Pricing, Competition and Innovation: A Profitable Business Model to Resolve the Tussle Involved in Peer-to-Peer Streaming Applications

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Abstract

Peer-to-Peer (P2P) streaming applications have lead to the disharmony among the involved parties: Content Service Providers (CSPs), Internet Service Providers (ISPs) and P2P streaming End-Users (EUs). This disharmony is not only a technical problem at the network aspect, but also an economic problem at the business aspect. To handle this tussle, this paper proposes a feasible business model to enable all involved parties to enlarge their benefits with the help of a novel QoS-based architecture integrated with caching techniques. We model the interactions, including competition and innovation, among CSPs, ISPs and EUs as a tripartite game by introducing a pricing scheme, which captures both network and business aspects of the P2P streaming applications. We study the tripartite game in different market scenarios as more and more ISPs and CSPs involve into the market. A three-stage Stackelberg game combining with Cournot game is proposed to study the interdependent, interactive and competitive relationship among CSPs, ISPs and EUs. Moreover, we investigate how the market competition motivates ISPs to upgrade the cache service infrastructure. Our theoretical analysis and empirical study both show that the tripartite game can result in a win-win-win outcome. The market competition plays an important role in curbing the pricing power of CSPs and ISPs, and this effect is more remarkable when the amounts of CSPs and ISPs become infinite. Interestingly, we find that in the tripartite game there exists a longstop at which ISPs may have no incentive to upgrade the cache service infrastructure. However, increasing the market competition level can propel the innovation of ISPs.

Keywords: Business Model; Game Theory; Pricing; P2P Streaming.

I. INTRODUCTION

Thanks to the emergence of Peer-to-Peer (P2P) streaming systems, individuals nowadays can watch video online easily. P2P streaming systems including on-demand and live broadcast, have attracted substantial research attentions [1]. More and more P2P streaming systems have been implemented and deployed with success in large scale real-world streaming applications. Even in China, nowadays there are about more than a dozen of commercial P2P streaming applications deployed in the Internet, e.g., CoolStreaming [2], PPTV [3].

Indeed, P2P streaming systems have been shown to greatly reduce the dependence on infrastructure servers, as well as bypassing bottlenecks between content service providers and end users. However, the popularity of the P2P streaming systems also leads to the disharmony among the involved parties: Content Services Providers (CSPs), Internet Service Providers (ISPs) and P2P streaming end users (EUs). This disharmony has fundamentally altered the relationship of them.

CSPs, as P2P streaming service providers, though possessing a considerable number of EUs, confront with many difficulties. Firstly, present P2P streaming systems are unable to provide QoS-guaranteed streaming programs, which is an obstacle for the commercialization of P2P streaming applications. Secondly, CSPs must face the conflict with ISPs over P2P streaming applications since the negative attitudes of ISPs will markedly keep P2P streaming services from rapid expansion. Thirdly, the most critical challenge for CSPs is how to make a profit from the P2P streaming services. None of present CSPs has found any distinct profitable business model leading to sustainable development yet. The absence of distinct profitable business model keeps CSPs from purchasing more competitive digital contents, which results in limited and homogeneous services provided by present CSPs.

For ISPs, on the one hand, they spend billions of dollars to maintain and upgrade their networks to support the ever increasing backbone traffic. However the growing popularity of P2P streaming applications has become a bandwidth “killer” that consumes a huge amount of network resources, which can also cause significant performance degradation of other Internet applications. On the other hand, ISPs do not see a notable revenue increase from the boom of P2P streaming applications, because EUs are often charged flat rates [4]. Moreover, ISPs are marginalized by CSPs’ directly charging consumers. As a result, in order to change this situation, unhappy ISPs start to put up various hurdles on P2P streaming applications by throttling P2P traffic or even entirely blocking certain flows [5].

For EUs, as they spend more and more time watching videos online, they become increasingly unsatisfied with the limited video quality, and have to tolerate undesirable disruptions of the streaming services as current P2P streaming systems do not ensure QoS-guaranteed video programs. EUs have realized that they prefer to enjoy high-quality videos with satisfied QoS. However, providing high quality Internet videos is very costly for CSPs and brings huge traffic burdens upon ISPs' backbone, which will even deteriorate current weak relationship between CSPs and ISPs.

Facing such dilemma, some P2P-friendly solutions have been recently proposed to make P2P streaming welcomed by all parties, such as traffic locality [6] and content caching [7]. However, it is unclear whether these P2P-friendly solutions can indeed help the involved parties to make any profit in operational environments. In fact, the tussle among the involved three parties is not only a technical problem at the network aspect, but also an economic problem at the business aspect. In order to fundamentally motivate CSPs, ISPs and EUs to embrace P2P streaming applications, a feasible solution has to address the following requirements:

- CSPs need to find a proper way of making profits from their provided streaming services to EUs;
- ISPs are able to get their share from the boom of the P2P streaming market;
- EUs enjoy better streaming services (e.g., better quality of viewing experience, more diversified programs and guaranteed QoS).

We believe that coping these requirements is of critical importance, especially in the P2P streaming market where the involved entities are competing and interdependent. Moreover, it is possible that each entity includes multiple participants, e.g., multiple CSPs in CSP market. If taking these factors into account, the competition among the three entities leads to more complicated relationships.

In this paper, we propose a feasible business model that can satisfy the above requirements effectively, which enables all involved parties to enlarge their benefits with the help of a QoS-based architecture integrated with caching technology. To analyze the feasibility of the proposed business model, we model the interactions among CSPs, ISPs and EUs as a tripartite game by introducing a pricing scheme, which captures both network and business aspects of the P2P streaming applications. We study the tripartite game in different market scenarios by following the logic flow indicated in Fig. 1, where more and more ISPs and CSPs are involved into the market. More specifically, we first investigate the tripartite game in a Monopoly Market (MM) where a CSP and an ISP are both dominant in determining the market price. We model the relationships among the three parties in the MM as a three-stage Stackelberg game and derive the equilibrium strategies of the three parties. Next, we extend the tripartite game into a more complicated scenario, Imperfect Competitive Market (ICM), where multiple CSPs and ISPs coexist in the market. The Cournot game is introduced to model the competition among the same entities, i.e., the CSPs (or ISPs). We tie the Cournot game to the three-stage Stackelberg game to model the interactions among the three parties. Building upon the analysis of the ICM, we derive the equilibrium strategies in a Perfect Competitive Market (PCM), which is an ideal market that coexists a large number of ISPs and CSPs. In particular, we further investigate the incentive for ISPs to upgrade the cache service infrastructure in different market scenarios.

Our analysis brings out several interesting observations:

1) The tripartite game can result in a win-win-win outcome and the proposed business model can significantly increase all game participants' welfare.
2) The market competition plays an important role in curbing the pricing power of CSPs and ISPs, and this effect is more obvious as more CSPs and ISPs involve in the tripartite game. Specially, when the amounts of CSPs and ISPs reach infinite, the market becomes a PCM where the business of the three parties can achieve an equilibrium strategy profile with maximal social welfare and Pareto efficiency.
3) We further show that if ISPs adopt a rational strategy, there will be a longstop at which the ISPs may have no incentive to upgrade the cache servers, even though the upgrading can increase the profit of EUs. Interestingly, increasing the market competition can motivate ISPs' innovation, and the higher the market competition is, the more remarkable incentive the ISPs have to engage in cache upgrading, which eventually leads to a better welfare of the whole system.

