Can P2P Technology Benefit Eyeball ISPs? A Cooperative Profit Distribution Answer

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Abstract—Peer-to-Peer (P2P) technology has been promoting the development of Internet applications, like Video on Demand (VoD) and file sharing. However, under the traditional pricing mechanism, the fact that most P2P traffic flows among peers can dramatically decrease the profit of ISPs, who may take actions against P2P and impede the adoption of P2P-assisted applications. So far, there is no proper profit distribution mechanism to solve this problem. In this paper, we develop a mathematical framework to analyze such economic issues. Inspired by the idea from cooperative game theory, we propose a cooperative profit-distribution model based on Nash Bargaining Solution (NBS), in which both eyeball ISPs and Peer-assisted Content Providers (PCPs) form coalitions and compute a fair Pareto point to determine profit distribution. Moreover, we design a fair and feasible mechanism for profit distribution within each coalition and give a model to discuss the potential competition among ISPs. We show that such a cooperative method not only guarantees the fair profit distribution among network participants, but also improves the economic efficiency of the network system; and the potential competition among ISPs will make the network more efficient. This paper systematically studies solutions to unbalanced profit distribution caused by P2P and presents a feasible cooperative method to increase and fairly distribute the profit.

Index Terms—P2P, internet service providers, content providers, profit distribution, nash bargaining solution

1 Introduction

As the foundation of many important Internet applications like Video on Demand (VoD) and file sharing, Peer-to-Peer (P2P) architecture makes a nontrivial contribution to the increase of the network traffic. A detailed introduction to the development of P2P is provided in Section 1.1 of the supplementary file which is available in the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2013.267.

P2P's superiority to the traditional Client/Server (C/S) architecture has been demonstrated by lots of academic work [3], [4], [5], [6], [7], [8] and many successful commercial systems (such as PPLive [9], UUSee [10], and PPStream [11]). PPVA [6] is proposed for universal and transparent P2P acceleration. We believe more and more Content Providers (CPs) will adopt P2P technology.

However, under the traditional Internet pricing mechanism, free-riding P2P traffic causes unbalanced profit distribution between Peer-assisted CPs (PCPs) and eyeball Internet Service Providers (ISPs) [12]. Here, the eyeball ISPs specialize in delivery to end customers. As we know, many eyeball ISPs charge a flat price [13], [14], [15]. Then P2P traffic transfers the cost of content delivery from CPs to ISPs. As a result, the profit of CPs increases, while that of ISPs decreases. Unlike eyeball ISPs, transit ISPs [12] often charge eyeball ISPs based on exchanged traffic [16] and do not give P2P the chance of free riding. Thus, transit ISPs do not need to consider the problem discussed in this paper, and all ISPs refer to eyeball ISPs.

The content-based revenues of CPs significantly exceed the connectivity-based revenues of eyeball ISPs, and the free-riding of P2P traffic intensifies the unbalanced profit distribution, which will drive ISPs to take actions against free-riding P2P, including engineering [17], [18], [19], [20] and pricing strategies [21], [22], [23]. But these actions will take customers away [14]. Another strategy is to charge volume-based rates instead of flat rates [14], [22]. Actually, in recent years, the flat-rate billing has been mostly discarded by ISPs such as Comcast, AT&T, Verizon and T-Mobile [24]. As a result, ISP profits can be guaranteed at a reasonable level. However, P2P users have to pay for the increasing P2P traffic and P2P applications become less attractive. Consequently, the volume of P2P traffic will sharply decrease and PCP profit will fall down quickly.

The unbalanced profit distribution can finally impede the adoption of P2P technology, which consequently leads to the question: *Can we find a profit-distribution model in which P2P technology can also benefit ISPs*? This paper will give a positive answer to this question.

Inspired by the idea from cooperative game theory, we propose a cooperative profit-distribution model based on the concept of Nash bargaining [25]. In this model, ISPs and PCPs form two coalitions and cooperate to maximize their total profit by stimulating the consumption of P2P service, and fairly divide the profit. To guarantee stability, we also consider a proper mechanism for profit distribution within

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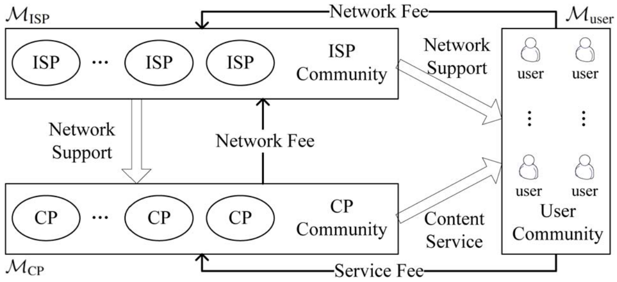

Fig. 1. Relationships among $\mathcal{M}_{\text{ISP}}$, $\mathcal{M}_{\text{CP}}$, and $\mathcal{M}_{\text{user}}$.

each coalition. The main contributions of this paper are listed as follows:

1. We build a mathematical framework to describe the multilateral interactions among ISPs, CPs and users in three possible non-cooperative states;
2. We propose a cooperative profit-distribution model in which P2P technology can fairly benefit both PCP and ISP coalitions;
3. We design a fair and feasible mechanism for profit distribution within each coalition and give examples to prove the effectiveness of the cooperative profit-distribution model;
4. We give a model to discuss the potential competition among ISPs and the effect of the competition on network traffic localization.

The rest of the paper is organized as follows. We first propose a network model in Section 2. Then, to compare the results between the non-cooperative game and the cooperative game, we discuss the non-cooperative interactions among ISPs, PCPs and users in Section 3, before proposing a cooperative profit distribution model in Section 4. Further, we present our mechanism for profit distribution within each coalition in Section 5 and discuss the potential competition among ISPs in Section 6. In Section 7, we discuss the related work, followed by our conclusion in Section 8.

2 Network Model

The network model consists of three communities: ISP community, CP community and user community, which are denoted by $\mathcal{M}_{\text{ISP}}$, $\mathcal{M}_{\text{CP}}$, and $\mathcal{M}_{\text{user}}$, respectively. Their relationships are illustrated in Fig. 1. In a practical network system, $\mathcal{M}_{\text{ISP}}$ often charges $\mathcal{M}_{\text{CP}}$ a bandwidth-based price (such as the 95-percentile billing for exploding bandwidth [16]) and charges $\mathcal{M}_{\text{user}}$ a flat price [15], [26]. Moreover, $\mathcal{M}_{\text{CP}}$ often charges $\mathcal{M}_{\text{user}}$ based on its consumed traffic volume.

It is the precondition of our model that the ISPs and the CPs form their own coalitions. In Section 1.3 of the supplementary file available online, we provide additional analysis on the formation of the coalitions from the perspectives of homogeneous and heterogeneous interactions.

The CPs who can adopt P2P technology become PCPs, then $\mathcal{M}_{\text{CP}} = \mathcal{M}_{\text{PCP}} \cup \mathcal{M}^r_{\text{CP}}$, where $\mathcal{M}_{\text{PCP}}$ is the set of PCPs, and $\mathcal{M}^r_{\text{CP}}$ consists of the CPs who cannot adopt P2P in their services. Table 2 in the supplemental file available online lists the notations in our model.

In the C/S network, all service contents flow from $\mathcal{M}_{\text{CP}}$ to $\mathcal{M}_{\text{user}}$ through $\mathcal{M}_{\text{ISP}}$'s network. Suppose the bandwidth bought by $\mathcal{M}_{\text{CP}}$ is b_{CP}, and that bought by $\mathcal{M}_{\text{user}}$ is b_{user}. For $\mathcal{M}_{\text{CP}}$ and $\mathcal{M}_{\text{user}}$, their average bandwidth utilization rates are ξ_{CP} and ξ_{user}, respectively. Usually, ξ_{CP} is higher than ξ_{user} (CPs use bandwidth more efficiently). Let v be the traffic volume, so we have:

$$v = b_{\text{CP}} \cdot \xi_{\text{CP}} = b_{\text{user}} \cdot \xi_{\text{user}}. \tag{1}$$

In the peer-assisted network, the service contents consist of two parts: the contents provided by $\mathcal{M}_{\text{PCP}}$ and that provided by $\mathcal{M}^r_{\text{CP}}$. The former is more complex because it comes from both $\mathcal{M}_{\text{PCP}}$ and $\mathcal{M}_{\text{user}}$. Suppose the traffic of $\mathcal{M}_{\text{PCP}}$ accounts for a proportion α in the total traffic of $\mathcal{M}_{\text{CP}}$. Generally, the P2P contents provided by the servers of $\mathcal{M}_{\text{PCP}}$ accounts for a small proportion β and the rest will be provided by $\mathcal{M}_{\text{user}}$. Note that the value of β is a statistical measurement of the percentage of the traffic delivered by servers. In this case, $\mathcal{M}_{\text{PCP}}$ can reduce its bought bandwidth to a smaller value b^*_{PCP}, so as to reduce the cost and keep its bandwidth utilization rate at ξ_{CP}, while $\mathcal{M}_{\text{user}}$ with fixed bandwidth at b_{user}, will increase its bandwidth utilization rate to a higher value ξ^*_{user}, which makes the link or path busier.

