevented from entering the market.

On the other hand, for $q_1 = 29$, when broker B_2 is upgrading the service quality obtained from S_2 , *i.e.*, $q_2 > Q_2$, as the gap between q_2 and Q_2 gets larger, S_2 starts to decrease its price to cover the cost of the quality upgrade for B_2 so as not to lose its market share. Since the value of q_1 is somewhere between Q_1 and Q_2 , it is more economical for B_1 to buy service from S_2 rather than S_1 at the optimal prices, *i.e.*, the optimal price of S_1 violates constraints (11) and it should update its price r_1 as we explained in Section III-F. Consequently, S_2 should also update its price. Since there is a substantial gap between q_1 and q_2 , both providers can compete in the market.

B. Positive Utility Results

We now consider the case of positive utility competition. Intuitively, we expect to see some restriction on the prices for all brokers and providers, otherwise they lose part of the market for which the utility ($\theta q - p$) is negative. Thus it is a compromise between price and demand. The numerical results confirm this intuition. Comparing the prices of brokers and providers under positive utility and unconstrained utility, for the same conditions, shows that the highest prices under positive utility are below half of the

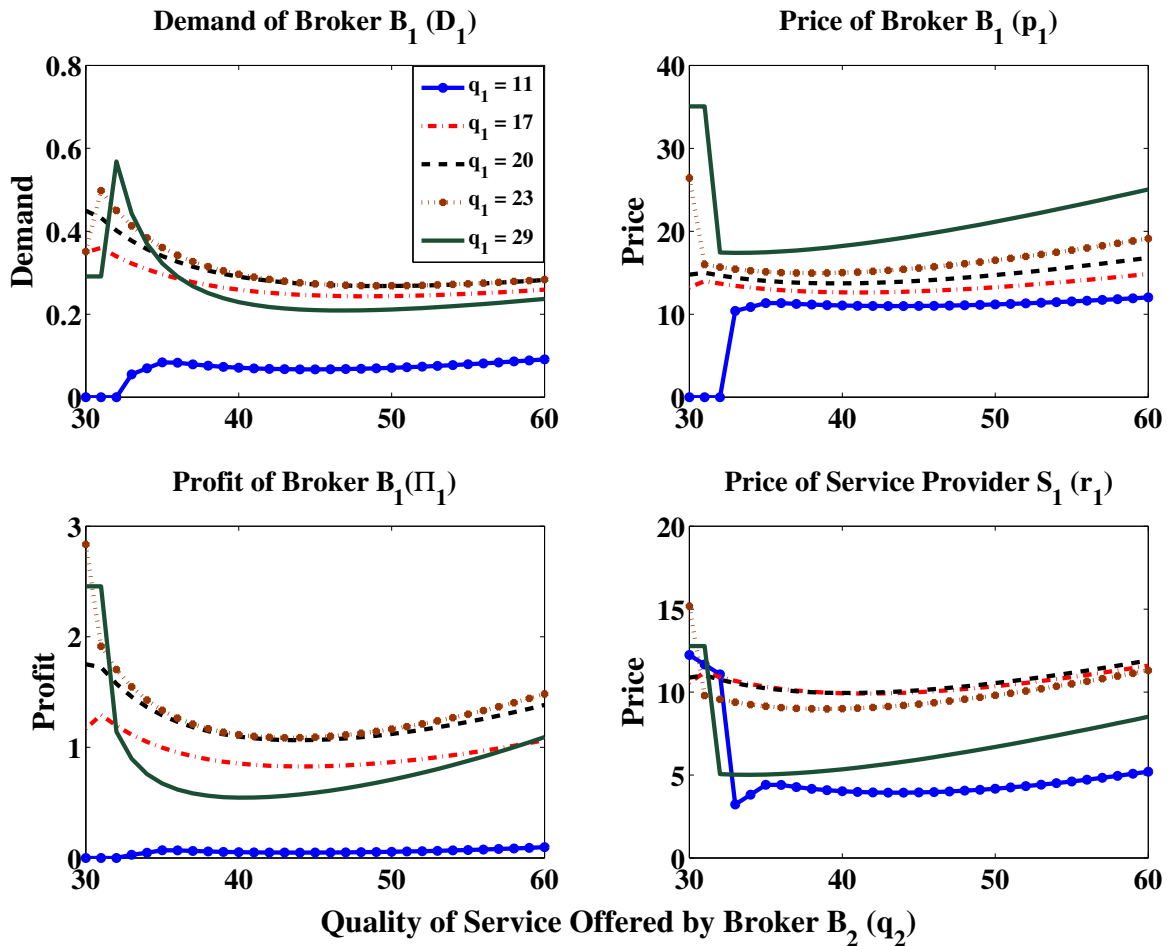


Fig. 4. Price, profit and demand distribution for the positive utility game, for $Q_1 = 20$, $Q_2 = 45$, $30 \leq q_2 \leq 60$, as the service quality offered by brokers changes.

prices in the latter case, while the demands are less as well; compare Figures 4 and 5 with Figures 2 and 3.