To the best of our knowledge, this paper is the first attempt to explicitly model the interdependence, interaction and competition among CSPs, ISPs and EUs as a tripartite game. We hope that our business model can shed lights on the deployment and evolution of the practical P2P

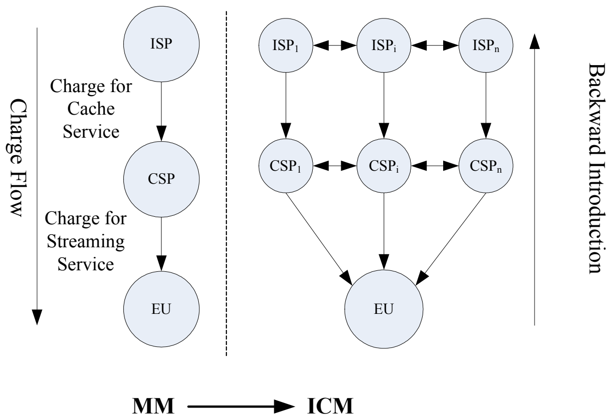

Fig. 1. Logic flow of the discussions of the tripartite game.

streaming market.

The rest of the paper is organized as follows. In section II, we introduce the proposed business model. We formulate interactions among involved three parties as a tripartite game in Section III. In Section IV, we discuss the tripartite game under different market scenarios. We evaluate the performance of the business model using practical data in Section V. We review some related work in Section VI and conclude the paper in Section VII.

II. Business Model

Given the disharmony among the parties involved in current P2P streaming applications, we propose a business model that captures both network and business aspects to solve this inefficiency. Our business model uses a novel content distribution architecture integrated with traffic caching and traffic locality technologies that is able to provide high quality streaming services.

As shown in Fig. 2 (a), there are three types of seeds that can provide video contents: data server, cache server and dynamic seeds. The data server is deployed by the CSP, it can be considered as a fixed seed, providing basic connection services. The cache server is a super seed, deployed at the edge of networks by the ISP, for the sake of reducing the ISP's backbone cost and accelerating the CSP's content delivery. The dynamic seeds are the altruistic peers that are available for sharing, which may be quite volatile and have fluctuating rates.

The P2P streaming system works as follows:

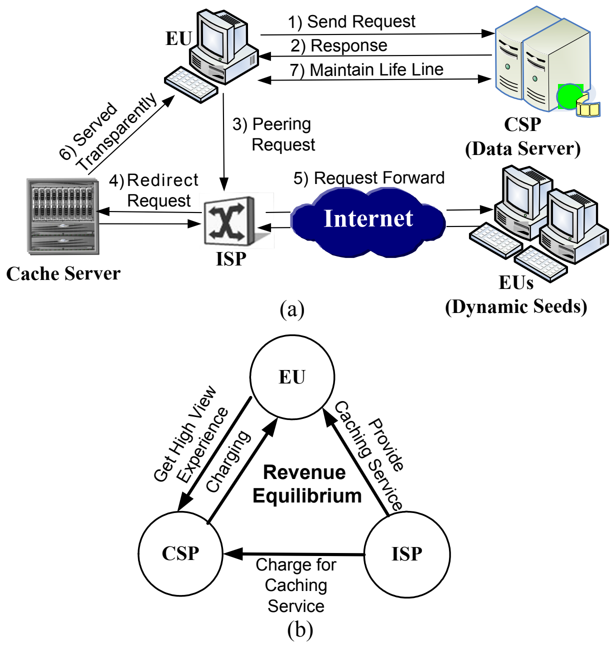

Fig. 2. P2P streaming system: (a) System architecture and (b) Charging flow.

1) An EU discovers video programs via a client interface and sends service requests to the data server.
2) The video meta-data and a list of dynamic seeds are replied to the EU from the data server.
3) The EU then tries to establish direct connections with these seeds by sending peering requests to the CSP.
4) When the outgoing EU's requests reach the edge of networks, the ISP checks the requests and redirects them to the cache server.
5) If the requested content does not exist in the cache server, the requests will be forwarded and the requested content will be simultaneously cached from the data server.
6) Otherwise the content is transmitted from the cache server to the EU transparently.
7) As downloading video meta-data from the dynamic seeds is in a best effort fashion, the EU needs to actively monitor the QoS of the content and maintains a life line from the data server. If the video data that the EU retrieves from the P2P mode cannot provide a sufficient QoS, the EU should adaptively retrieve contents from the data server as needed.

The charging flow among the engaged three parties is illustrated in Fig. 2(b). The ISP deploys high-capacity cache servers at the edge of networks, and charges the CSP for the usage of the cache servers. It seems easily to motivate the ISP to adopt P2P caching technologies, since the ISP can make certain profits and save remarkable costs on providing bandwidths to meet the growing demands for multimedia contents without massive network upgrading. From the perspective of EUs, they can also derive an improved viewing experience of streaming contents. This experience differentiates itself from other ordinary P2P streaming services, which makes commercial P2P streaming services feasible in a long term. The CSP may charge EUs by taking account of their price sensitivity. With collected profits from EUs, the CSP is capable of purchasing popular and competitive contents, therefore can gain a larger market share which will bring more externality profits (e.g., advertisements or venture capitals) that lead the CSP to sustainable development.

Intuitively, the proposed business model can improve the welfare of all involved parties. In the next sections, we will apply game theory to deeply analyze this model.

III. Tripartite Game Formulation

In this section, we present our basic model. Without loss of generality, we consider a P2P streaming application with three entities: CSP, ISP and EU. By introducing the pricing scheme, we formulate the dynamic interactions among all the parties involved in our business model as a tripartite game, which captures some key factors that determine the decisions of the parties, e.g., the operation cost of CSP, the backbone cost of ISP, the viewing experience of EU. We will cast this tripartite game into different market scenarios in microeconomics and rigorously characterize the corresponding equilibrium strategies of each party in following sections.

In this tripartite game, the CSP provides streaming services and adopts a "volume-based" tariff, i.e., the price is charged per-unit of bandwidth. The EU, which prefers to consume high-quality streaming services provided by the CSP, determines its bandwidth consumption by taking account of its price sensitivity and gets its revenue from the high quality of viewing experience, which can be interpreted as utility. It should be noted that we treat the consumed bandwidth as the major metric of the viewing experience, because it determines the data loss rate and time delay of the streaming services, which have dominant impacts on the EU's viewing experience. Assume the viewing experience of EU can be represented as a continuous utility function $u(x)$ and the corresponding first-order derivative of $u(x)$ regarding to x is denoted by $u'(x)$. It is reasonable to assume that $u(x)$ is a monotonically increasing and concave function of the consumed bandwidth

x due to the marginal effect of the bandwidth on the user's viewing experience. Specially, through paper, we use a concave function $u(x) = \frac{x^{1-a}}{1-a}$, which is a classic utility function frequently used in communication networks economics [8], to describe the EU's viewing experience[1]. Here, $a \in (0, 1)$ is a factor that captures the elasticity of EU's consumption with the changing of price. Moreover, as the cache sever can be regarded as a super seed, the expected viewing experience of the EU served with the cache server can be higher than that served with the ordinary pure P2P mode. Taking this fact into account, we define a hit ratio β to be the probability that the requested program exists in the cache server and a function $\sigma = E(\beta)$ to describe the expected enhancement of the viewing experience magnified via the cache server, compared with the ordinary pure P2P mode. Thus, the revenue function of the EU can be represented as:

$$R_{\mathrm{EU}} = \sigma u(x) - px, \tag{1}$$

where $\sigma u(x)$ indicates the utility that the EU derives from watching a program with x units of consumed bandwidths, p is the price of per-unit bandwidth, px is the payment of the EU for watching the program. Note that the EU will watch the program only if $R_{EU} > 0$; otherwise, the EU prefers to quit the system.

The CSP provides paid streaming services and receives revenue from the EU who is willing to pay for the services. At the same time, the CSP has to undertake various costs for providing such services, which can be classified roughly into two categories. One is the usual operating cost generated by the services' daily operation. The other is the rental fee charged by the ISP for the usage of cache services, since the CSP needs to rent cache servers for the sake of accelerating content delivery. The exact rental fee is related to the price of its services and the corresponding performance, i.e., the cache server's hit ratio.

For simplicity, we use c to denote the CSP's marginal operating cost, i.e., the extra cost that is incurred by serving another unit of bandwidth request. Let q denote the price set by the ISP for per-unit bandwidth usage of cache services, then the rental fee is $q\beta x$. The operating cost of CSP can be written as $c(1-\beta)x$ since partial traffic load has been reserved by the cache server.