We assume the emergence of P2P traffic will not impact the traffic of $\mathcal{M}^r_{\text{CP}}$ because the traditional services provided by $\mathcal{M}^r_{\text{CP}}$ such as web and email, have a low elasticity of demand and the consumption will not be affected by P2P applications. Then $\mathcal{M}^r_{\text{CP}}$ will keep its traffic at $v_{\text{cs}} = b_{\text{CP}} \cdot (1-\alpha) \cdot \xi_{\text{CP}}$. We denote the amount of the user-side P2P upload traffic by v_{up}, and then we have:

$$\begin{aligned} v_{\text{p2p}} \cdot \beta &= b^*_{\text{PCP}} \cdot \xi_{\text{CP}} \\ v_{\text{p2p}} \cdot (1-\beta) &= v_{\text{up}} \end{aligned}$$

which means that user's demand for $\mathcal{M}_{\text{PCP}}$ with a β proportion is satisfied by the servers of the PCP, and the other $1-\beta$ proportion is satisfied by other user's upload. Then we can derive the user-side total traffic volume, which is generated by user's consumption of the contents from $\mathcal{M}_{\text{PCP}}$:

$$v_{\text{p2p}} + v_{\text{up}} = v_{\text{p2p}} \cdot (2-\beta) = b^*_{\text{PCP}} \cdot \xi_{\text{CP}} \cdot \frac{2-\beta}{\beta}. \tag{2}$$

Similar to the case of C/S network, we have:

$$\begin{aligned} v_{\text{p2p}} + v_{\text{up}} + v_{\text{cs}} &= b^*_{\text{PCP}} \cdot \xi_{\text{CP}} \cdot \frac{2-\beta}{\beta} + b_{\text{CP}} \cdot (1-\alpha) \cdot \xi_{\text{CP}} \\ &= b_{\text{user}} \cdot \xi^*_{\text{user}}. \end{aligned} \tag{3}$$

v_{up} shows the extra burden on the users brought by P2P. We assume $\xi_{\text{CP}} \geq \xi^*_{\text{user}} \geq \xi_{\text{user}}$ because even if the emergence of P2P traffic increases user's bandwidth utilization rate, the CPs with professional technical team and cost saving mechanism can gain a higher one. Here, we assume $\beta > 0$, which means the server always provides contents and makes the equation meaningful.

3 Non-Cooperative Game Model

In this section, we will explore the multi-lateral economic relationships among ISPs, CPs and users with the analysis

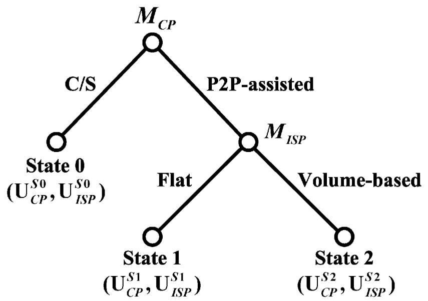

Fig. 2. Strategy-chosen game tree.

of two games, the *strategy-chosen* game between ISPs and CPs, and the two-stage *price-decision* game among ISPs, CPs and users. A detailed analysis of the relationship between these two games is presented in Section 4.1 of the supplementary file available online.

3.1 Strategy-Chosen Game

We use a dynamic game between $\mathcal{M}_{\text{ISP}}$ and $\mathcal{M}_{\text{CP}}$ to analyze their strategies on technology and pricing. As discussed in Sections 1 and 2, the CPs can choose between C/S networks and P2P-assisted networks, and the ISPs can choose to charge users flat rates or volume-based rates.

The game tree is shown in Fig. 2. States 0, 1, and 2 refer to the possible market states determined by the strategies chosen by $\mathcal{M}_{\text{ISP}}$ and $\mathcal{M}_{\text{CP}}$. $\mathbb{U}_{\text{CP}}^{\text{S}i}$ and $\mathbb{U}_{\text{ISP}}^{\text{S}i}$ refer to the profit of $\mathcal{M}_{\text{CP}}$ and $\mathcal{M}_{\text{ISP}}$ in State i ($i = 0,\ 1,\ 2$). Theoretically, another possible state exists in the market and the extended game is analysed in Section 2.3 of the supplementary file available online.

The payoffs of $\mathcal{M}_{\text{ISP}}$ and $\mathcal{M}_{\text{CP}}$ in each state are determined by the equilibrium of the two-stage *price-decision* game in Section 3.2 and the values of the payoffs will determine the equilibrium of this *strategy-chosen* game.

3.2 Two-Stage Price-Decision Game

A three-player non-cooperative game can be used to characterize the interactions among $\mathcal{M}_{\text{ISP}}$, $\mathcal{M}_{\text{CP}}$ and $\mathcal{M}_{\text{user}}$. We introduce $\mathcal{M}_{\text{user}}$ because user's reactions are involved in the price decision of $\mathcal{M}_{\text{ISP}}$ and $\mathcal{M}_{\text{CP}}$. The precondition for this game is that both $\mathcal{M}_{\text{ISP}}$ and $\mathcal{M}_{\text{CP}}$ have chosen their strategies, which have been discussed in Section 3.1. We analyze a two-stage game to determine b_{user}, the bandwidth requirement of $\mathcal{M}_{\text{user}}$, and the basic traffic usage v at equilibrium. We use *backward induction* to solve this game and obtain an initial equilibrium market state (State 0).

3.2.1 Game Formulation

We give an overview of the two-stage price-decision game in Fig. 3 to demonstrate the strategies of participants and the repeated game between $\mathcal{M}_{\text{ISP}}$ and $\mathcal{M}_{\text{CP}}$. At the first stage, $\mathcal{M}_{\text{ISP}}$ and $\mathcal{M}_{\text{CP}}$ decide the prices through a non-cooperative repeated game; at the second stage, $\mathcal{M}_{\text{user}}$ makes the optimal traffic usage decision according to the prices set at the first stage.

Initially, $\mathcal{M}_{\text{ISP}}$ charges $\mathcal{M}_{\text{CP}}$ a bandwidth-based price p_b and charges $\mathcal{M}_{\text{user}}$ a flat price τ. In reality, the ISPs always expect to gain a higher (at least the same) unit bandwidth profit from users than from CPs. Thus, τ is set based on

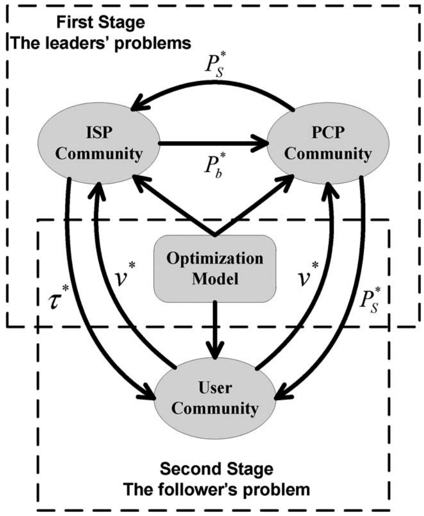

Fig. 3. Overview of the two-stage price-decision game. The arrows illustrate the input and the output of each community and the * represents the final optimal reaction, i.e., the NE.

a given ξ_{user} ($\tau = \frac{1}{\delta} \cdot \frac{v}{\xi_{\text{user}}} \cdot p_b$, $0 < \delta \leq 1$). Then, the profit of $\mathcal{M}_{\text{ISP}}$ is

$$\begin{aligned}\mathbb{U}_{\text{ISP}}^{\text{S0}}(p_b) &= b_{\text{CP}} \cdot p_b + \tau - \mathbf{C}_{\text{ISP}}(v)\\ &= \left(\frac{v}{\xi_{\text{CP}}} + \frac{1}{\delta} \cdot \frac{v}{\xi_{\text{user}}}\right) \cdot p_b - \mathbf{C}_{\text{ISP}}(v)\end{aligned} \tag{4}$$

where $\mathbf{C}_{\text{ISP}}(\cdot)$ is a composite cost function [27].

For $\mathcal{M}_{\text{CP}}$, p_s is the unit service price and $\mathbf{F}_{ad}(\cdot)$ is a volume-based advertisement fee function. Then, its profit is

$$\begin{aligned}\mathbb{U}_{\text{CP}}^{\text{S0}}(p_s) &= v \cdot p_s + \mathbf{F}_{ad}(v) - b_{\text{CP}} \cdot p_b - \mathbf{C}_{\text{CP}}(v)\\ &= v \cdot p_s + \mathbf{F}_{ad}(v) - \frac{v}{\xi_{\text{CP}}} \cdot p_b - \mathbf{C}_{\text{CP}}(v)\end{aligned} \tag{5}$$

where $\mathbf{C}_{\text{CP}}(\cdot)$ is a volume-based cost function.