Also in this positive utility game, whether brokers upgrade or downgrade the service obtained from their providers, the behavior is different from that in the unconstrained utility game. Specifically, since the positive utility market is more sensitive to prices, a smaller gap between the service quality offered by the broker and the quality it gets from its provider yields more profit. Furthermore, while for both brokers, upgrading the service obtained from lower-level providers (and in turn, selling a higher quality service to customers) is generally more profitable, B_2 makes more profit when B_1 downgrades the obtained (lower-level) service, and B_1 makes slightly more profit when B_2 upgrades the obtained (lower-level) service.

Unlike the unconstrained utility game, if profit increases for one player, profit decreases for the other player. Another interesting observation from these plots is when the market is a monopoly: while there are conditions under which broker B_1 or B_2 can lose their market share, service provider S_1 can manage to stay in the market under all conditions.

C. Results with Three and Four Brokers

In this section we extend our setting to three and four brokers to see if the maximum differentiation principle holds for more brokers. We assume that two brokers offering the lowest and the highest quality of service to users are already in the market and define the range of feasible quality. We then let the other

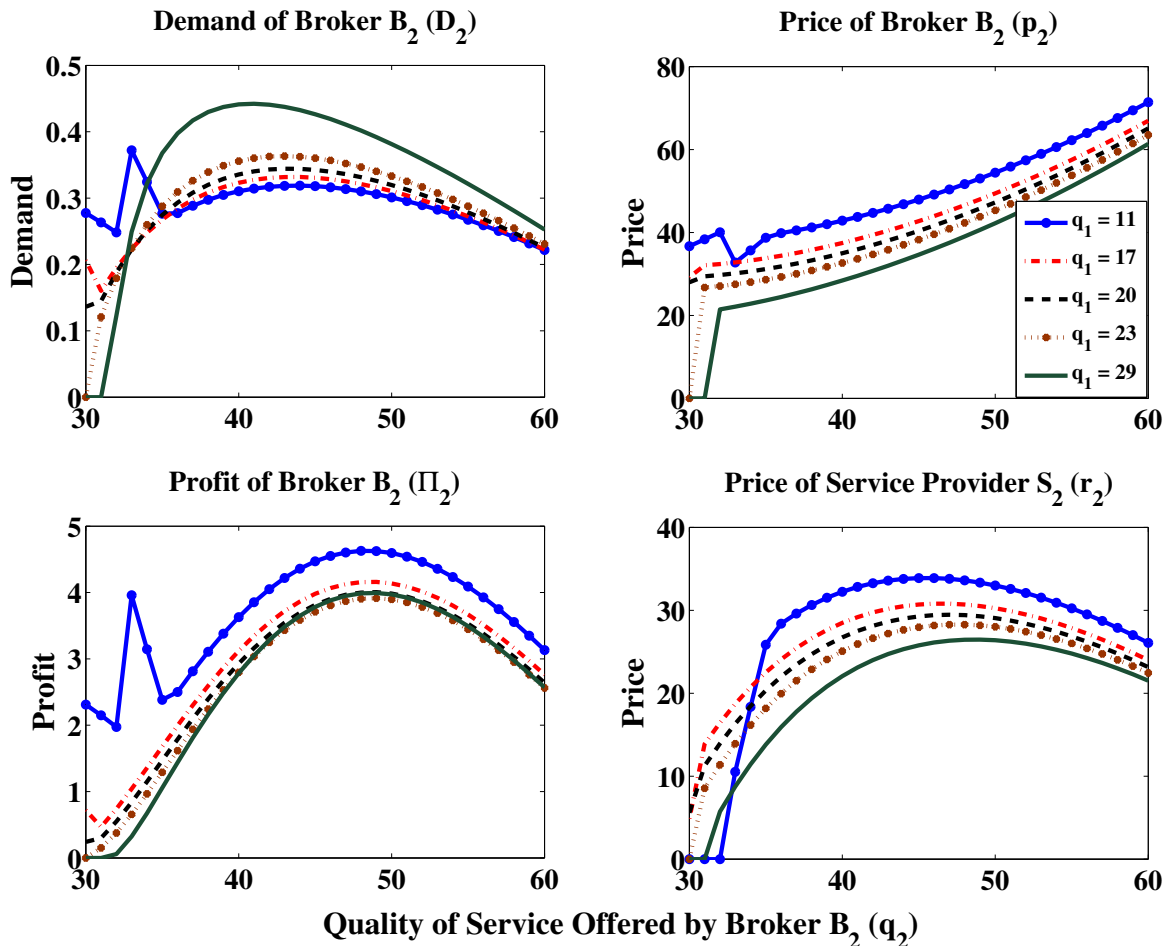


Fig. 5. Price, profit and demand distribution for the positive utility game, for $Q_1 = 20$, $Q_2 = 45$, $30 \leq q_2 \leq 60$, as the service quality offered by brokers changes.