In addition, the CSP will obtain external profits from every EU's bandwidth consumption due to networks' externality effects, e.g., revenues generated from advertisements. Let b denote

[1]Although more complex utility function may be used in our model, we believe that it does not fundamentally alter the results obtained in the paper

the marginal profit from networks' externality effects. The CSP's revenue function R_{CSP} can be represented as:

$$R_{CSP} = px + bx - c(1-\beta)x - q\beta x, \tag{2}$$

where px corresponds to the payment collected from the EU, bx is the externality profits associated with EU's bandwidth consumptions.

The ISP charges the CSP a fee for renting the high-performance cache server deployed at the edge of networks. Each program demanded by the EU will generate a request to the cache server and the hit requested programs will be served by the cache server while the missed ones will be obtained through the Internet. Therefore, we could divide the cost of ISP into two parts, one is the operating cost that is related to the expected bandwidths served by the cache server, denoted as $\delta\beta x$, the other is the backbone cost that is the traffic passing through ISP's backbone network, expressed as $\gamma(1-\beta)x$. Here, δ and γ are the corresponding marginal costs. It is reasonable to assume that the marginal backbone cost γ is larger than the marginal operating cost δ.

Assume that the ISP also adopts a volume-based pricing scheme for the usage of cache server and the price per unit bandwidth charged by the ISP is denoted as q. Here, $q < p$; otherwise the CSP will have no motivation to rent the cache services. Therefore, the revenue of the ISP can be represented as:

$$R_{ISP} = q\beta x - \delta\beta x - \gamma(1-\beta)x. \tag{3}$$

It should be noted that for conciseness, in this section of model formulation, we use the singular term "CSP" (or "ISP") to refer to the entire of CSPs (or ISPs). In the following sections where multiple CSPs and ISPs considered, we identify each CSP (ISP) by adding an subscript, e.g., we use R_{CSP_i} and c_i $(i = 1, .., n)$ to denote the revenue of CSP i and its corresponding marginal cost. However, throughout this paper, we use the convention that the term "EU" is considered as the whole users of networks.

For this tripartite game, the objective of CSP and ISP is to maximize their revenue functions at proper prices p and q, respectively. EU determines its consumptions according to the given price p. The CSP, ISP and EU interact through a strategy profile $\{p, q, x\}$. This interaction may be extraordinarily complex as the market conditions may be changed and different actions are available to different parties. The three parties need to negotiate for a fair point where all the participants choose their best strategies to get their own desired revenues, respectively. Such a fair point is called *equilibrium strategy profile*.

IV. Game-theoretic Analysis under Different Markets

In this section, we study the equilibrium strategies of the tripartite game under different market scenarios.

A. Monopoly Market (MM)

We first investigate the tripartite game in a monopoly market scenario where a CSP and an ISP are both dominate, i.e., the price p of the streaming service is under the complete control of the monopolistic CSP. Likewise, the ISP also has the power to determine the price q of the cache server's usage.

In this tripartite game, the CSP has the power to determine the price of per-unit bandwidth. In what follows, the EU chooses its bandwidth request to optimize its own revenue in response to the price given by the CSP. The ISP does not provide streaming services to the EU directly, it earns its revenue by charging the CSP for the usage of the cache server. Combining the interaction among the three parties, we can formalize the tripartite game as a dynamic three stage Stackelberg game depicted in Fig. 1. In the first stage, the ISP acts as a leader by setting the price q for the usage of the cache server. Next, the CSP acts as the follower of the ISP to decide its price p by taking account of the fee charged by the ISP. In the third stage, the EU determines its best bandwidth consumption x for the given service price p of CSP. In the monopoly market, the CSP, ISP and EU, seek to maximize their own revenues by determining the strategy profile $\{p, q, x\}$. We derive the equilibrium strategy profile for the three-stage Stactkelberg game by applying the concept of backward induction, which works as follows:

Firstly, in the third stage, for a given price p of the streaming services, the EU determines its optimal bandwidth consumption along with its corresponding revenues, i.e., the EU takes the price p given by the CSP as input and decides the optimal bandwidth demand x as output. Then back to the second stage, the CSP, acting as a leader, is aware of EU's bandwidth requirement. The CSP can choose its optimal price p^* by expecting the EU's consumption. The game then rolls back to the first stage, where the CSP becomes a game follower and the ISP acts as a leader of this stage. The ISP seeks to maximize its profit by adjusting the price q of cache services.

Note that the fee that the ISP charges the CSP will be shifted onto the EU ultimately as a part of CSP's cost, which indirectly influences the bandwidth consumption of the EU. For ease of presentation, we use $x = D_p(p)$ and $x = D_q(q)$ to denote the EU's bandwidth demand function in face of the prices p and q, respectively. In addition, for later use, we introduce the concept of price elasticity, which describes the degree that the EU's bandwidth consumption x varies with respect to the price. The EU's price elasticity with respect to the price p are denoted as $E_p = \frac{D'_p(p)}{x/p}$, where $D'_p(p)$ is the first order derivative of the demand function $D_p(p)$ with respect to p. Similarly, we can obtain the EU's price elasticity E_q with respect to q. Finally, the equilibrium strategy profile $\{p^*, q^*, x^*\}$ of the dynamic three-stage game can be derived. The detailed analysis is listed in Theorem 1.

***Theorem** 1:* There exists a subgame equilibrium for the tripartite game in the MM and the equilibrium strategy profile $\{p^*, q^*, x^*\}$ satisfies:

$$p^* = \frac{(1-\beta)c + q^*\beta - b}{1-a}, q^* = \frac{\beta\delta + (1-\beta)\gamma}{1-a}, x^* = (\frac{\sigma}{p^*})^{\frac{1}{a}}. \tag{4}$$

Proof: First, for the given price p of streaming services, EU aims to determine its maximization by solving the following problem:

$$\max_{x\geq 0} R_{EU} = \sigma u(x) - px. \tag{5}$$

By applying the first order optimality condition with respect to x, we can obtain the EU's best response in face of the price p, $p = \sigma u'(x)$, which indicates that the price of per-unit bandwidth p equals to the marginal utility $\sigma u'(x)$. Recall that $u(x) = \frac{x^{1-a}}{1-a}$ and its corresponding first order derivative is $u'(x) = x^{-a}$, we can convert $p = \sigma u'(x)$ to a bandwidth demand function $x = D_p(p) = \frac{1}{\sigma} u'^{-1}(p) = (\frac{\sigma}{p})^{\frac{1}{a}}$, and the corresponding price elasticity of EU is $E_p = \frac{D'_p(p)}{x/p} = -\frac{1}{a}$.

The CSP simply uses its revenue to determine its strategy. By expecting EU's demand function $x = D_p(p)$, the CSP aims to solve the following revenue maximization problem:

$$\max_{p\geq 0} R_{CSP}(p, x) = q\beta x - \delta\beta x - \gamma(1-\beta)x. \tag{6}$$

By applying the first optimal order condition with respect to p, we obtain $D'_p(p)D_p(p) + pD'_p(p) + bD'_p(p) - c(1-\beta)D'_p(p) - q\beta D'_p(p) = 0$. Rearranging it, we get

$$p^* = \frac{(1-\beta)c + q\beta - b}{1-a}. \tag{7}$$

Notice that the optimal price p^* is also a function of price q. By substituting the best response of EU $p = \sigma u'(x)$ into Eq. 7, we get

$$\sigma u'(x) = \frac{(1-\beta)c + q\beta - b}{1-a}. \tag{8}$$

Rearrange Eq. 8, we can obtain the EU's demand function with respect to q, $x = D_q(q) = [\frac{\sigma(1-a)}{(1-\beta)c+q\beta}]^{\frac{1}{a}}$, and the corresponding price elasticity is $E_q = -\frac{1}{a}$.

Substituting the EU's demand function $x = D_q(q)$ into the ISP's revenue function indicated in Eq. 3, and applying first order condition with respect to q, we get the optimal price $q^* = \frac{\beta\delta+(1-\beta)\gamma}{1-a}$.