$\mathbf{E}_{\text{user}}(v)$ denotes the *utility* of $\mathcal{M}_{\text{user}}$, who consumes contents with volume v. Then, the *net utility* is

$$\begin{aligned}\mathbb{U}_{\text{user}}^{\text{S0}}(v) &= \mathbf{E}_{\text{user}}(v) - (b_{\text{user}} \cdot p_b + v \cdot p_s)\\ &= \mathbf{E}_{\text{user}}(v) - \left(\frac{p_b}{\xi_{\text{user}}} + p_s\right) \cdot v.\end{aligned} \tag{6}$$

In this C/S network, a three-player game can characterize the interactions. $\mathcal{M}_{\text{ISP}}$ and $\mathcal{M}_{\text{CP}}$ act as leaders to price $\mathcal{M}_{\text{user}}$, who acts as a follower to decide traffic usage. In addition, since $\mathcal{M}_{\text{ISP}}$ and $\mathcal{M}_{\text{CP}}$ jointly affect the resource usage of $\mathcal{M}_{\text{user}}$, between them starts a two-player non-cooperative game.

According to *backward induction* in the leader-follower game, we first analyze the second stage, assuming that $\mathcal{M}_{\text{ISP}}$ and $\mathcal{M}_{\text{CP}}$ have set the prices at the first stage.

The Follower's Problem

Given p_b and p_s, $\mathcal{M}_{\text{user}}$ will maximize the net utility in Eq. (6). By solving the follower's problem, we can obtain the volume consumed by $\mathcal{M}_{\text{user}}$:

$$\hat{v}(p_b, p_s) = \min\left\{\arg\max_{v} \mathbb{U}_{\text{user}}(v), b_{\text{user}} \cdot \xi_{\text{user}}\right\} \tag{7}$$

which is $\mathcal{M}_{\text{user}}$'s optimal traffic usage decision within purchased capacity. According to the first order condition for Eq. (6), $\mathbf{E}'_{\text{user}}(v) = \frac{\mathrm{d}\mathbf{E}_{\text{user}}(v)}{\mathrm{d}v} = d \cdot p_b + p_s > 0$ $(d = 1/(\delta \cdot \xi_{\text{user}}))$, so $\mathbf{E}_{\text{user}}(v)$ is continuously increasing. We assume that $\mathbf{E}'_{\text{user}}(v)$ is a one-to-one mapping, then we have $\hat{v}(p_b, p_s) = \mathbf{E}'^{-1}_{\text{user}}(d \cdot p_b + p_s)$.

The Leaders' Problems

According to the follower's reaction, users will choose $v = \hat{v}(p_b, p_s)$ to optimize their net utility. Then the leaders' problems become:

$$\text{For } \mathcal{M}_{\text{ISP}} : \max_{p_b} \mathbb{U}_{\text{ISP}}(p_b, \hat{v}(p_b, p_s))$$
$$\text{For } \mathcal{M}_{\text{CP}} : \max_{p_s} \mathbb{U}_{\text{CP}}(p_s, \hat{v}(p_b, p_s)).$$

Afterward a two-player non-cooperative game between $\mathcal{M}_{\text{ISP}}$ and $\mathcal{M}_{\text{CP}}$ happens. $\mathcal{M}_{\text{ISP}}$ and $\mathcal{M}_{\text{CP}}$ take turns to optimize their own object $\mathbb{U}_{\text{ISP}}$ and $\mathbb{U}_{\text{CP}}$ by varying their own decision variable p_b and p_s, respectively, keeping that of the other player as a constant. The existence of NE for this multi-leader-follower game depends on the properties of each net utility function and the existence and the uniqueness of pure NE have been well proved for particular continuous games [28].

3.2.2 Game Solution

Let (p_b^*, p_s^*) be the NE. According to the definition of NE, the solution turns out to be:

$$\begin{cases} p_b^* = \arg\max\limits_{p_b} \mathbb{U}_{\text{ISP}}\big(p_b, \hat{v}(p_b, p_s^*)\big) \\ p_s^* = \arg\max\limits_{p_s} \mathbb{U}_{\text{CP}}\big(p_b^*, \hat{v}(p_b^*, p_s)\big). \end{cases} \tag{8}$$

We have the following theorem on the simplified sufficient conditions of NE for this problem, and the proof can be found in Section 3 of the supplementary file available online.

Theorem 1. *Let (p_b^*, p_s^*) be the NE defined in Eq. (8) and $v^* = \hat{v}(p_b^*, p_s^*)$. Let:*

$$\begin{aligned} \mathbf{\Phi}_1(v) &= c \cdot v \cdot \frac{1}{d} \cdot \frac{\mathrm{d}\mathbf{E}'_{\text{user}}(v)}{\mathrm{d}v} - \frac{\mathrm{d}\mathbf{C}_{\text{ISP}}(v)}{\mathrm{d}v} \\ \mathbf{\Phi}_2(v) &= v \cdot \frac{\mathrm{d}\mathbf{E}'_{\text{user}}(v)}{\mathrm{d}v} + \frac{\mathrm{d}\mathbf{F}_{ad}(v)}{\mathrm{d}v} - \frac{\mathrm{d}\mathbf{C}_{\text{CP}}(v)}{\mathrm{d}v}. \end{aligned} \tag{9}$$

Then, it must satisfy the following two conditions:

1. $\mathbf{E}'_{\text{user}}(v^*) + \mathbf{\Phi}_1(v^*) + \mathbf{\Phi}_2(v^*) = 0$
2. $(\frac{c}{d} \cdot \frac{\mathrm{d}\mathbf{E}'_{\text{user}}(v)}{\mathrm{d}v} + \frac{\mathrm{d}\mathbf{\Phi}_1(v)}{\mathrm{d}v})|_{v^*} < 0$, $(\frac{\mathrm{d}\mathbf{E}'_{\text{user}}(v)}{\mathrm{d}v} + \frac{\mathrm{d}\mathbf{\Phi}_2(v)}{\mathrm{d}v})|_{v^*} < 0$

where $c = \frac{1}{\xi_{\text{user}}} + \frac{1}{\xi_{\text{cp}}}$, and $e = \frac{1}{\xi_{\text{cp}}}$.

This theorem provides a way to computing the NE of the game which represents the steady state of this network market (State 0). If $\mathbf{E}_{\text{user}}(v)$, $\mathbf{F}_{ad}(v)$ and the cost of $\mathcal{M}_{\text{ISP}}$ and $\mathcal{M}_{\text{CP}}$ are known with satisfactory properties, we can derive the NE in closed-form directly from this theorem.

3.3 P2P-Involved Profit Computing Model

One important job of this paper is to measure and quantify P2P traffic's impact on the network market under traditional pricing mechanisms, which helps us analyze and predict potential changes to the market. For example, if P2P causes a seriously unfair profit distribution, a new charging way might be adopted to make up the deficiency. However, the decision will affect the profit of others since user demand internally determines the profit of both $\mathcal{M}_{\text{ISP}}$ and $\mathcal{M}_{\text{CP}}$. In this subsection, we will give a detailed analysis on these issues.

Based on the results of Section 3.2.2, we first analyze the impact of P2P traffic on the profit or utilities of the participants when the pricing strategy remains unchanged, which we define as State 1. It is clear that $\mathcal{M}_{\text{ISP}}$ will bear an increasingly large burden with the growth of P2P traffic since its profit is calculated based on Eq. (4). Therefore we illustrate an analysis of $\mathcal{M}_{\text{ISP}}$'s reactive behavior conditionally and study its corresponding state, i.e., State 2. Finally, we present a state transition graph to summarize these possible non-cooperative market states and their transition conditions.

3.3.1 State 1

In the peer-assisted network, we have assumed that v_{cs} will not be impacted by the emergence of P2P traffic (i.e., $v_{\text{cs}} = v^*_{\text{cs}} = v^* \cdot (1 - \alpha)$). Compared with C/S, P2P improves the experience of $\mathcal{M}_{\text{user}}$ because users get contents more quickly by P2P. For example, the P2P video streaming system PPLive improves the viewing experience of users [3]. Let $\widehat{\mathbf{E}}_{\text{user}}$ be $\mathcal{M}_{\text{user}}$'s new utility for contents volume $v = v_{\text{p2p}} + v^*_{\text{cs}}$, and we assume $\widehat{\mathbf{E}}_{\text{user}}(v) > \mathbf{E}_{\text{user}}(v)$ as long as $v > v^*_{\text{cs}}$ (i.e., $v_{\text{p2p}} > 0$).

Let $a (a > 1)$ be the acceleration rate of P2P, and then we have $\widehat{\mathbf{E}}_{\text{user}}(v) = \mathbf{E}_{\text{user}}(a \cdot (v - v^*_{\text{cs}}) + v^*_{\text{cs}})$. We simply assume that a and β satisfy a linear relationship, and we can get $a = 1 + \frac{30}{7}(1 - \beta)$. More experimental analysis on their relationship is presented in Section 2.1 of the supplementary file available online.

Remark 1. Intuitively, $1 - \beta$ reflects P2P's power, and when it becomes larger, the performance of P2P service becomes better because of its distributed sharing nature. So we assume a increases in accordance with $1 - \beta$. PCPs' servers guarantee system stability, so they are generally indispensable (i.e., $\beta > 0$).