one or two brokers enter the market with a quality level chosen in such range. After fixing a quality level, the third (and fourth) broker obtains service from the (lower-level) provider that minimizes the quality difference between them. This in turn minimizes the broker's cost in providing service to its customers. As in previous case studies with only two brokers, we show results at the equilibrium of the game by identifying indifferent customers between available service qualities. We also apply all constraints on the providers' level to have an oligopoly market.

1) *Three Brokers*: We simulate the game with $\theta_{min} = 1$, $\theta_{max} = 70$, two providers S_1 and S_2 with $Q_1 = 30$ and $Q_2 = 60$, and three brokers, B_1 , B_2 and B_3 , with qualities q_1 , q_2 and q_3 , respectively. We assume that the quality levels of B_1 and B_3 are fixed and we let the quality of broker B_2 change in the interval (q_1, q_3) . Broker B_2 chooses the service provider with least quality difference to reduce its (service conversion) cost. Given the above settings, we observe a tipping point for the quality of broker B_2 (q_2): for $q_2 < 45$, B_2 chooses provider S_1 and for $q_2 > 45$ B_2 chooses provider S_2 ; for the frontier value of $q_2 = 45$, although there is no quality differentiation between the two (lower-level) providers, we observe that downgrading the service has less cost than upgrading it, therefore B_2 chooses to get its service from S_2 . The jump in profit at $q_2 = 45$ in Figure 6 is because of B_2 's switching provider.

As we can see in Figure 6, for brokers B_1 and B_3 , which have been already in the market, it is more profitable if broker B_2 chooses to offer a quality with the maximum difference from their quality, while for broker B_2 it is more profitable to have maximum difference with both B_1 and B_3 . As we have observed in the case of two brokers, it is not advisable to choose a quality of service similar to that of other providers.