Therefore, the Equilibrium strategy profile $\{p^*, q^*, x^*\}$ that represents the stable state of the three-stage Stackelberg game could be derived as Eq. 4. ■

We can verify that the demand functions, $x = D_p(p) = (\frac{\sigma}{p})^{\frac{1}{a}}$ and $x = D_q(q) = [\frac{\sigma(1-a)}{(1-\beta)c+q\beta}]^{1/a}$ are decreasing with the increasing of prices p and q, respectively. The demand functions reflect the rational responses of the EU to the prices, which is well consistent with the common sense. From the equilibrium strategy profile indicated in Eq. 4, we can see that the numerator of the monopolistic price p^* is the CSP's marginal revenue $(1-\beta)c + q^*\beta - b$. Notice that $a \in (0, 1)$, so the denominator of p^* is less than 1, which leads to the fact that the monopolistic price p^* is always larger than the marginal revenue. We can see that the upper bound of price p^* is determined by the EU's price elasticity $E_p = -\frac{1}{a}$, which implies that the CSP could extract the surplus from the EU as much as possible through setting a high price by taking consideration of the EU's price elasticity. The larger EU's price elasticity is, the more surplus the CSP may extract from the EU. The same results are also suitable for the ISP.

B. Imperfect Competitive Market (ICM)

The Monopoly Market is an extreme case which is hardly achievable in realistic market scenarios. In this subsection, we extend the tripartite game to a more common market scenario: Imperfect Competitive Market (ICM), which includes both multiple CSPs which compete for providing streaming services and ISPs which compete for providing caching services. We assume the CSPs (or ISPs) offer same type of services, i.e., the streaming services provided by the CSPs, or the caching services provided by the ISPs, are indifferent from one another and substitutable from the EU's point of view. However, the CSPs (or ISPs) may have different marginal costs, network externalities, etc.

In the ICM, the CSPs are the price takers, as they have limited power to determine their own prices due to the competition among the CSPs. Because the services provided by the CSPs are substitutable, the price of streaming services is essentially determined by the service supplies of the whole market. We can use the Cournot game to characterize the competition among the CSPs, and in the equilibrium they converge to the same price and consequently determine the equilibrium amount of services each CSP produces. Likewise, since the cache services provided by the ISPs are substitutable, the Cournot game is also applicable to analyze the competition among the ISPs.

In this tripartite game, the EU's revenue function is still represented as Eq. 1 since we treat the EU as one entity that includes all the users of the network. The EU always maximizes its own revenue by choosing optimal bandwidth consumption x, according to the price given by the market. Note that the total supplies of CSPs equal to the optimal bandwidth consumption of EU at the equilibrium state of the game; otherwise, the CSPs will keep on reducing the price p to attract more consumptions until the total supplies equal to the consumptions. Therefore, the price of streaming services is dominated by the sum of bandwidth supplies of CSPs.

Assume there are n CSPs in the market. Let x_i to denote the bandwidth supplies of CSP i, and b_i and c_i denote the corresponding marginal externality and marginal cost, respectively ($i = 1, ..., n$). The revenue of CSP i can be represented as

$$R_{CSP_i} = px_i + b_i x_i - c_i(1-\beta)x_i - q\beta x_i. \tag{9}$$

Similarly, there are m ISPs competing to provide cache services. Let y_i denote the amount of cache services that ISP i provides, δ_i and γ_i denote the corresponding marginal operating cost of cache server and marginal backbone cost, respectively ($i = 1, ..., m$). The revenue of ISP i can be represented as

$$R_{ISP_i} = q\beta y_i - \delta_i \beta y_i - \gamma_i(1-\beta)y_i. \tag{10}$$

We use $y = \sum_{i=1}^{n} y_i$ to denote the total supplies of ISPs. At the equilibrium state, $y = \sum_{i=1}^{m} y_i = \sum_{i=1}^{n} x_i = x$; otherwise, the ISPs will keep on reducing the price q until their services are all sold out.

Connecting the Cournot competitions among CSPs, and the competition among ISPs, to the interactions among the three entities, produces an extensive Stackelberg game. We further proceed to investigate the equilibrium strategy profile of the extensive tripartite game. The essential idea is to follow the backward induction with three-stage procedure. Comparing with the procedure of the MM, the key difference is that we should take the impact of interior competitions of CSPs (and ISPs) into consideration. The three-stage procedure with detailed analysis is presented as follows:

Procedure 1: Getting the inverse demand function. We first seek the inverse demand function that characterizes the price p of streaming services varying with the changing of EU's bandwidth requirements. This procedure is similar to the procedure in the MM described in subsection IV.A. By applying the first order optimality condition to Eq. 1 with respect to x, we obtain the EU's best response $p = \sigma u'(x)$, where $x = \sum_{i=1}^{n} x_i$ is the total bandwidth demand of the streaming services. From $p = \sigma u'(x)$, we can derive that p is a function of x. Note that at the equilibrium state, the consumptions equal to the total supplies. Thus, $p = \sigma u'(x)$ can be interpreted as an inverse demand function $p(x)$, which represents that the price varies with the changing of the total supplies.

Procedure 2: Solving the Cournot game among CSPs. Substituting the inverse demand function $p(x)$ into the revenue function of CSP i indicated in Eq. 9, we have

$$R_{CSP_i} = p(x)x_i + b_i x_i - c_i(1-\beta)x_i - q\beta x_i. \tag{11}$$

Note that $x = \sum_{i=1}^{n} x_i$ is the total amount of bandwidth supplies, the competition among CSPs leads each CSP to its own optimal bandwidth providing x_i^*; Meanwhile, by substituting $x^* = \sum_{i=1}^{n} x_i^*$ into the optimal bandwidth providing, the equilibrium price of the streaming services is determined. This solution is expressed in the following lemma.

***Lemma** 1: The Cournot competition of multiple CSPs leads to the following equilibrium state:*

$$x_i^* = \frac{[p - (1-\beta)c_i - q\beta + b_i] \cdot x^*}{p \cdot a}, \quad p^* = \frac{(1-\beta)\overline{c} + q\beta - \overline{b}}{1 - \frac{a}{n}}, \tag{12}$$

where $x^* = \sum_{i=1}^{n} x_i^*$, $\overline{c} = \frac{1}{n}\sum_{i=1}^{n} c_i$ and $\overline{b} = \frac{1}{n}\sum_{i=1}^{n} b_i$

Procedure 3: Solving the Cournot game among ISPs. ISPs also face a supplies adjustment so as to maximize their own revenues. Since the EU is the ultimate consumer of cache services, if the total supplies of ISPs is larger than the EU's cache service consumptions, the ISPs have to adjust the price q to attract more consumptions of EU until the supplies of cache services equal to the EU's consumptions. In other words, the price q is determined by the total supplies of cache services.

Notice that the optimal price p^* indicated in Eq. 12 contains the price of cache services q. Recall that $E_p = -\frac{1}{a}$, by substituting the inverse demand function $p(x)$ into Eq. 12, we obtain

$$q = \frac{\sigma x^{-a}(1 - \frac{a x_i}{x}) - (1-\beta)c_i + b_i}{\beta}. \tag{13}$$

Notice that q is a function of x, which can be intuitionally interpreted as an inverse demand function of price $q(x)$ that characterizes the changing of price q with the EU's bandwidth consumptions. Then, the corresponding price elasticity E_q with respect to q can be obtained by $E_q = \frac{1}{a}$.

To seek the optimal supplies of ISP i, we substitute Eq. 13 into the revenue function of ISP i indicated in Eq. 10, which yields a function of y_i:

$$R_{ISP_i} = q(x)\beta y_i - \delta_i \beta y_i - \gamma_i(1-\beta)y_i. \tag{14}$$

Note that when the market reaches the equilibrium, it yields $x^* = y^*$. Therefore, the corresponding optimal y_i^* could be found by applying the first-order necessary condition with respect to y_i. The equilibrium price of ISPs can also be derived. The equilibrium strategy profile of the extensive Stackelberg game is shown in the following Lemma.