As we have discussed in Section 2, $\xi^*_{\text{user}} \leq \xi_{\text{CP}}$. Then, similar to Eq. (3), we have $v_{\text{p2p}} \cdot (2 - \beta) + v^*_{\text{cs}} = b^*_{\text{user}} \cdot \xi^*_{\text{user}} \leq b^*_{\text{user}} \cdot \xi_{\text{CP}}$. For convenience, let $\widetilde{v}_{\text{p2p}} = \frac{b^*_{\text{user}} \cdot \xi_{\text{CP}} - v^*_{\text{cs}}}{2 - \beta}$. When $v_{\text{p2p}} \leq \widetilde{v}_{\text{p2p}}$, the fee charged from $\mathcal{M}_{\text{user}}$ will be kept at $\tau = b^*_{\text{user}} \cdot p^*_b$, and when $v_{\text{p2p}} > \widetilde{v}_{\text{p2p}}$, $\mathcal{M}_{\text{ISP}}$ will charge additional fee for the excessive volume $(v_{\text{p2p}} - \widetilde{v}_{\text{p2p}}) \cdot (2 - \beta)$ according to volume-based pricing. For bandwidth-based price p^*_b, its equivalent volume-based price is $\frac{p^*_b}{\xi_{\text{user}}}$. Thus, the net utility of $\mathcal{M}_{\text{user}}$ becomes:

$$\mathbb{U}^{\text{S1}}_{\text{user}} = \begin{cases} \widehat{\mathbf{E}}_{\text{user}}(v^{\text{S1}}) - v^{\text{S1}} \cdot p_s - \tau, & \text{if } v^{\text{S1}}_{\text{p2p}} \leq \widetilde{v}_{\text{p2p}}; \\ \widehat{\mathbf{E}}_{\text{user}}(v^{\text{S1}}) - v^{\text{S1}} \cdot p_s - \tau & \\ \quad - \left(v^{\text{S1}}_{\text{p2p}} - \widetilde{v}_{\text{p2p}}\right) \cdot (2 - \beta) \cdot \frac{p_b}{\delta \cdot \xi_{\text{user}}}, & \text{otherwise.} \end{cases} \tag{10}$$

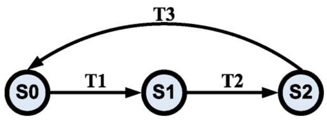

Fig. 4. State transitions among States 0, 1, and 2 (We use S0, S1, and S2 for short). The conditions for the three transitions T1, T2, and T3 are: (1) T1: $\mathbb{U}_{\rm CP}^{\rm S1} > \mathbb{U}_{\rm CP}^{\rm S0}$; (2) T2: $\mathbb{U}_{\rm ISP}^{\rm S2} > \mathbb{U}_{\rm ISP}^{\rm S1}$; (3) T3: $\mathbb{U}_{\rm CP}^{\rm S2} < \mathbb{U}_{\rm CP}^{\rm S0}$.

Here, $\mathcal{M}_{\rm user}$ will decide $v_{\rm p2p}^{\rm S1}$ ($v^{\rm S1} = v_{\rm p2p}^{\rm S1} + v_{\rm cs}^*$ based on our assumption) to maximize $\mathbb{U}_{\rm user}$, i.e.,

$$v_{\rm p2p}^{\rm S1} = \arg\max_{v_{\rm p2p}} \mathbb{U}_{\rm user}. \tag{11}$$

Then, based on $v_{\rm p2p}^{\rm S1}$, we can get $\mathbb{U}_{\rm CP}$ and $\mathbb{U}_{\rm ISP}$ as follows.

For $\mathcal{M}_{\rm CP}$, $\mathbb{U}_{\rm CP}$ becomes

$$\mathbb{U}_{\rm CP}^{\rm S1} = v^{\rm S1} \cdot p_s + \mathbf{F}_{ad}(v^{\rm S1}) - \frac{v_{\rm p2p}^{\rm S1} \cdot \beta + v_{\rm cs}^*}{\xi_{\rm CP}} \cdot p_b - \widehat{\mathbf{C}}(v^{\rm S1}) \tag{12}$$

where $v^{\rm S1} = v_{\rm p2p}^{\rm S1} + v_{\rm cs}^*$, and $\frac{v_{\rm p2p}^{\rm S1} \cdot \beta + v_{\rm cs}^*}{\xi_{\rm CP}}$ denotes the bandwidth purchased by $\mathcal{M}_{\rm CP}$ when the β proportion traffic is provided by their own servers. Similar to $\widehat{\mathbf{E}}_{\rm user}(v)$, we define $\widehat{\mathbf{C}}_{\rm CP}(v) = \mathbf{C}_{\rm CP}((v - v_{\rm cs}^*) \cdot \beta + v_{\rm cs}^*)$ ($0 < \beta \leq 1$) to measure the cost reduced by P2P.

Accordingly, $\mathbb{U}_{\rm ISP}$ becomes:

$$\mathbb{U}_{\rm ISP}^{\rm S1} = \begin{cases} \tau + \frac{v_{\rm p2p}^{\rm S1} \cdot \beta + v_{\rm cs}^*}{\xi_{\rm CP}} \cdot p_b - \mathbf{C}_{\rm ISP}(v^{\rm S1}), & \text{if } v_{\rm p2p}^{\rm S1} \leq \widetilde{v}_{\rm p2p}; \\ \tau + \left(v_{\rm p2p}^{\rm S1} - \widetilde{v}_{\rm p2p}\right) \cdot (2-\beta) \cdot \frac{p_b}{\delta \cdot \xi_{\rm user}} & \\ \quad + \frac{v_{\rm p2p}^{\rm S1} \cdot \beta + v_{\rm cs}^*}{\xi_{\rm CP}} \cdot p_b - \mathbf{C}_{\rm ISP}(v^{\rm S1}), & \text{otherwise.} \end{cases} \tag{13}$$

3.3.2 State 2

For $\mathcal{M}_{\rm ISP}$, a major reason for the profit loss is that it charges $\mathcal{M}_{\rm user}$ a flat price, which leads to P2P free-riding. To defeat such free-riders, one effective way is to turn flat pricing into volume-based pricing [14], [22], [23]. Similar to State 2, we adopt $\frac{p_b^*}{\xi_{\rm user}}$ as the volume-based price. Then, the net utility of $\mathcal{M}_{\rm user}$ becomes:

$$\mathbb{U}_{\rm user}^{\rm S2} = \widehat{\mathbf{E}}_{\rm user}(v^{\rm S2}) - v^{\rm S2} \cdot p_s - \left[v_{\rm p2p}^{\rm S2} \cdot (2-\beta) + v_{\rm cs}^*\right] \cdot \frac{p_b}{\delta \cdot \xi_{\rm user}}. \tag{14}$$

Similar to Eq. (11), $\mathcal{M}_{\rm user}$ chooses

$$v_{\rm p2p}^{\rm S2} = \min\left\{\arg\max_{v} \mathbb{U}_{\rm user}, \widetilde{v}_{\rm p2p}\right\} \tag{15}$$

to obtain the optimal traffic usage. Then the utilities of $\mathcal{M}_{\rm ISP}$ and $\mathcal{M}_{\rm CP}$ can be obtained. The calculation of $\mathbb{U}_{\rm CP}$ is similar to Eq. (12). Accordingly, $\mathbb{U}_{\rm ISP}$ becomes:

$$\mathbb{U}_{\rm ISP}^{\rm S2} = \left[v_{\rm p2p}^{\rm S2} \cdot (2-\beta) + v_{\rm cs}^*\right] \cdot \frac{p_b}{\delta \cdot \xi_{\rm user}} + \frac{v_{\rm p2p}^{\rm S2} \cdot \beta + v_{\rm cs}^*}{\xi_{\rm CP}} \cdot p_b - \mathbf{C}_{\rm ISP}(v^{\rm S2}) \tag{16}$$

where $v^{\rm S2} = v_{\rm p2p}^{\rm S2} + v_{\rm cs}^*$.

3.3.3 Non-Cooperative State Analysis

As shown in Fig. 4, we summarize the state transition conditions among States 0, 1, and 2. Unlike the way we analyze dynamic games of complete information using *game trees* directly [29], we summarize all the possible equilibrium states (i.e., Subgame Perfect Nash Equilibriums, SPNEs). The state transition here specifies that in practical networks, a proper NE may not be reached through analysis and prediction, but may be attained through several steps of state transitions.

For example, as pricing strategies act as the long-term behaviors of $\mathcal{M}_{\rm ISP}$, it cannot be dynamic and flexible. Thus, after the system passes through a long path (transforming among different states), it is likely to arrive at a reasonable NE finally.

TABLE 1
Utilities in Different States

	$\mathbb{U}_{\rm ISP}$	$\mathbb{U}_{\rm CP}$	$\mathbb{U}_{\rm user}$
State 0	2.2438	3.9942	2.3281
State 1	1.5964	7.2021	9.6230
State 2	3.5180	5.6450	5.1712

3.4 Example and Analysis

We have discussed the derivations of the utilities in Sections 3.2 and 3.3. Now we give a numerical example to validate the state transition process and analyze the impact of the parameters on the market status.