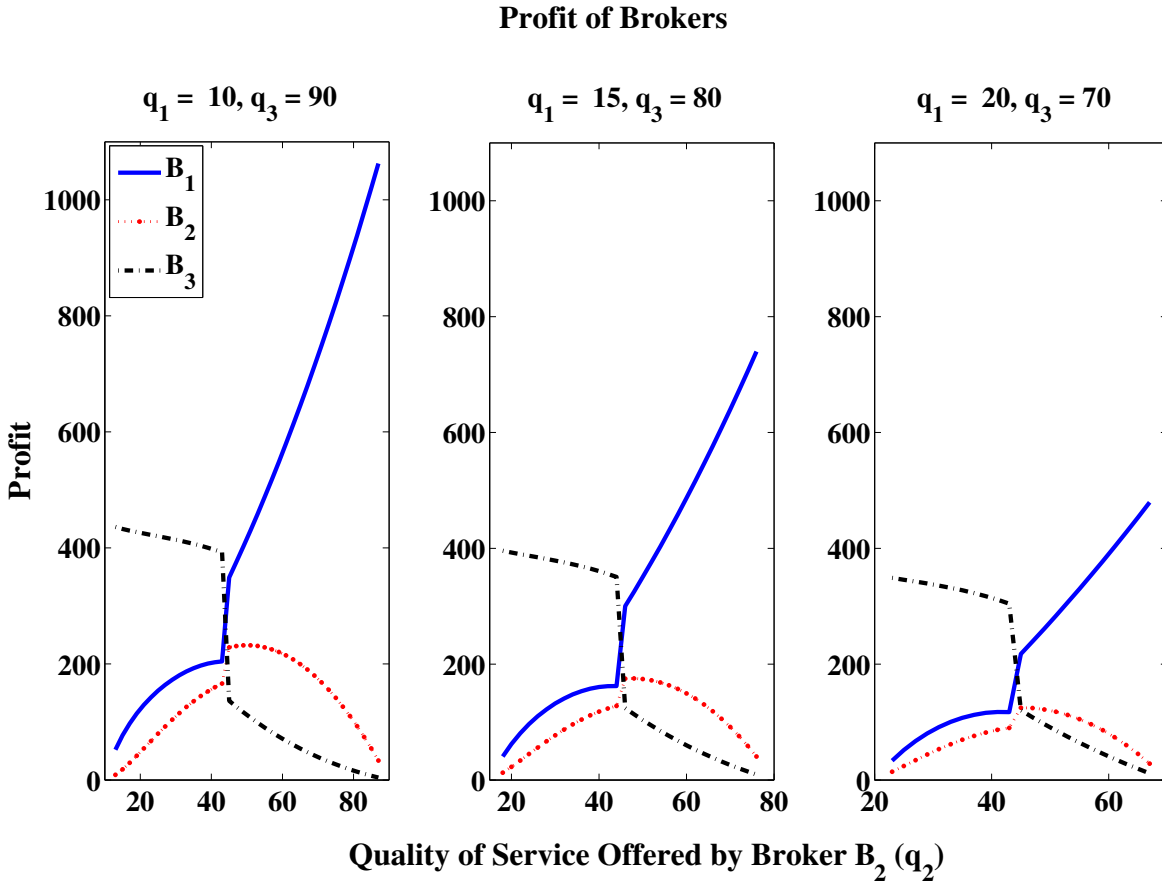


Fig. 6. Profit of each broker in a three-broker case for varying q_2 .

Intuitively, this is because the more difference in the service quality that they offer customers, brokers are more likely to serve customers at a higher price. We note this by observing that the optimal quality for broker B_2 is the average of the other fixed brokers' qualities (q_1 and q_3). For example, in the first plot from left in Figure 6, the optimal $q_2 = 50$, which is obtained from $(q_1 + q_3)/2 = (10 + 90)/2$.

We also change the fixed service qualities of brokers B_1 and B_3 toward the optimal quality for B_2 to see how the market changes and compare such results with those of Hotelling's location model with more than two firms [3]. As we can see in Figure 6, unlike the Hotelling's model [3] where corner firms have a tendency to move toward internal firms, here all brokers make less profit when quality differentiation decreases. However, for broker B_3 , its market share increases (Figure 7), though the effect of dropping the price (Figure 8) is more pronounced than the extra share of the market. Therefore, unlike the Hotelling's location model, for three firms, the market follows the maximum differentiation principle and brokers make more profit when their service qualities are more different from each other. In the following setting we study four brokers to see if this pattern repeats.

2) *Four Brokers*: In this setting, we simulate a scenario with two brokers, B_1 and B_4 already in the market and offering fixed service qualities $q_1 = 10$ and $q_4 = 90$, respectively, and two other brokers, B_2 and B_3 , that enter the market later. Without loss of generality, we assume that $q_2 < q_3$. Figure 9 shows the changes in profit for brokers B_2 and B_3 . We omit the results for B_1 and B_4 since they follow the same pattern as in the previous case study with three brokers, *i.e.*, the more differentiation between their qualities and those we set for B_2 and B_3 , the higher is their profit. This means that such brokers are not the decision makers in this situation.

As we observe in Figure 9, for broker B_3 , whose quality is between q_2 and q_4 , the optimal quality