***Lemma** 2: The Cournot competition of the multiple ISPs leads to the following equilibrium state:*

$$y_i^* = \frac{q - \beta\delta_i - (1-\beta)\gamma_i}{q \cdot a}, q^* = \frac{\beta\overline{\delta} + (1-\beta)\overline{\gamma}}{1 - \frac{a}{n}}, \tag{15}$$

where $y^* = \sum_{i=1}^{n} y_i^*$, $\overline{\delta} = \frac{1}{n}\sum_{i=1}^{n} \delta_i$ and $\overline{\gamma} = \frac{1}{n}\sum_{i=1}^{n} \gamma_i$.

Combining Lemma 1 and Lemma 2 yields the following theorem, where the equilibrium strategy profile of tripartite game can be derived.

***Theorem** 2:* There exists a Nash equilibrium for the extensive Stackelberg game with Cournot competition in the ICM and the equilibrium strategy profile $\{p^*, q^*, x^*\}$ satisfies:

$$p^* = \frac{(1-\beta)\overline{c} + q^*\beta - \overline{b}}{1 - \frac{a}{n}}, q^* = \frac{\beta\overline{\delta} + (1-\beta)\overline{\gamma}}{1 - \frac{a}{n}}, x^* = (\frac{\sigma}{p^*})^{\frac{1}{a}}, \tag{16}$$

where $\overline{c} = \frac{1}{n}\sum_{i=1}^{n} c_i$, $\overline{b} = \frac{1}{n}\sum_{i=1}^{n} b_i$, $\overline{\delta} = \frac{1}{n}\sum_{i=1}^{n} \delta_i$ and $\overline{\gamma} = \frac{1}{n}\sum_{i=1}^{n} \gamma_i$.

Comparing the equilibrium strategy profile in the ICM with that in the MM, we can see that the equilibrium price p^* in the ICM is lower than that in the MM as a result of the Cournot competition among the CSPs. This is primarily due to that, the rival CSPs responding to the higher competition is to increase their own supplies, but this in turn leads to higher residual service supplies and lower market prices. The same result is suitable for the ISPs, both the price of cache services and the corresponding revenue meet a relative shrinkage comparing with these in the MM. In contrast, the equilibrium bandwidth consumptions of the EU increases as the price p decreases. Thus, the EU may get relatively better welfare in the ICM than that in the MM. This observation shows that the market competition can improve EU's welfare.

As an extreme case, when a huge number of CSPs and ISPs are involved in the market, i.e., the numbers of CSPs and ISPs in the market become infinite, such market scenario can be interpreted as a Perfect Competitive Market (PCM). In the PCM, the streaming services provided by a single CSP x_i^* is small compared with the total market service supply x^*, so $-\frac{a}{n}$ indicated in Eq. 16 equals to zero. Therefore, the equilibrium price of CSP in PCM can be further reduced to

$$p^* = (1-\beta)\overline{c} + q^*\beta - \overline{b}. \tag{17}$$

Likewise, the solution of the Cournot game among n ISPs also can be derived as

$$q^* = \beta\overline{\delta} + (1-\beta)\overline{\gamma}. \tag{18}$$

The equilibrium strategy profile of the three parties in the PCM is presented as Theorem 3.

***Theorem** 3: There exists a Nash equilibrium for the tripartite game in the PCM and the equilibrium strategy profile* $\{p^*, q^*, x^*\}$ *satisfies:*

$$p^* = (1-\beta)\overline{c} + q^*\beta - \overline{b}, q^* = \beta\overline{\delta} + (1-\beta)\overline{\gamma}, x^* = (\frac{\sigma}{p^*})^{\frac{1}{a}}. \tag{19}$$

The equilibrium condition of the PCM reveals some interesting results: the optimal consumption of EU $p^* = \sigma u'(x^*)$ shows that it is possible for the CSP to charge the EU a relatively high price in the presence of the cache server ($\sigma > 1$), and the larger the hit ratio is, the higher price the CSP may charge. We also notice that the optimal price of CSP is $p^* = (1-\beta)\overline{c}+q^*\beta-\overline{b}$, due to the existence of the external effective coefficient $\overline{b}$, the bandwidth price in the PCM is possibly very low, and may even equal to zero by taking into account the fact that the average value of CSPs' marginal cost $\overline{c}$ is always very low. The optimal price of ISP $q^* = \beta\overline{\delta} + (1-\beta)\overline{\gamma}$ becomes lower when the hit ratio increases. This is a justifiable result because a high hit ratio can reduce the backbone cost remarkably. From the comparison of the prices p^* and q^* in the MM, ICM and PCM, we can verify that the price decreases as the increasing number of involved CSPs and ISPs. On the contrary, the EU's consumption increases, which implies that the competition can benefit the improvement of the welfare of EU.

V. Incentive for Cache Server's Upgrading

From the above analysis, we can see that the hit ratio β of cache server plays an important roll in determining the strategies of game participants. The existence of cache service could improve the welfare of all involved parties. For instance, for the EU's revenue function indicated in Eq. 1, the sensitivity of its profit with respect to β is always positive, which implies that upgrading the cache server's hit ratio can improve EU's revenue. From the viewpoint of CSPs, the improved performance of the cache server can enhance the EU's viewing experience. It opens the door for charging a higher price to the EU because $p = E(\beta)u'(x)$ and $E(\beta)$ increase with β. However, the decision of whether upgrading a cache server is barely at the hands of ISPs. Therefore, we are interested in the attitude of ISPs towards the upgrading of the cache service infrastructure, which can be regarded as an innovation. Moreover, as there may be multiple ISPs involved in the market, we also investigate how the competition among ISPs affects such innovation.

For clarity of exposition, we consider an innovation as an investment made by an ISP, which will result in the cache sever's hit ratio β being improved. It is reasonable to assume that the hit ratio β depends on the investment that the ISP has invested in cache facilities, regardless of other possible technological factors, e.g., caching algorithms. For instance, in order to get a more capable cache server with a higher hit ratio, more investments are needed. Thus we further make the following assumption on the investment function of ISP: The investment function of a cache server $C_3(\beta)$ is strictly increasing, convex, and twice continuously differentiable. The first-order derivative of $C_3(\beta)$ is denoted by $C_3'(\beta)$. We consider $C_3(\beta)$ as a convex function because it is costly to increase the hit ratio with the consideration of diversified user interests and huge contents in current P2P streaming market. It is reasonable to assume that $C_3(0) = 0$ and $C_3(1) = \infty$.

A. Longstop for Cache Server's Upgrading

We first investigate the incentive for innovations in the MM. Consider the monopolistic ISP whose revenue function is indicated in Eq. 3. As upgrading the cache server would result in an investment cost $C_3(\beta)$, the monopolistic ISP will keep on enhancing the cache server's hit ratio β until achieving the maximal revenue:

$$\beta^* \in arg \max_{\beta}(q\beta y - \delta\beta y - \gamma(1-\beta)y - C_3(\beta)). \tag{20}$$

It seems easy to motivate the ISP to innovate, as the ISP can decrease the backbone cost and charge more from the CSP for the increased traffic via the cache server. However, this fact may no longer hold since continuously upgrading the cache server may cost too much for the ISP when β reaches a certain level. The following theorem verifies this intuition.