We analyze the settings of the functions and parameters in detail in Section 2.2 of the supplementary file available online. Here we analyze the situation where $\delta = 1$, i.e., the ISP expects the same unit bandwidth profit from the CP with that from the user. Additional analysis on the situations where $0 < \delta < 1$ is shown in Sections 2.4.2 and 2.5.2 of the supplementary file available online. Based on the numerical computation in Section 2.4.1 of the supplementary file available online, we can get the values of $\mathbb{U}_{\rm ISP}$, $\mathbb{U}_{\rm CP}$ and $\mathbb{U}_{\rm user}$ in different states, as shown in Table 1. Compared with State 0, $\mathbb{U}_{\rm CP}$ increases by 80.31 percent, while $\mathbb{U}_{\rm ISP}$ decreases by 28.85 percent. Thus, motivated by profit increase, some CPs will adopt P2P. Then, the system will change from State 0 to State 1. After $\mathcal{M}_{\rm ISP}$ adopts volume-based pricing, $\mathbb{U}_{\rm ISP}$ increases by 120.66 percent, while $\mathbb{U}_{\rm CP}$ decreases by 29.42 percent. Motivated by profit increase, $\mathcal{M}_{\rm ISP}$ will charge $\mathcal{M}_{\rm user}$ a volume-based price instead of the flat price. Then, the system will change from State 1 to State 2. Since $\mathbb{U}_{\rm CP}^{\rm S2} > \mathbb{U}_{\rm CP}^{\rm S0}$, $\mathcal{M}_{\rm PCP}$ still benefits from P2P and will not take further actions against $\mathcal{M}_{\rm ISP}$.

Remark 2. Economically, the only condition for the system to change from State 0 to State 1 is that under the traditional pricing mechanism, $\mathbb{U}_{\rm CP}^{\rm S1} > \mathbb{U}_{\rm CP}^{\rm S0}$. According to Eqs. (6) and (10), it is easily proved that $v_{\rm p2p}^{\rm S1} + v_{\rm cs}^* > v^*$ (See Fig. 5).

Remark 3. The conditions for the system to change from State 1 to State 2 are $\mathbb{U}_{\rm ISP}^{\rm S1} < \mathbb{U}_{\rm ISP}^{\rm S0}$ and $\mathbb{U}_{\rm ISP}^{\rm S2} > \mathbb{U}_{\rm ISP}^{\rm S1}$. For the first one: if $\mathbb{U}_{\rm ISP}^{\rm S1} > \mathbb{U}_{\rm ISP}^{\rm S0}$, $\mathcal{M}_{\rm ISP}$ will benefit from P2P. However, according to Eqs. (10) and (14), it is easy to prove that $v_{\rm p2p}^{\rm S2} < v_{\rm p2p}^{\rm S1}$. Then, $\mathcal{M}_{\rm ISP}$ does not need to change its pricing strategy on $\mathcal{M}_{\rm user}$.

Remark 4. For $\mathcal{M}_{\rm PCP}$, if $\mathbb{U}_{\rm CP}^{\rm S2} < \mathbb{U}_{\rm CP}^{\rm S0}$ (since the demand is suppressed by $\mathcal{M}_{\rm ISP}$'s new pricing strategy, the saved

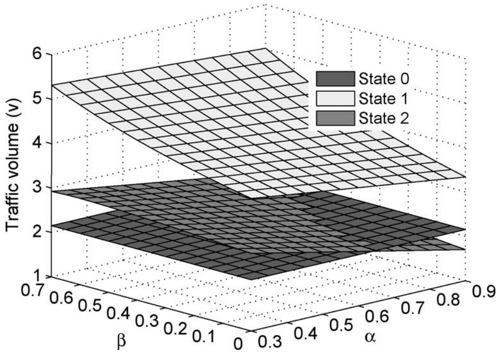

Fig. 5. Traffic volume (v) in States 0, 1, and 2 for different α and β. Note that $v = v_{\mathrm{p2p}} + v^*_{\mathrm{cs}}$ in States 1 and 2.

cost cannot cover the reduced income), it may give up P2P due to the reduced profit. Then, the system will be forced to change from State 2 to State 0.

3.4.1 Analysis

As the game tree in Fig. 2 shows, the game starts from $\mathcal{M}_{\mathrm{CP}}$'s decision of whether to adopt P2P technology or not. If $\mathcal{M}_{\mathrm{CP}}$ adopts P2P, the game then goes to $\mathcal{M}_{\mathrm{ISP}}$'s decision of which pricing model will be used to charge $\mathcal{M}_{\mathrm{user}}$, i.e., flat or volume-based. Once $\mathcal{M}_{\mathrm{ISP}}$ makes a choice, the game is over. Based on *backward induction* and the payoff results given in this example, we get *(P2P-assisted, volume-based)* as the SPNE, and the payoff vector is (5.0835, 3.5226). We can verify that it satisfies the conditions for State 2 to be the final state (i.e., T1 instead of T2 in Fig. 4).

In a practical system, the pricing strategy lags behind the technology application, so $\mathbb{U}^{\mathrm{S1}}_{\mathrm{CP}} > \mathbb{U}^{\mathrm{S0}}_{\mathrm{CP}}$ is always true, and related measurement works are introduced in Section 1. Thus, the system will always change from State 0 to State 1. If $\mathbb{U}^{\mathrm{S1}}_{\mathrm{ISP}} \geq \mathbb{U}^{\mathrm{S0}}_{\mathrm{ISP}}$, which only applies to large β in Fig. 6a, and $\mathcal{M}_{\mathrm{ISP}}$ predicts $\mathbb{U}^{\mathrm{S1}}_{\mathrm{ISP}} \geq \mathbb{U}^{\mathrm{S2}}_{\mathrm{ISP}}$, the system will stay in State 1; otherwise, if $\mathbb{U}^{\mathrm{S1}}_{\mathrm{ISP}} < \mathbb{U}^{\mathrm{S0}}_{\mathrm{ISP}}$ and $\mathbb{U}^{\mathrm{S2}}_{\mathrm{ISP}} > \mathbb{U}^{\mathrm{S0}}_{\mathrm{ISP}}$ (as shown in Fig. 6a), it will change from State 1 to State 2. Then, if $\mathbb{U}^{\mathrm{S2}}_{\mathrm{CP}} > \mathbb{U}^{\mathrm{S0}}_{\mathrm{CP}}$ (as shown in Fig. 6b), the system will stop in State 2, otherwise it will change from State 2 to State 0 and finally stop in State 0. Therefore, according to the state transition conditions in Fig. 4, we can conclude the conditions for each SPNE. Under a certain condition, each state could be a proper NE.

For different traffic profiles (α, β), we get the optimal traffic usage with "flat" and "volume-based" pricing strategies of $\mathcal{M}_{\mathrm{ISP}}$ based on Eqs. (11) and (15). Then, according to Eqs. (12), (13), and (16), we can correspondingly derive the net utilities of $\mathcal{M}_{\mathrm{ISP}}$ and $\mathcal{M}_{\mathrm{CP}}$.

Fig. 6 shows $\mathbb{U}_{\mathrm{ISP}}$ and $\mathbb{U}_{\mathrm{CP}}$ for different β $(\alpha = 0.3)$. According to the conditions introduced in Fig. 4, T1 and T2 are always satisfied and T3 is never satisfied. Therefore, we can conclude that the system will stay in State 2, where $\mathcal{M}_{\mathrm{ISP}}$ charges $\mathcal{M}_{\mathrm{user}}$ a volume-based price. Here, $\mathbb{U}^{\mathrm{S2}}_{\mathrm{ISP}}$ is 120.66 percent more than $\mathbb{U}^{\mathrm{S1}}_{\mathrm{ISP}}$ and 56.99 percent more than $\mathbb{U}^{\mathrm{S0}}_{\mathrm{ISP}}$; $\mathbb{U}^{\mathrm{S2}}_{\mathrm{CP}}$ is 29.42 percent less than $\mathbb{U}^{\mathrm{S1}}_{\mathrm{CP}}$, but it is 27.27 percent more than $\mathbb{U}^{\mathrm{S0}}_{\mathrm{CP}}$.

4 Cooperative Profit-Distribution Model

Nash Bargaining Solution (NBS) [25] and the Shapley value [30] are both widely accepted solutions to profit distribution problems. Shapley value is more often used in multiplayer profit distribution such as the profit distribution problems among different types of ISPs [12], [31]. In two-player profit distribution, NBS and the Shapley value are equivalent, but NBS can avoid the definition of character functions and is simpler to calculate. Therefore, we propose a cooperative profit distribution model based on the concept of NBS, in which eyeball ISPs and PCPs first form two coalitions to cooperatively maximize their total profit and then fairly distribute the profit.

According to our analysis in Section 3.3.1, in the peer-assisted network, $\mathcal{M}_{\mathrm{user}}$ may use up its original bandwidth at a flat price without buying additional bandwidth at a volume-based price. Here, we consider the following cooperation: $\mathcal{M}_{\mathrm{PCP}}$ sells contents at a discount rate γ_{PCP} and $\mathcal{M}_{\mathrm{ISP}}$ charges the extra bandwidth bought by $\mathcal{M}_{\mathrm{user}}$ at a discount rate γ_{ISP} $(0 \leq \gamma_{\mathrm{PCP}}, \gamma_{\mathrm{ISP}} \leq 1)$. Both of them try to incentivize $\mathcal{M}_{\mathrm{user}}$ to consume more contents and to buy more bandwidth for P2P services. As shown in Fig. 7, if γ_{ISP} is large, v_{p2p} will not increase even if $\gamma_{\mathrm{PCP}} = 0$, which implies that without the cooperation of $\mathcal{M}_{\mathrm{ISP}}$, $\mathcal{M}_{\mathrm{PCP}}$ cannot unilaterally incentivize $\mathcal{M}_{\mathrm{user}}$ to consume more P2P contents, and thus the total profit will not increase. For $\mathcal{M}_{\mathrm{PCP}}$, besides the fee charged for its traffic volume $v \cdot \beta$, some of its profit should be shared with $\mathcal{M}_{\mathrm{ISP}}$.