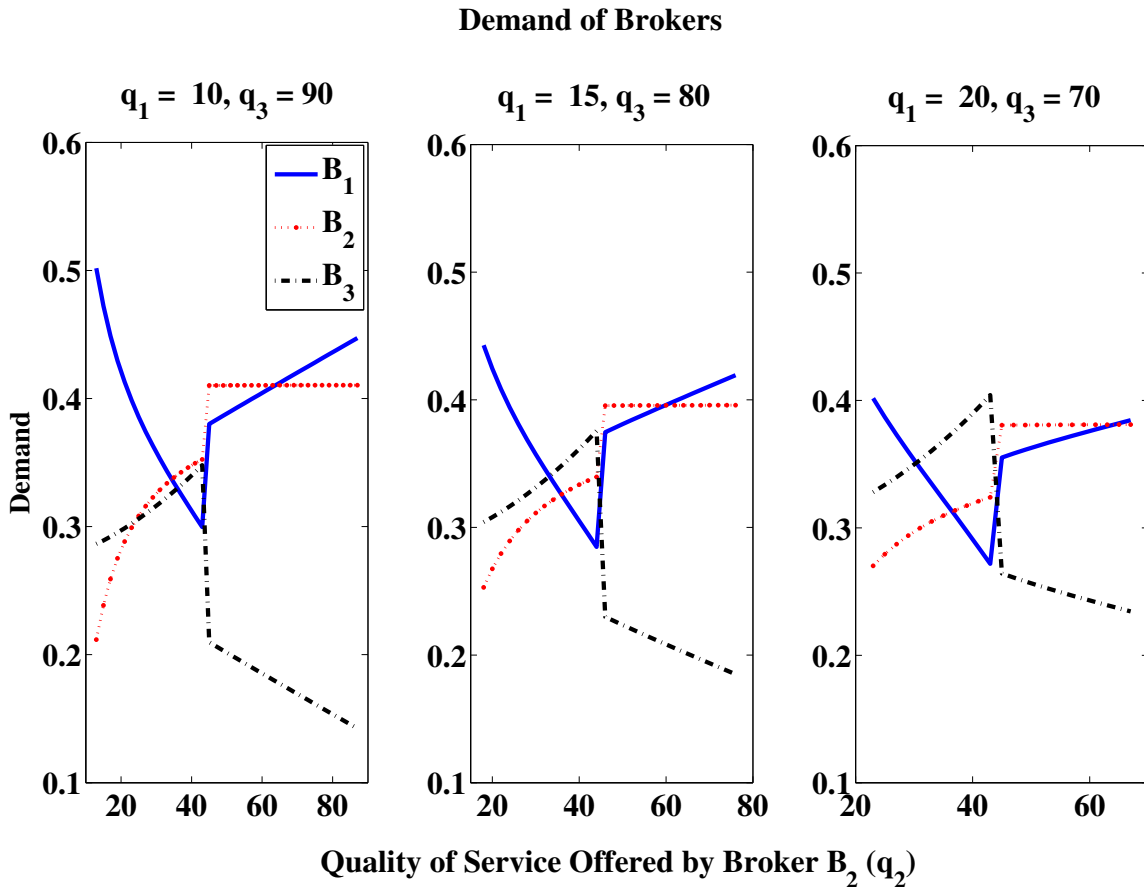


Fig. 7. Demand of each broker in a three-broker case for varying q_2 .

q_3 value is one that yields maximum differentiation from both qualities q_2 and q_4 , which is close to the average of q_2 and q_4 . For broker B_2 we expect instead that the optimal quality level is around $q_2 = 37$, that is, the quality with maximum difference from q_1 (10) and the optimal q_3 (which equals 64 given maximum quality differentiation among all brokers). However, we observe that the optimal quality for B_2 is at $q_2 = 45$, when broker B_2 switches from provider S_1 to provider S_2 and instead of upgrading the quality, downgrades the service that it obtains from provider S_2 (recall that $Q_1 = 30$ and $Q_2 = 60$). To understand why B_2 violates the maximum differentiation rule, we analyze the situations under both $q_2 = 37$ and $q_2 = 45$.

For $q_2 = 37$, the optimal value for B_3 is $q_3 = 56$, and not the expected value of $q_3 = 64$. To explain this situation, we should consider that in making profit, besides quality differentiation with other competitors (brokers), the cost of buying the lower-level service is also important. In this case, broker B_3 makes more profit if it chooses $q_3 = 56$ and downgrades the service it obtains from S_2 (recall $Q_2 = 60$) instead of choosing $q_3 = 64$ and upgrading the service. Broker B_3 can then offer a quality-price combination that attracts more customers, while because of the sufficient gap between q_2 and q_3 , the competition on the price is not tough. However, in this situation, broker B_2 is upgrading the service that it obtains from provider S_1 (recall $Q_1 = 30$) and to compete with broker B_3 , it cannot offer a high price, and the profit that it makes is relatively low.