***Theorem** 4: There exists a hit ratio* $\beta^* \in (0,1)$ *at which an ISP achieves the revenue maximization such that the ISP has no incentive to further upgrade the cache server.*

Proof: The optimal hit ratio β^* for an ISP can be found by solving the maximization problem indicated in Eq. 20. By applying the first-order condition to Eq. 20 with respect to β, we have

$$\frac{\partial R_{ISP}}{\partial \beta} = qy - \delta y + \gamma y - C_3'(\beta). \tag{21}$$

Recall that the equilibria price in the MM is $q^* = \frac{\beta\delta+(1-\beta)\gamma}{1-a}$. The ISP will get its revenue maximized and stop upgrading the cache server when there exists $\beta^* \in (0,1)$ that satisfies $\frac{\partial R_{ISP}}{\partial \beta} = 0$. By substituting q^* of the MM into Eq. 21, we obtain

$$\frac{\partial R_{ISP}}{\partial \beta} = \frac{\beta\delta y + \gamma y - \beta\gamma y}{1-a} - \delta y + \gamma y - C_3'(\beta). \tag{22}$$

To study whether such β^* exists, we first set $\beta = 0$, which can be regarded as that the ISP does not deploy the cache server at the edge of the network, then $C_3'(0)$ is zero and the corresponding $\frac{\partial R_{ISP}}{\partial \beta} = \frac{\gamma y}{1-a} + (\gamma - \delta)y$ is obviously positive since $\gamma > \delta$.

We proceed to set $\beta = 1$, which implies that the bandwidth requests of the EU are served by the cache server and there is no request passing through the backbone of the ISP, the backbone cost γy of the ISP is zero and $\frac{\partial R_{ISP}}{\partial \beta} = \frac{\delta y}{1-a} + (\gamma - \delta)y - C_3'(\beta)$. It can be verified that $\frac{\partial R_{ISP}}{\partial \beta}$ is negative since $C_3'(\beta)$ tends to infinite when $\beta = 1$.

So there must exist $\beta^* \in (0,1)$ that satisfies $\frac{\partial R_{ISP}}{\partial \beta} = 0$ where the ISP achieves the revenue maximization and has no incentive for the innovation. ■

Theorem 4 shows that there might exist a possible maximal revenue for the ISP for a given cache hit ratio $\beta \in (0,1)$, and the ISP may stop increasing β after achieving the maximization, which means that there is a longstop that the ISP may have no incentive to upgrade the permanence of the cache server, even though the upgrading can increase the profit of EU. This negative attitude of ISP will be an obstacle for innovations in the P2P streaming service, and in long term, it would limit the evolution of the entire P2P streaming market.

B. The Impact of Competition on Cache Server's Upgrading

We have shown that there might exist a longstop of innovation in the P2P streaming service. A possible solution is to introduce competitions into the system. We proceed to study the impact of the competition among ISPs on innovations. As cache server's upgrading made by ISP i would result in an extra cost $C_3(\beta)$ for itself, ISP i needs to solve the following maximization problem

$$\beta^* \in arg \max_{\beta}(q\beta y_i - \delta_i \beta y_i - \gamma_i(1-\beta)y_i - C_3(\beta)). \tag{23}$$

Since more ISPs involve in the market, ISP i will confront with more intense market competition and meet shrinkage of the market share. The following theorem verifies that the ISP would have motivations to conduct a service innovation which would lead to a revenue increase.

***Theorem** 5: The ISP would have incentives for innovations as the competition increases.*

Proof: By applying the first-order condition to Eq. 23 with respect to β, we have

$$\frac{\partial R_{ISP_i}}{\partial \beta} = qy_i - \delta_i y_i + \gamma_i y_i - C_3'(\beta). \tag{24}$$

Recall that the equilibria price q^* in the ICM is $q^* = \frac{\beta\delta_i + (1-\beta)\gamma_i}{1-\frac{ay_i}{y}}$. By substituting q^* into Eq. 24, we obtain

$$\frac{\partial R_{ISP_i}}{\partial \beta} = \frac{y_i[\beta\delta_i + (1-\beta)\gamma_i]}{1-\frac{ay_i}{y}} - \delta_i y_i + \gamma_i y_i - C_3'(\beta). \tag{25}$$

ISP i achieves its maximal revenue when $\frac{\partial R_{ISP_i}}{\partial \beta} = 0$, thus Eq. 25 can be further reduced to

$$C_3'(\beta) = [\frac{\beta\delta_i + (1-\beta)\gamma_i}{1-\frac{ay_i}{y}} + (\gamma_i - \delta_i)]y_i. \tag{26}$$

From Eq. 26, we can verify that y increases when the market competition increases, i.e., the number of ISPs engaging in the market increases, which leads to the increasing of $C_3'(\beta)$ of Eq. 26. Because $C_3'(\beta)$ is an increasing function of β, which implies that the optimal hit ratio β^* when the ISP achieves the revenue maximization will keep on increasing as the market competition increases. Thus, ISP i always has the motivation to upgrade the performance of cache server due to the increasing of the market competition. ■

Theorem 5 shows that as more ISPs participate in the market, the corresponding hit ratio β at which ISP i attains maximal revenue increases. Theorem 4 indicates that it is difficult for a monopoly ISP to upgrade its cache facilities without any external influence. However, Theorem 5 shows that out of competition come innovations, which benefits all participants and the overall social welfare increases. Our findings can have implications for the policy regulator.

VI. Simulation

TABLE I

MODEL'S PARAMETERIZATIONS

Category	Parameter Description	Setting
EU	Utility Function: $\frac{x^{1-a}}{1-a}$	$a = 0.4$
	Demand Function: $x = (\frac{\sigma}{p})^{1/a}$	$\sigma = 2$
CSP	Marginal Cost c	$c = 0.8$
	Network Externality b	$b = 0.6$
ISP	Marginal Operation Cost δ	$\delta = 0.4$
	Marginal Backbone Cost γ	$\gamma = 0.8$
	Cache Server's Hit Ratio β	$\beta = 0.4$
	Fixed Cost of Cache Server $C_3(\beta) = k\beta^3$	$k = 278$

In this section, we conduct numerical experiments to verify the results derived from previous discussions. In particular, we concentrate on examining the effect of the market competition on three parties' revenues. We also investigate how the increasing of market competition affects the ISP's incentives to upgrade the cache server infrastructure. Throughout the experiments, unless otherwise stated, all other parameters are set to the default values indicated in Table I when one of these parameters is varied.

- **Utility Function:** A classical Utility function used in analyzing networks economic is Cobb-Douglas function $u(x) = \frac{x^{1-a}}{1-a}$ [8].
- **Variable Cost of CSP:** We approximate the variable cost of CSP by using the data derived from an investigation of Chinese P2P streaming market [9].

- **Transit Cost of ISP:** The transit cost of ISP is used in [4] based on pricing data of 20 regional ISPs in five different geographic regions from year 2004-2005 [10].
- **Fixed Cost Function of Cache Server:** We approximate the fixed cost function of cache server as $k\beta^{\tau}$, τ is cost coefficient. The related data is derived from [11].

A. Effect of the market competition

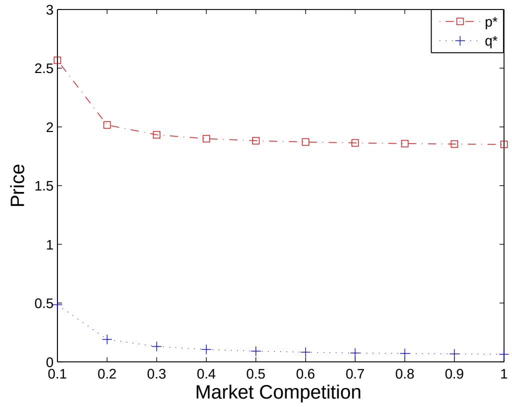

Fig. 3. The effect of the market competition on p^* and q^*.

We first study the effect of the market competition on the prices p and q, as well as the corresponding bandwidth consumptions of EU in the equilibrium strategy profile. We increase the market competition intensity by varying the amount of CSPs and ISPs engaged in the market from 1 to 10. Fig. 3 shows the changing of p and q. We can see that as the market competition increases from 1 to 10, both the prices of p and q decrease. The intuition behind this observation is that as more and more competitors participate in the market, the service supplies increase, which results in reduced service prices. Notice that the prices of p and q decrease significantly at the initial range of the competition, e.g., the market competition varies from 1 to 3, and then becomes gentle afterwards. This observation shows that monopolistic ISP and CSP are more sensitive to the market competition and they react more intensively in face of competition.