In this cooperation, the net utility of $\mathcal{M}_{\mathrm{user}}$ becomes:

$$\mathbb{U}_{\mathrm{user}} = \begin{cases} \widehat{\mathbf{E}}_{\mathrm{user}}(v) - \left(v_{\mathrm{p2p}} \cdot \gamma_{\mathrm{PCP}} + v^*_{\mathrm{cs}}\right) \cdot p_s - \tau, & \text{if } v_{\mathrm{p2p}} \leq \widetilde{v}_{\mathrm{p2p}}; \\ \widehat{\mathbf{E}}_{\mathrm{user}}(v) - \left(v_{\mathrm{p2p}} \cdot \gamma_{\mathrm{PCP}} + v^*_{\mathrm{cs}}\right) \cdot p_s - \tau & \\ \quad - (v_{\mathrm{p2p}} - \widetilde{v}_{\mathrm{p2p}}) \cdot (2-\beta) \cdot \frac{p_b}{\delta \cdot \xi_{\mathrm{user}}} \cdot \gamma_{\mathrm{ISP}}, & \text{otherwise.} \end{cases}$$

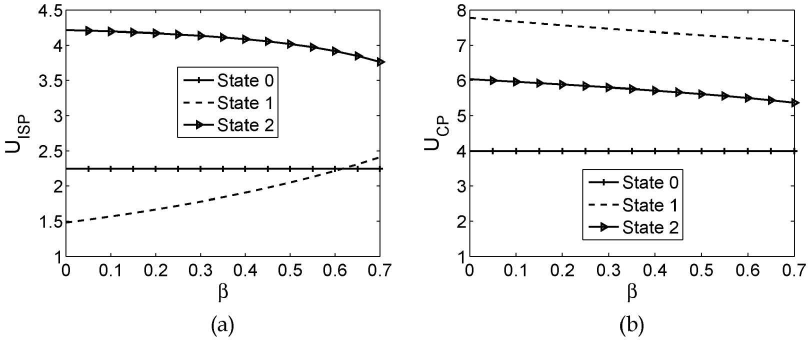

Fig. 6. (a) $\mathbb{U}_{\mathrm{ISP}}$ and (b) $\mathbb{U}_{\mathrm{CP}}$ for different β $(\alpha = 0.3)$.

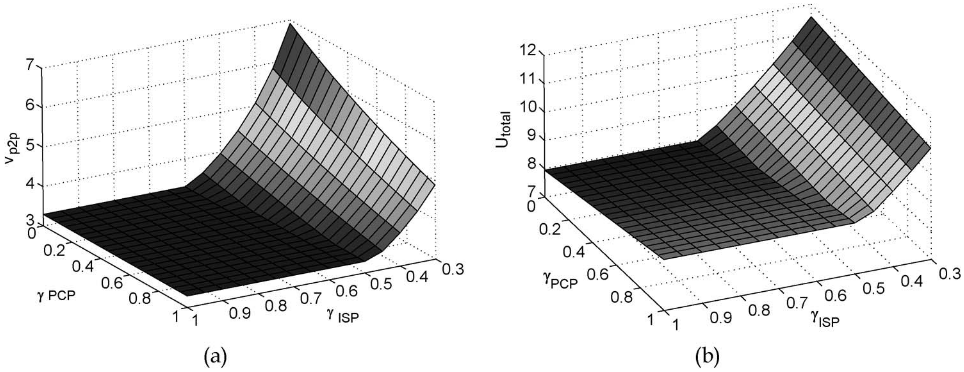

Fig. 7. (a) $v_{\rm p2p}$ and (b) $\mathbb{U}_{\rm total}$ for different $\gamma_{\rm ISP}$ and $\gamma_{\rm PCP}$ with traffic profiles $(\alpha, \beta) = (0.6, 0.3)$.

Accordingly, $\mathbb{U}_{\rm ISP}$ will become:

$$\mathbb{U}_{\rm ISP} = \begin{cases} \tau + \frac{v_{\rm p2p}\cdot\beta + v^*_{\rm cs}}{\xi_{\rm CP}}\cdot p^*_b - \mathbf{C}_{\rm ISP}(v), & \text{if } v_{\rm p2p} \le \widetilde{v}_{\rm p2p}; \\ \tau + (v_{\rm p2p} - \widetilde{v}_{\rm p2p})\cdot(2-\beta)\cdot\frac{p^*_b}{\delta\cdot\xi_{\rm user}}\cdot\gamma_{\rm ISP} & \\ \quad + \frac{v_{\rm p2p}\cdot\beta + v^*_{\rm cs}}{\xi_{\rm CP}}\cdot p^*_b - \mathbf{C}_{\rm ISP}(v), & \text{otherwise.} \end{cases}$$

Also, $\mathbb{U}_{\rm CP}$ will become:

$$\mathbb{U}_{\rm CP} = \left(v_{\rm p2p}\cdot\gamma_{\rm PCP} + v^*_{\rm cs}\right)\cdot p^*_s + \mathbf{F}_{ad}(v) - \frac{v_{\rm p2p}\cdot\beta + v^*_{\rm cs}}{\xi_{\rm CP}}\cdot p^*_b - \widehat{\mathbf{C}}_{\rm CP}(v).$$

Here, between the cooperative group and $\mathcal{M}_{\rm user}$ starts a leader-follower game. The former changes $\gamma_{\rm ISP}$ and $\gamma_{\rm PCP}$ to maximize its total profit:

$$\mathbb{U}_{\rm total} = \mathbb{U}_{\rm ISP} + \mathbb{U}_{\rm CP}$$

$\mathcal{M}_{\rm user}$ as the price taker changes $v_{\rm p2p}$ to maximize $\mathbb{U}_{\rm user}$:

$$\begin{aligned} &\text{for } \mathcal{M}_{\rm user}: \\ &\quad \widehat{v} = \arg\max_{v_{\rm p2p}} \mathbb{U}_{\rm user}(\gamma_{\rm ISP}, \gamma_{\rm PCP}) \\ &\text{for the cooperative group}: \\ &\quad \max_{\gamma_{\rm ISP},\gamma_{\rm PCP}} \mathbb{U}_{\rm total}(\gamma_{\rm ISP}, \gamma_{\rm PCP}, \widehat{v}(\gamma_{\rm ISP}, \gamma_{\rm PCP})). \end{aligned} \tag{17}$$

For all cases, $\mathbb{U}_{\rm ISP} + \mathbb{U}_{\rm CP} \le \mathbb{U}^{\rm S3}_{\rm total}$. Thus,

$$\mathbb{U}_{\rm ISP} + \mathbb{U}_{\rm CP} = \mathbb{U}^{\rm S3}_{\rm total} \tag{18}$$

is the corresponding *Pareto boundary*.

Now, we are facing an important question: *How can $\mathcal{M}_{\rm ISP}$ and $\mathcal{M}_{\rm PCP}$ choose a fair point on the Pareto boundary as their profit distribution*? As discussed previously, without cooperation, their profit may reach one of the following points (see Fig. 4): $(\mathbb{U}^{\rm S0}_{\rm ISP}, \mathbb{U}^{\rm S0}_{\rm CP})$, $(\mathbb{U}^{\rm S1}_{\rm ISP}, \mathbb{U}^{\rm S1}_{\rm CP})$, or $(\mathbb{U}^{\rm S2}_{\rm ISP}, \mathbb{U}^{\rm S2}_{\rm CP})$. In Nash bargaining, such a point is called the *starting point* [32], which we denote by $(\mathbb{U}^s_{\rm ISP}, \mathbb{U}^s_{\rm CP})$. If no agreement can be reached, the starting point will be the outcome of the game. Then, according to the fairness concept of NBS, the fair profit distribution can be deduced by:

$$\begin{aligned} \underset{\mathbb{U}_{\rm ISP},\mathbb{U}_{\rm CP}}{\text{maximize}} \quad & \left(\mathbb{U}_{\rm ISP} - \mathbb{U}^s_{\rm ISP}\right)\left(\mathbb{U}_{\rm CP} - \mathbb{U}^s_{\rm CP}\right), \\ \text{subject to} \quad & \mathbb{U}_{\rm ISP} + \mathbb{U}_{\rm CP} = \mathbb{U}^{\rm S3}_{\rm total}. \end{aligned} \tag{19}$$

NBS satisfies the following four axioms [25], [32], [33]:

1. Invariant to equivalent utility representations;
2. Pareto optimality;
3. Independence of irrelevant alternatives; and
4. Symmetry.