On the other hand, for $q_2 = 45$, the situation is reversed. B_2 downgrades the service that it obtains from provider S_2 , while B_3 at its optimal point is upgrading the service. So the combination of quality-price of broker B_2 attracts more customers which leads to making more profit. Therefore in this game, besides maximum quality differentiation, the cost that brokers undergo is also playing an important role

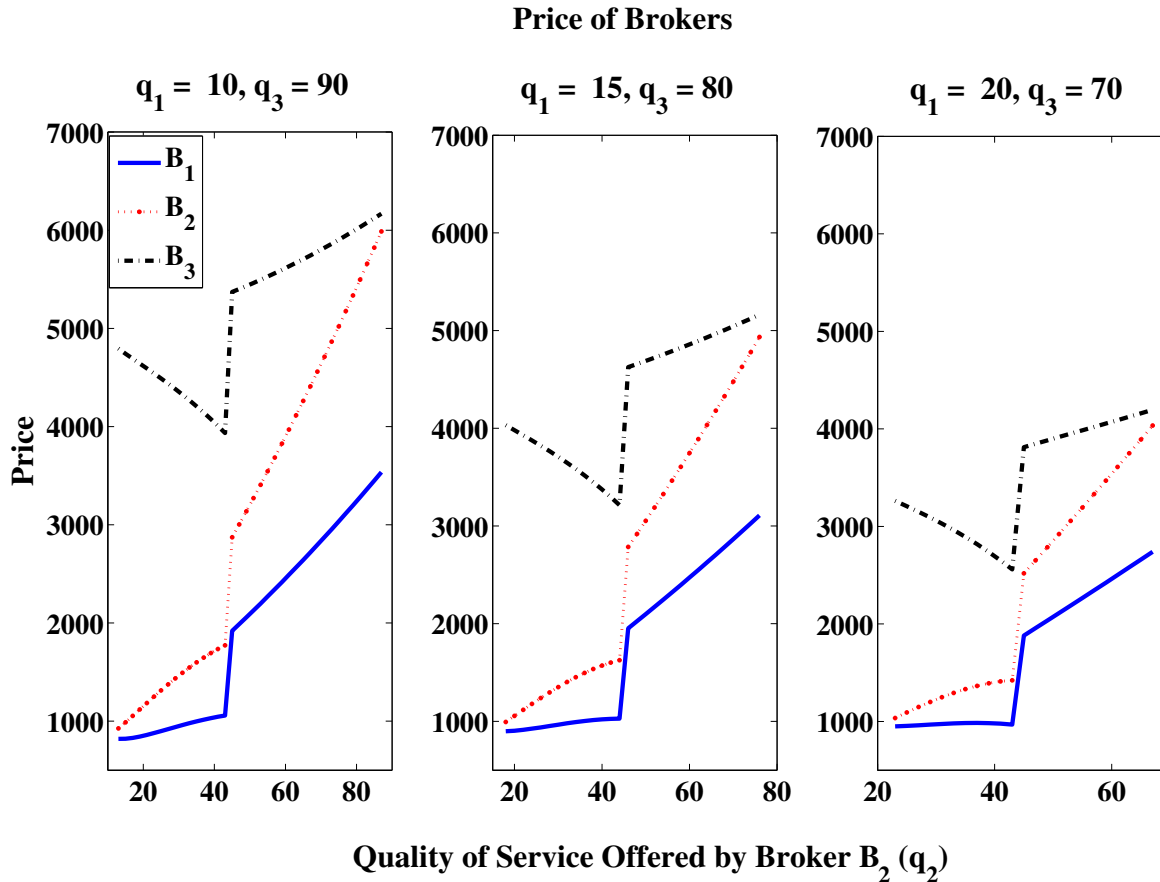


Fig. 8. Price of each broker in a three-broker case for varying q_2 .

and sometimes brokers should compromise on maximum differentiation to reduce cost.

Assuming rational players, *i.e.*, the two new brokers pick the quality that maximizes their profit, we compare the price of the service that such brokers offer for the case studies of three and four brokers (Figures 8 and 10). In the case of three brokers, we observe that the optimal quality for broker B_2 is at $q_2 = 50$ while $q_1 = 10$ and $q_3 = 90$. The optimal price for brokers in this setting is $p_1 = 2092$, $p_2 = 3203$ and $p_3 = 5447$, respectively. When four brokers are playing the game, the optimal quality for broker B_2 is $q_2 = 45$ and for broker B_3 is $q_3 = 66$. In this situation, the optimal prices are $p_1 = 1746$, $p_2 = 2535$, $p_3 = 3442$ and $p_4 = 4869$. As we can see, the price of service with quality 10 and 90 drops from 2092 and 5447 to 1746 and 4869, respectively. So, when there are more competitors in the market, the gap between their service qualities decreases, the competition on the price becomes tougher and brokers should offer their services at lower prices to be able to attract customers and make profit.