As the market competition increases, the EU's service consumption x under the equilibrium strategy profile is shown in Fig. 4. In contrast, the EU's consumption increases with the increasing of market competition. This is easily understood: as the market competition increases, the price p decreases and leads to the increasing of EU's consumptions.

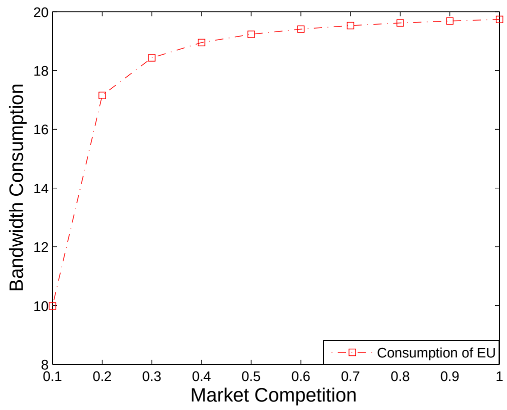

Fig. 4. The effect of the market competition on x^*.

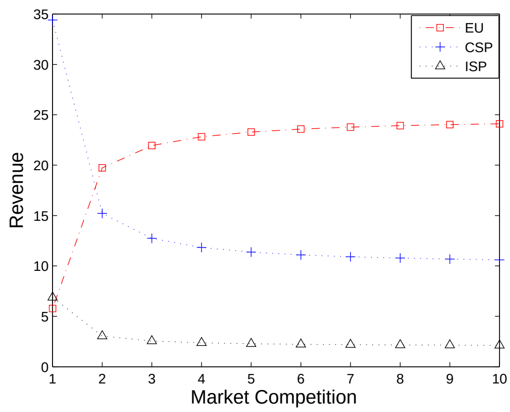

Fig. 5. The effect of the market competition on the revenues of three parties.

We proceed to investigate the effect of market competition on the three parties' revenues. The market competition increases as the number of engaged ISPs and CSPs increase. Fig. 5 shows the revenues of three parties when the market competition varies. We can see that the revenues of CSP and ISP both decrease when the market competition increases; in contrast, the EU's revenue increases when the market competition increases. This phenomenon is not surprising, as increasing the market competition suppresses the prices of CSP and ISP, which leads to a larger service consumption of EU in the equilibrium. In other words, the increasing of market competition reduces the revenues of CSP and ISP. Thus, the EU can achieve a better revenue level when the market competition becomes intensive.

B. Effect of the hit ratio

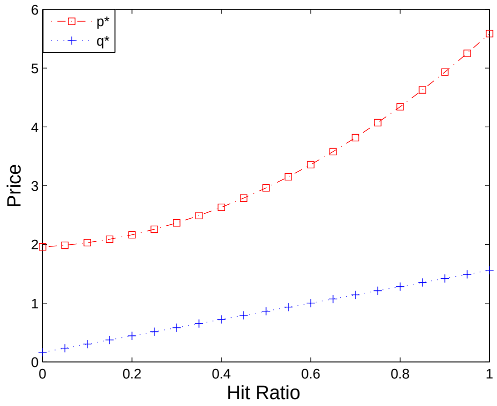

Fig. 6. The effect of the hit ratio on p^* and q^*.

As seen from previous analysis, the hit ratio β of the cache server plays an important role in determining the strategies of the involved parties. The effect of varying β on the prices of p and q is shown in Fig. 6 while β varies from 0 to 1. We can see that both p and q increase as β increases, which means that the increasing of the hit ratio benefits both CSP and ISP for charging a high price. However, the price of CSP increases more remarkably because the price of CSP needs to take the consideration of the increasing price of ISP.

Lastly, we study the effect of the hit ratio on three parties' revenues in different market scenarios. We set various market competitions, i.e., the numbers of engaged providers equal to 1, 5 and 20, which represent the MM, ICM and PCM, respectively.

For the MM shown in Fig. 7(a), we can see that as β increases, the revenue of EU increases monotonically. We notice that the higher hit ratio results in a very slow revenue growth of CSP. This is because that, the higher β is, the more rental fee the CSP pays for the cache server. We can also see that there exists a maximal revenue of ISP when $\beta = 0.33$, and then the ISP's revenue decreases when β continues increasing. These observations suggest that both the CSP and ISP will have no incentive to upgrade the cache server when the hit ratio achieves a certain level, even through the upgrading can increase the revenue of EU.

From the comparison of three market scenarios shown in Fig. 7(a-c), we can see that the ISP always has an optimal β that maximizes its revenue in different market scenarios. However, such

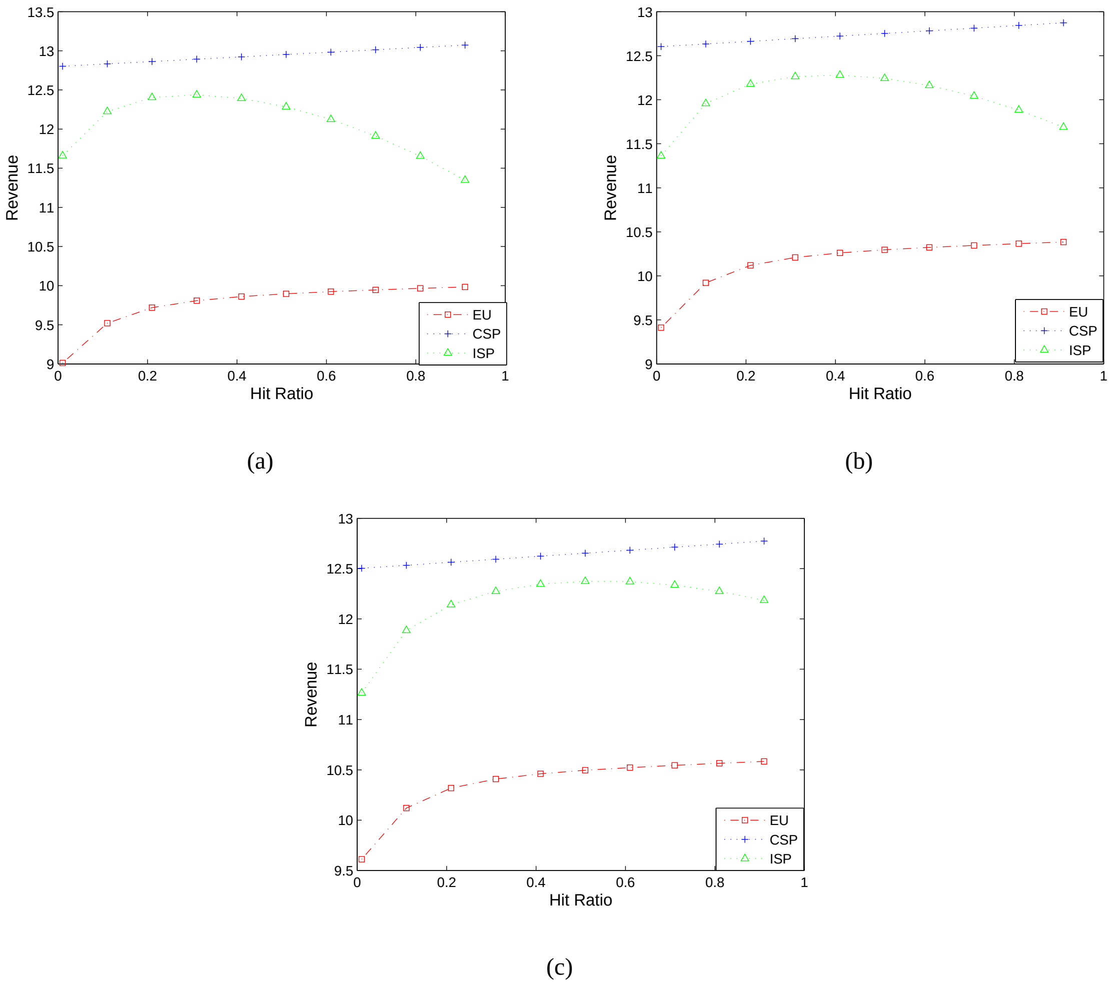

Fig. 7. The effect of the hit radio on the revenues of three parties under different market scenarios: (a) MM; (b) ICM; (c) PCM.

optimal $\beta = 0.42$ in the ICM is larger than $\beta = 0.33$ in the MM and is lower than $\beta = 0.51$ in the PCM. This observation implies that the market competition can motivate the ISP to upgrade the cache service infrastructure. These findings could be useful, e.g., they can be used to help policy regulators to make decisions on whether introducing more competition into the streaming market so as to propel the ISP to upgrade the cache services and improve the overall social welfare ultimately.