By solving the above optimization problem, we can obtain a fair profit distribution:

$$\begin{aligned} \mathbb{U}^{\rm S3}_{\rm ISP} &= \mathbb{U}^s_{\rm ISP} + \frac{\mathbb{U}^{\rm S3}_{\rm total} - \mathbb{U}^s_{\rm ISP} - \mathbb{U}^s_{\rm CP}}{2}, \\ \mathbb{U}^{\rm S3}_{\rm CP} &= \mathbb{U}^s_{\rm CP} + \frac{\mathbb{U}^{\rm S3}_{\rm total} - \mathbb{U}^s_{\rm ISP} - \mathbb{U}^s_{\rm CP}}{2}. \end{aligned} \tag{20}$$

Then, the profit that $\mathcal{M}_{\rm PCP}$ should transfer to $\mathcal{M}_{\rm ISP}$ is $\mathcal{R} = \mathbb{U}^{\rm S3}_{\rm ISP} - \mathbb{U}^{\rm S3'}_{\rm ISP} = \mathbb{U}^{\rm S3'}_{\rm CP} - \mathbb{U}^{\rm S3}_{\rm CP}$.

To better illustrate the cooperative profit maximization and distribution, we provide additional numerical analysis in Section 2.5.1 of the supplementary file available online. From Fig. 9 in the supplementary file available online, we can see that $\mathbb{U}_{\rm ISP}$ increases by more than 110 percent, and $\mathbb{U}_{\rm CP}$ increases by more than 70 percent, compared with the starting point.

Specifically, for $(\alpha, \beta) = (0.6, 0.3)$, the Nash bargaining between $\mathcal{M}_{\rm ISP}$ and $\mathcal{M}_{\rm PCP}$ is illustrated in Fig. 8, from which we can see that the starting point is $(\mathbb{U}^{\rm S2}_{\rm ISP}, \mathbb{U}^{\rm S2}_{\rm CP}) = (3.5180, 5.6450)$. According to Eq. (20), we can obtain $(\mathbb{U}^{\rm S3}_{\rm ISP}, \mathbb{U}^{\rm S3}_{\rm CP}) = (8.6508, 10.7778)$ as the final profit distribution. Then, the profit that $\mathcal{M}_{\rm PCP}$ should assign to $\mathcal{M}_{\rm ISP}$

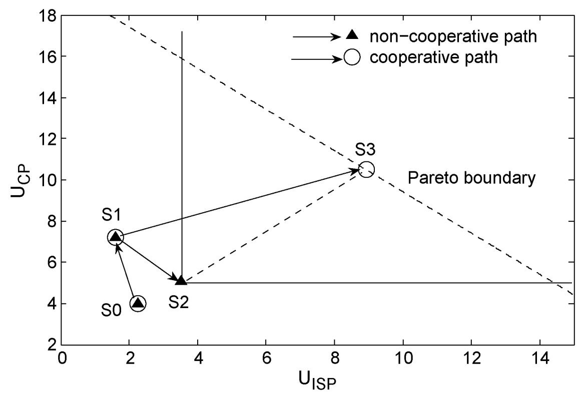

Fig. 8. An example of Nash bargaining between $\mathcal{M}_{\rm ISP}$ and $\mathcal{M}_{\rm PCP}$, $(\alpha, \beta) = (0.6, 0.3)$.

is $\mathcal{R} = 3.7449$. Compared with the starting point, $\mathbb{U}_{\text{ISP}}$ increases by 145.90 percent, and $\mathbb{U}_{\text{CP}}$ increases by 90.92 percent. Thus, both $\mathcal{M}_{\text{ISP}}$ and $\mathcal{M}_{\text{PCP}}$ benefit a lot from this cooperation.

5 Profit Distribution within Each Coalition

From the discussion in Section 4, we can see that $\mathcal{M}_{\text{PCP}}$ should assign some profit $\mathcal{R}$ to $\mathcal{M}_{\text{ISP}}$ in the cooperation. In this section, we will propose a mechanism to determine profit distribution within each coalition.

To ensure the stability of each coalition, the profit distribution mechanism should guarantee the fairness. Before introducing such a mechanism, we first provide some definitions.

Suppose there are m ISPs and n PCPs. For the i-th PCP $(1 \leq i \leq n)$, we define two *traffic matrices*:

1. $\mathbf{T}_i = (t^i_{j,k})_{m\times m}$, where $t^i_{j,k}$ denotes the amount of the i-th PCP's traffic volume transmitted from the users in the j-th ISP's network to the users in the k-th ISP's network;
2. $\widetilde{\mathbf{T}}_i = \mathrm{diag}(\tilde{t}^i_1, \tilde{t}^i_2, \ldots, \tilde{t}^i_m)$, where $\tilde{t}^i_j$ denotes the amount of the i-th PCP's traffic volume transmitted from its servers to the users in the j-th ISP's network (this part of upload traffic will be charged by the corresponding ISP on the i-th PCP side).

According to the network model in Section 2, the PCP traffic delivered by P2P accounts for $1 - \beta$ proportion, and the rest is provided by PCP servers. Then, we have:

$$\sum_{i=1}^{n}\left(\sum_{1\leq j,k\leq m} t^i_{j,k}\right) = v_{\text{p2p}} \cdot (1-\beta)$$
$$\sum_{i=1}^{n}\left(\sum_{j=1}^{m} \tilde{t}^i_j\right) = v_{\text{p2p}} \cdot \beta. \tag{21}$$

Thus, in $\mathcal{M}_{\text{PCP}}$, the amount of traffic volume generated by the i-th PCP accounts for:

$$\varphi_i = \frac{\left(\sum_{1\leq j,k\leq m} t^i_{j,k}\right) + \left(\sum_{j=1}^{m} \tilde{t}^i_j\right)}{v_{\text{p2p}}}. \tag{22}$$

Based on Eq. (21), it is clear that $\sum_{i=1}^{n} \varphi_i = 1$.

For $\mathcal{M}_{\text{ISP}}$, its two *aggregated traffic matrices* are defined as:

$$\mathbb{T} = \sum_{i=1}^{n} \mathbf{T}_i \quad \widetilde{\mathbb{T}} = \sum_{i=1}^{n} \widetilde{\mathbf{T}}_i.$$

Suppose $\mathbb{T} = (t_{j,k})_{m\times m}$ and $\widetilde{\mathbb{T}} = \mathrm{diag}(\tilde{t}_1, \tilde{t}_2, \ldots, \tilde{t}_m)$.

In the l-th ISP's network $(1 \leq l \leq m)$, the amount of P2P traffic generated by $\mathcal{M}_{\text{PCP}}$ on user side is:

$$\varpi_l = \left(\sum_{k=l}^{k=m} t_{l,k}\right) + \left(\sum_{k=l}^{k=m} t_{k,l}\right) + \tilde{t}_l \tag{23}$$

v_l and b_l denote the total traffic volume on user side and the total bandwidth bought by all the users with a flat price, respectively. Note that $\sum_{l=1}^{m} b_l = b^{\text{S0}}_{\text{user}}$. Then, we can verify that the amount of the C/S traffic volume is $v_l - \varpi_l$, and the free-riding P2P traffic volume is $v_l - b_l \cdot \xi_{\text{user}}$ (where ξ_{user} is the bandwidth utilization rate assumed by $\mathcal{M}_{\text{ISP}}$ when setting the flat price). According to the network model in Section 2, we have:

$$\sum_{l=1}^{m}[b_l \cdot \xi_{\text{user}} - (v_l - \varpi_l)] = v^{\text{S0}} \cdot \alpha.$$

In addition, we can deduce that:

$$\sum_{l=1}^{m}(v_l - b_l \cdot \xi_{\text{user}}) = v_{\text{p2p}} \cdot (2-\beta) - v^{\text{S0}} \cdot \alpha. \tag{24}$$

Thus, the l-th ISP's contribution to the free-riding of P2P traffic accounts for:

$$\psi_l = \frac{v_l - b_l \cdot \xi_{\text{user}}}{v_{\text{p2p}} \cdot (2-\beta) - v^{\text{S0}} \cdot \alpha}. \tag{25}$$

Based on Eq. (24), it is clear that $\sum_{l=1}^{m} \psi_l = 1$.

Consequently, we propose a fair and feasible profit distribution mechanism. For a given $\mathcal{R}$, the profit that the i-th PCP should assign to $\mathcal{M}_{\text{ISP}}$ is $\mathcal{R} \cdot \varphi_i$, and the profit that $\mathcal{M}_{\text{ISP}}$ should assign to the l-th ISP is $\mathcal{R} \cdot \psi_l$.

We analyze the proposed mechanism based on the example (introduced in Section 4) in Section 2.6 of the supplementary file available online. The implementation issues of the profit distribution mechanism are discussed in Section 4.2 of the supplementary file available online, where we also discuss the fairness and feasibility of the mechanism.

6 Potential Competition among ISPs

As discussed in Section 5, the profit distribution within $\mathcal{M}_{\text{ISP}}$ is based on the P2P traffic proportion contributed by each ISP, which can be changed by specific strategies. Therefore, potential competitions exist among ISPs. Our analysis shows that although the competition does not change the profit of each ISP, it increases traffic localization rate.

6.1 Motivations and Possible Actions of ISPs

P2P technology significantly increases the traffic among ISPs and therefore increases the costs of ISPs, while the localization of P2P traffic will decrease the cost. Besides, the profit distribution mechanism within $\mathcal{M}_{\text{ISP}}$ is based on the contribution made by each ISP to the total P2P traffic, which means that the ISP can increase its proportion by localizing its P2P traffic under the condition where other ISPs do not take this action.