V. CONCLUSION

In this paper, we developed a game-theoretic model that captures the interaction among players in a multi-level market. In our model, brokers, as the intermediaries between users and service providers, adapt the quality of the service that they get from lower-level providers so as to attract more customers and maximize their profit. The game consists of two service providers, two, three or four brokers, and users, though we study more extensively the case with two brokers. Numerical results show that the more differentiation between the quality of service offered by brokers, the higher is their profit. However in some situations, besides quality differentiation, cost plays an important role and forces brokers to compromise on quality differentiation with their competitors to reduce cost and make more profit. An interesting result

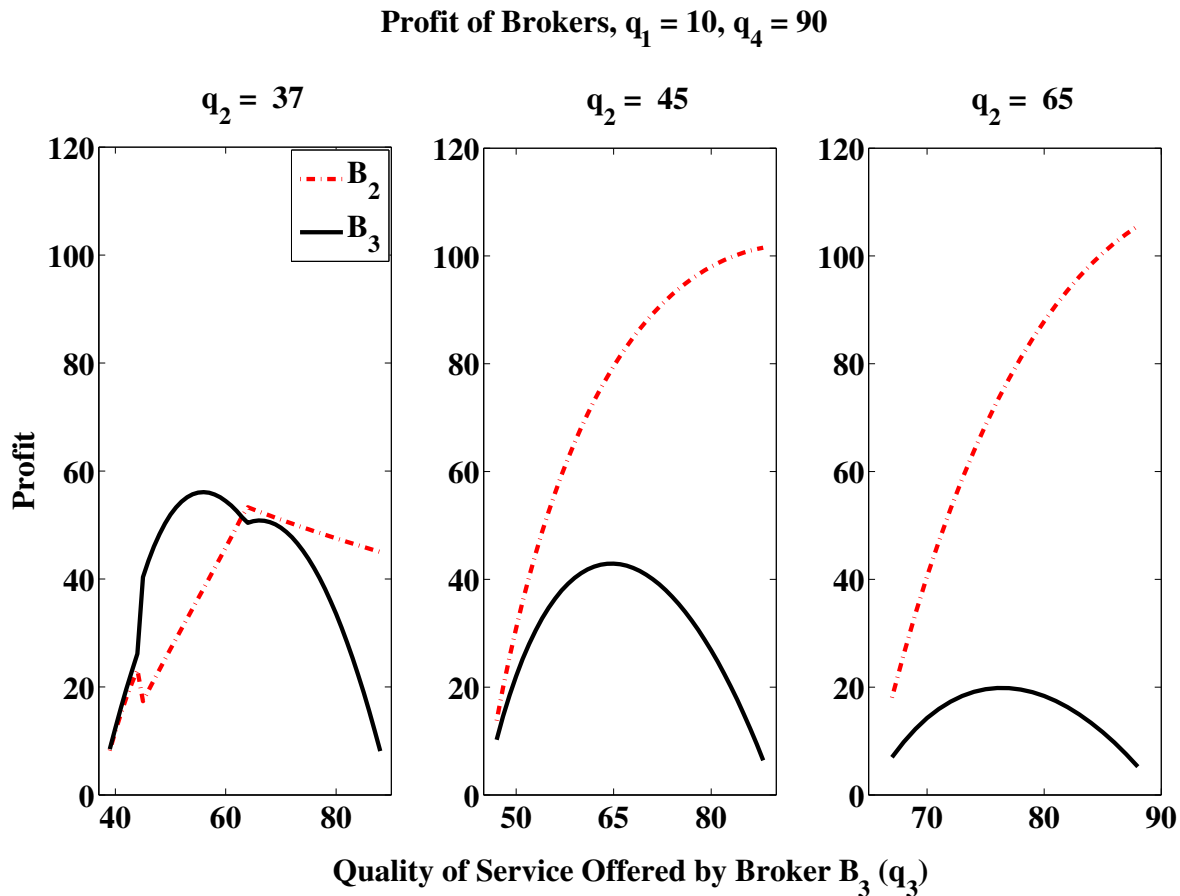


Fig. 9. Profit of brokers B_2 and B_3 in a four-broker setting.

in the two brokers game is that although players compete for more profit, the competition only affects their market share; the profit increases for one player if it increases for the other one. But this is not the case for more brokers. When there are more than two brokers, the market is more competitive and brokers should offer their services at lower prices to be able to stay in the market.