VII. Related work

Due to the significant impact that P2P applications have on networks, P2P-friendly solutions have been extensively studied recently. A common approach is the P2P traffic locality. A typical work is the P4P project [12] which claimed that their designs can result in a “win-win” situation for both EUs and ISPs. However, there are many limitations on P2Ps determining locality since the efficiency of the method relies heavily on the global topology. Another effective approach is to cache the P2P traffic. Karagiannis et al. [13] showed that current P2P protocols are not ISP-friendly because they impose unnecessary traffic in ISPs. The study in [7] indicated that the P2P traffic responds well to the caching and suggested deploying caches at the edge of networks.

Employing economic models in various networks is a very active research area. The core of employing economic models is the pricing mechanisms, which are introduced to optimize the allocation of network resources. Kunniyur et al. [14] proposed to apply a pricing mechanism to the congestion control in Internet. In [15] [16], the authors proposed pricing algorithms in a DiffServ environment based on the cost of providing different levels of services. However, in such studies, prices were used mainly as the control information in distributed algorithms, which failed to reflect the actual value of the consumed network resources.

Over the past few years, combining economic models with game theoretic analysis has become increasingly popular in network economics. Park et al. [17] constructed a formal game theoretic model to investigate the issues of incentives in file sharing. Antoniadis et al. [18] developed a theoretical framework that abstracts the shared contents as public goods and a social planner that improves the cooperation through a proper pricing scheme. This line of works mostly focuses on handling the free-riding behaviors in P2P networks [19]. Other recent works that worth noting are [20] [21] [22]. In [20], economic models were introduced to analyze the dynamic interactions between an incumbent and an entrant. The authors in [21] focused on a broad topic of innovation and incentives. The work in [22] studied the issue that is related to accountability, contracts, competition, and innovation in the specific context of network monitoring and contracting system.

Those economic models are more care about the profits of service providers, regardless of the experience of EUs. This treatment clearly does not match well with the real situation of nowadays Internet, since the preference of EUs actually motivates their consumptions of services. Distinguished from existing game theoretical frameworks, our work concentrates on analyzing the tussle among the parties involved in P2P streaming applications, where EUs are regarded as an important entity. In addition, we not only consider the incentives of invocation in P2P streaming applications, but also investigate the equilibrium conditions under various market competition scenarios.

VIII. Conclusion and Future Work

In this paper, we proposes a feasible business model to enable all involved parties to enlarge their benefits with the help of a novel QoS-based architecture integrated with caching techniques. We model the interactions among CSPs, ISPs and EUs as a tripartite game by introducing a pricing scheme that captures both network and business aspects of the P2P streaming applications. We explore the relationships among the three parties in the MM by applying a three-stage Stackelberg game and derive the corresponding equilibrium strategy profile. We further extend the tripartite game into two more complicated scenarios of ICM and PCM, where the Cournot game is introduced to model the competition among multiple CSPs and ISPs. We also investigate the incentive for ISPs to upgrade the cache service infrastructure in different market scenarios. We find that there exists a longstop at which ISPs may have no incentive to upgrade the cache service infrastructure. However, we show that the increasing of market competition can propel the ISPs to improve the cache server's performance. An interesting future work worthy of attention is to construct a proper pricing scheme and achieve the maximal welfare of the whole P2P streaming system.

References

[1] C. Huang, J. Li, and K. Ross, "Can Internet Video-on-Demand be Profitable?" in *Proc. of ACM SIGCOMM*, 2007.

[2] X. Zhang, J. Liu, B. Li, and T.-S. P. Yum, "CoolStreaming/DONet: A Data-Driven Overlay Network for Peer-to-Peer Live Media Streaming," in *Proc. of IEEE Infocom*, 2005.

[3] PPTV.com. [Online]. Available: http://www.pptv.com/

[4] H. Chang, S. Jamin, and W. Willinger, "To Peer or Not to Peer: Modeling the Evolution of the Internet's AS-Level Topology," in *Proc. of IEEE Infocom*, 2006.

[5] R. Keralapura, N. Taft, C. N. Chuah, and G. Iannaccone, "Can ISPs Take the Heat from Overlay Networks?" in *Proc. of ACM HotNets*, Nov 2004.

[6] R. Choffnes and F. E. Bustamante, "Taming the Torrent: A Practical Approach to Reducing Cross-ISP Traffic in P2P Systems," in *Proc. of ACM SIGCOMM*, 2008.

[7] M. Hefeeda and B. Noorizadeh, "On the Benefits of Cooperative Proxy Caching for Peer-to-Peer Traffic," *IEEE Trans. on Parallel Distributed Systems*, vol. 21, no. 7, 2010.

[8] W. Meeusen and J. V. D. Broeck, “Efficiency Estimation from Cobb-Douglas Production Functions with Composed Error,” in *Oxford University Press*, 1977, pp. 435–444.

[9] iResearch Consulting Group, “China P2P Streaming Research Report 2007,” in *Investigate Report*, 2007.

[10] W. B. Norton, “Current Street Prices for US Internet Transit,” in *Posting to the NANOG mailing list*, Aug 2004.

[11] PeerApp.com, “Intelligent Media Caching Solutions P2P Streaming.” [Online]. Available: http://www.peerapp.com

[12] H. Xie, R. Yang, A. Krishnamurthy, Y. Liu, and A. Silberschatz, “P4P: Provider Portal for P2P Applications,” in *Proc. of ACM SIGCOMM*, 2008.

[13] T. Karagiannis, P. Rodriguez, and K. Papagiannaki, “Should Internet Service Providers Fear Peer-assisted Content Distribution?” in *Proc. of ACM SIGCOMM*, Oct 2005.

[14] S. Kunniyur and R. Srikant, “Analysis and Design of an Adaptive Virtual Queue Algorithm for Active Queue Management,” in *Proc. of ACM SIGCOMM*, 2001.

[15] L. He and J. Walrand, “Pricing and Revenue Sharing Strategies for Internet Service Providers,” in *Proc. of IEEE Infocom*, 2005.

[16] G. Tan and S. A. Jarvis, “A Payment-Based Incentive and Service Differentiation Scheme for Peer-to-Peer Streaming Broadcast,” *IEEE Trans. on Parallel Distributed Systems*, vol. 19, no. 7, 2008.

[17] J. Park and M. Schaar, “Pricing and Incentives in Peer-to-Peer Networks,” in *Proc. of IEEE Infocom*, 2010.

[18] C. Courcoubetis and R. Weber, “Incentives for Large Peer-to-Peer Systems,” *IEEE JSAC*, vol. 24, no. 5, pp. 1034–1050, 2006.

[19] M. Feldman and J. Chuang, “Overcoming Free-riding Behavior in Peer-to-Peer Systems,” in *ACM SIGecom Exchanges*, 2005.

[20] Y. Jin, S. Sen, R. Guerin, K. Hosanagar, and Z. L. Zhang, “Dynamics of Competition between Incumbent and Emerging Network Technologies,” in *Proc. of ACM NetEcon*, 2008.

[21] S. Scotchmer, “Innovation and Incentives,” in *MA: MIT Press*, 2004.

[22] P. Laskowski and J. Chuang, “Network Monitors and Contracting System: Competition and Innovation,” in *Proc. of ACM SIGCOMM*, 2006.