Inspired by the idea about P4P [20], ISPs can take actions to localize P2P traffic to gain more profit from the reduced cost and profit distribution. To promote P2P traffic localization, ISPs can deploy tiered pricing [34] to encourage users to adopt P4P applications, so as to decrease the amount of P2P traffic among ISPs.

6.2 Competition Analysis

We denote the l-th ISP's number of P2P users by $\mathcal{S}_l$ and the average amount of downloaded traffic of each user by $\bar{d}$. We consider the situation where there are three ISPs.

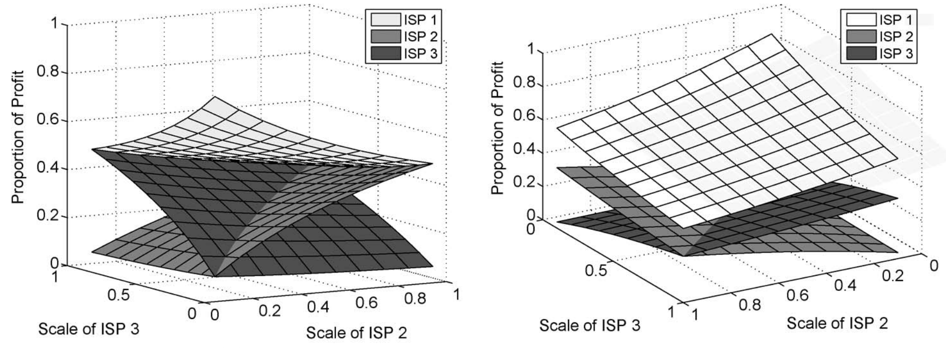

Fig. 9. Profit distribution proportion of each ISP in Situation 1 (a) and Situation 2 (b).

We define three situations:

- **Situation 1**: None of the ISPs takes the action of traffic localization.
- **Situation 2**: ISP 1 takes the action of traffic localization, while ISP 2 and ISP 3 do not take this action.
- **Situation 3**: All ISPs take the action of traffic localization.

In Situation 1, suppose that every user downloads contents uniformly from all P2P users in the three ISPs. Fig. 9a shows how the profit distribution proportions change with the P2P user scales in different ISPs. Suppose the P2P user scale of ISP 1 is 1. From Fig. 9a, we can conclude that the ISP with more P2P users will gain a larger proportion of the profit, which can be illustrated by Eq. (25).

In Situation 2, only ISP 1 takes action for traffic localization. Table 2 shows the downloaded and uploaded amounts of P2P traffic of each ISP. We denote the amount of downloaded and uploaded P2P traffic of the l-th ISP by $\mathcal{D}_l$ and $\mathcal{U}_l$, respectively. Then we have $\mathcal{D}_l + \mathcal{U}_l = v_l - b_l \cdot \xi_{\text{user}}$. In addition, based on Eq. (25), we have:

$$\psi_l = \frac{\mathcal{D}_l + \mathcal{U}_l}{\sum_{l=1}^{3}(\mathcal{D}_l + \mathcal{U}_l)}. \tag{26}$$

Afterwards, we can derive ψ_l from the downloaded and uploaded amounts of P2P traffic provided in Table 2. Fig. 9b shows the profit distribution proportion of each ISP with different P2P user scales of ISP 2 and ISP 3. We can conclude that the ISP who takes action for traffic localization gains more profit and others gain less. Fig. 10 shows the growth rate of profit distribution proportion of ISP 1 with different P2P user scales of ISP 2 and ISP 3. The result shows that the ISP with a smaller scale will gain a higher growth rate in its profit distribution proportion. Therefore, this action is more appealing to small ISPs than to large ones.

In Situation 3, all the ISPs take action for traffic localization and each ISP has the same profit distribution proportion as in Situation 1.

TABLE 2
Downloaded and Uploaded Traffic of Each ISP

ISP	Downloaded Traffic	Uploaded Traffic
ISP 1	$\mathcal{S}_1 \cdot \bar{d}$	$\mathcal{S}_1 \cdot (\bar{d} + \frac{\mathcal{S}_2 \cdot \bar{d} + \mathcal{S}_3 \cdot \bar{d}}{\sum_{l=1}^{3} \mathcal{S}_l})$
ISP 2	$\mathcal{S}_2 \cdot \bar{d}$	$\mathcal{S}_2 \cdot \frac{\mathcal{S}_2 \cdot \bar{d} + \mathcal{S}_3 \cdot \bar{d}}{\sum_{l=1}^{3} \mathcal{S}_l}$
ISP 3	$\mathcal{S}_3 \cdot \bar{d}$	$\mathcal{S}_3 \cdot \frac{\mathcal{S}_2 \cdot \bar{d} + \mathcal{S}_3 \cdot \bar{d}}{\sum_{l=1}^{3} \mathcal{S}_l}$

6.3 Stable State after Competition

Motivated by its own profit increase, ISP 1 first takes the localization action. Because of the reduced profit, ISP 2 and ISP 3 will also take the same action, bringing the system to a stable state (Situation 3), because none of the ISPs can take further action to increase its own profit.

Fig. 11 shows the transfer of ISP 1 among the three situations, supposing that the three ISPs have the same number of P2P users. The profit of ISP 1 in the stable situation remains the same with that in the original situation. However, P2P traffic localization rate increases from about 33 percent to 100 percent. Although the competition does not change the profit of each ISP, it makes a contribution to the healthy development of the network by increasing traffic localization rate.

7 Related Work

The increasing free-riding P2P traffic generated by more and more P2P applications decreases the profit of eyeball

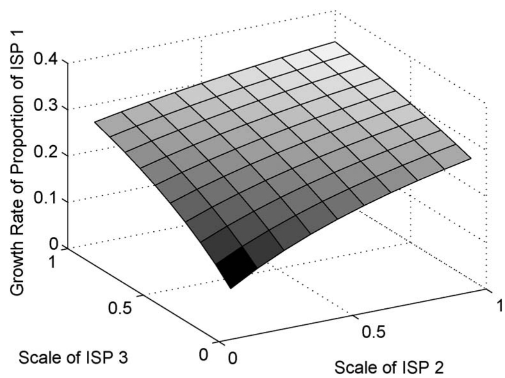

Fig. 10. Profit growth rate of ISP 1.

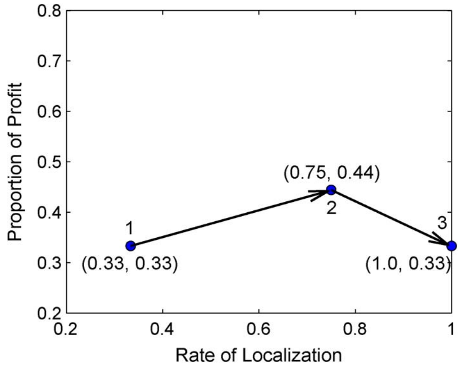

Fig. 11. Transfer of ISP 1 among different situations.

ISPs. There are two types of strategies for ISPs to handle this problem.

One type belongs to the engineering scheme, which includes resistance to P2P by throttling, shaping, and blocking [14], [17], and cooperation with PCPs to efficiently manage P2P traffic [18], [19], [20], [35], [36]. The former impedes the progress of P2P and may lead to PCPs' countermeasures, such as encryption and dynamic ports; the latter involves legality and privacy issues.

Another type belongs to the economic scheme. He *et al.* [23] surveyed Internet pricing models and concluded that pricing acts as an important auxiliary to control traffic and to improve performance. Regarding this problem, one research direction is that ISPs change their pricing strategies [22], [23], such as proposing uplink pricing so as to provide differential pricing for P2P and regular users. More types of the relationships are also studied to provide a fine-grained perspective for more efficient pricing mechanisms. For example, two layers of relationships (ISP-users and ISP-ISP) are studied based on the non-cooperative game model in [32] and [33].

More related work is presented in Section 5 of the supplementary file available online.

8 CONCLUSION

Under the traditional Internet pricing mechanism, free-riding P2P traffic causes an unbalanced profit distribution between PCPs and eyeball ISPs, which will drive eyeball ISPs to take action against P2P and can finally impede the wide adoption of P2P applications. This paper proposes a new cooperative profit-distribution model based on Nash bargaining, in which both eyeball ISPs and PCPs form coalitions and then cooperate to maximize their total profit. The fair profit distribution between the two coalitions is determined by NBS. To guarantee the stability of each coalition, a fair mechanism for profit distribution within each coalition has been designed. Such a cooperative profit-distribution method not only guarantees the fair profit distribution among network participants, but also improves the economic efficiency of the overall network system. Under this profit distribution mechanism, competition may occur among ISPs, which will promote the healthy development of the network environment by increasing traffic localization rate.

ACKNOWLEDGMENT

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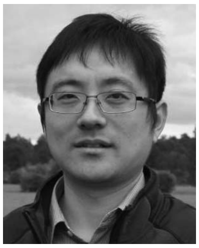

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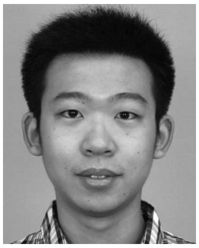

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