We also studied situations where all brokers prefer to buy service from just one of the lower-level providers, *i.e.*, the providers' market is about to become a monopoly. We developed a Bertrand game with price constraints to keep the market as an oligopoly if possible. Moreover, for the two brokers game, we explored the case where customers buy the service only if the combination of price-quality has positive utility for them. In this situation, players (brokers) try to offer the service cheaper to attract more customers. Unlike the unconstrained utility game with two brokers, if profit increases for one player, profit decreases for the other player.

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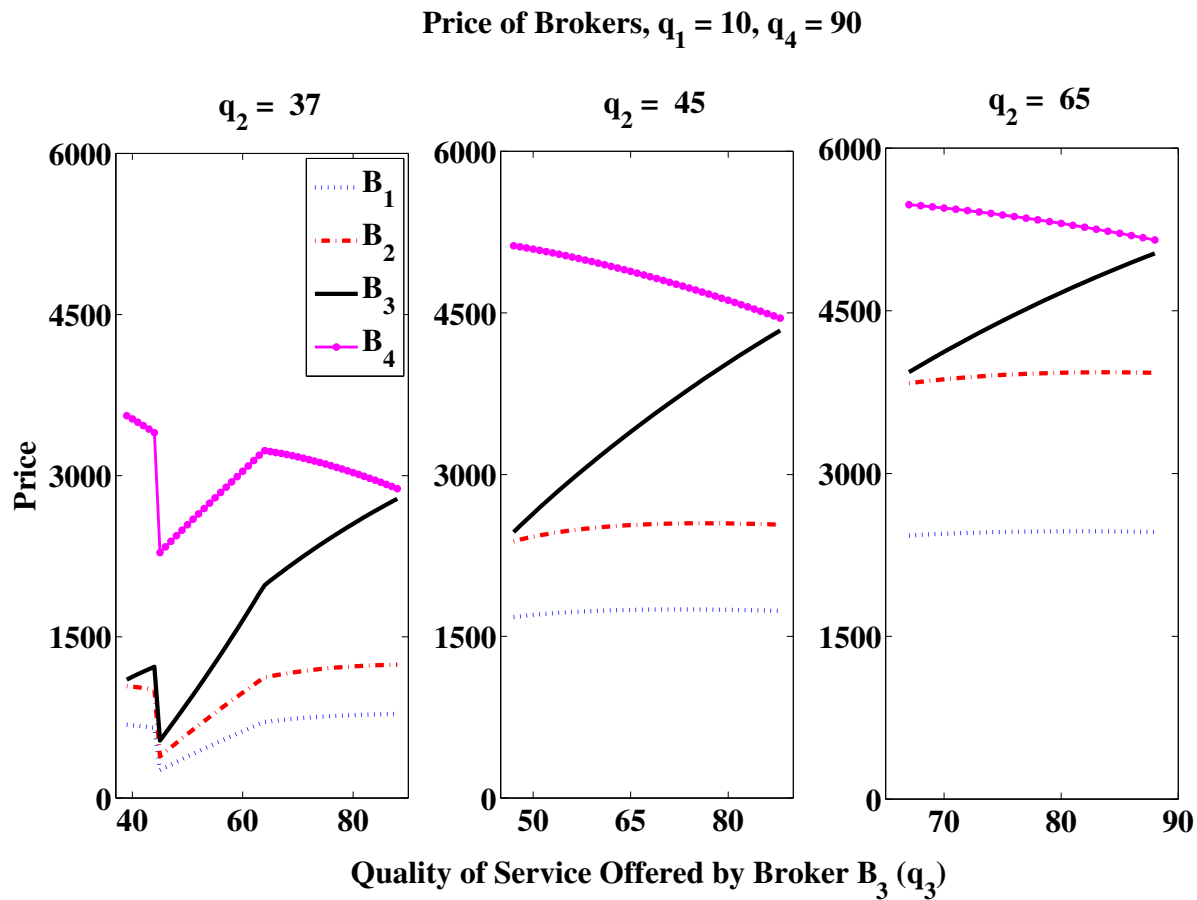


Fig. 10. Price of each broker in a four-broker setting.

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