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Feasibility Analysis of Content Charge by ISPs

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***Abstract*—As content delivered on the Internet becomes richer, the use of content delivery services in which users pay a fee for each content delivery to the content provider (CP) increases. For Internet service providers (ISPs), on the other hand, the increased investment cost required to maintain stable quality is a problem, and ISPs need to recover this cost from CPs because it is difficult to do so by increasing fees to users. However, CPs usually pay an access fee whose increase ratio diminishes as the volume of transmitted data increases, so the profit obtained by the ISPs is not sufficient to cover their investment cost. To address this problem, a content charge in which ISPs charge a fee for each content delivery to CPs would seem to be effective. However, it is anticipated that CPs will switch to another ISP if the original ISP introduces a content charge, so introducing a content charge may not always increase the revenue of ISPs. This paper investigates the feasibility of adding a content charge by ISPs and evaluates the effect such a charge would have by modeling the relationship between CPs and ISPs using a two-stage Stackelberg game.**

I. INTRODUCTION

In video delivery services on networks, users mainly view small-sized content produced by content providers (CPs) and users. However, as the transmission capacity of access links grows, large-sized rich content, such as TV dramas and movies produced by major content producers, is increasingly being provided by many CPs. When providing rich content on networks, the CPs need to pay a royalty to copyright holders, so they need a business model that enables them to earn a profit after paying the royalty fee. Although the business model to obtain profits through advertisements has been widely used, another business model in which CPs obtain a fee directly from users has recently been introduced and is expected to become more common in the near future [6][9][29][31].

When rich content is delivered, a huge amount of traffic is transmitted over the network. For example, when delivering content with high definition TV (HDTV) quality about 100 minutes in length and at a bit rate of about 25 Mbps [2], the total amount of data transmitted is about 19 Gbytes. Internet service providers (ISPs) need to construct a network infrastructure that maintains stable service quality, so an increase in the investment cost of the network infrastructure is a serious issue for ISPs. ISPs need to cover the investment cost by obtaining fees from users and CPs. However, the access network market is highly competitive, so it is difficult for ISPs to ask users to pay the additional charge for rich content delivery. Moreover, if users pay a fee to CPs for each content delivery, it is difficult to ask users to pay an extra fee to the ISPs in addition to the fee paid to CPs. On the other hand, the CPs can obtain large revenue from content delivery services [5], and the CPs seem able to afford to return part of the profit to the ISPs as a reward for the ISP contributions in supporting the business of CPs.

CPs normally connect their servers to ISPs and become customers of the ISP transit services. CPs pay ISPs a transit fee, which is a usage-based charge based on the 95th percentile value of the transmission bit rate of data in many cases [4][8]. If the transit fee is proportional to the total amount of data transmitted, ISPs can basically obtain enough profit to cover the cost of investing in the networks. However, in many cases, the increase ratio of the transit fee decreases as the amount of data transmitted increases [4][8], so ISPs cannot obtain sufficient profit to cover the investment cost, which rapidly increases because of rich content delivery.

How to allocate the network cost among players has been widely discussed as a *network neutrality* problem [5][33]. The discussion on network neutrality can be classified into two categories: (i) who should pay for the investment cost of networks that is necessary to deal with the rapid increase in traffic and (ii) how to maintain fairness for all users in using networks [30]. In the USA, the Federal Communications Commission regards the principle of network neutrality as satisfying user rights to freely access content and receive services. They also decided that regulation of ISPs should be avoided because network neutrality is already satisfied [12]. Moreover, in Europe, the European Commission judged that network neutrality should be considered as a general principle and that regulation of ISPs should also be avoided [11]. In Japan, the government ruled that CP and ISP markets should have free competition and that the charging methods between CPs and ISPs should be based on agreements between those players [30].

Therefore, to allocate the network investment cost among players fairly and enable ISPs to recover that cost, a content charge in which ISPs obtain a fee from CPs for each content delivery seems effective. By receiving part of the fee that CPs obtain from users, ISPs can cover the cost of investing in the networks. Recently, many studies have modeled the business relationship between ISPs and CPs and have investigated preferable charging methods and ways that ISPs can obtain revenue from content delivery services [19][20][21][24][35].

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Although these studies assumed a content charge levied by ISPs on CPs, such a content charge has still not been realized [5], and a transit charge is used instead.

When there is only one ISP, this ISP can always introduce a content charge and obtain a sufficient profit to cover the investment cost because CPs have no choice but to enter into a transit agreement with this ISP. However, when there are multiple ISPs competing with one another, the CPs can switch to another ISP, so introducing a content charge is not always a good solution for the ISPs. Therefore, when introducing a content charge by ISPs to CPs, it is important to investigate the conditions for achieving it and the effect it will have on the ISPs. However, no studies on such issues have been reported. In this paper, we assume a situation where two ISPs exist, and we model the business relationship between these two ISPs and CPs using a two-stage Stackelberg game. We also derive the optimum charging parameter of a content charge. Moreover, we investigate the conditions for introducing a content charge by ISPs and investigate the effects of the content charge on the revenue of the ISPs by numerically comparing the content charge and the transit charge. In Section II, we briefly summarize related works. In Section III, we model the relationship between ISPs and CPs. Section IV investigates the conditions necessary to levy a content charge and describes how to optimally set the charging parameter. We present the numerical results in Section V and conclude the paper in Section VI.

II. RELATED WORKS

Many studies have investigated the optimum strategies of players and the effect on the revenue of players by modeling the relationship among players and deriving the equilibrium state. For example, Ma et al. discussed whether governments should regulate ISPs to ensure there is no discrimination in service quality or in price among users and to satisfy network neutrality [22]. They assumed a monopoly market consisting of a single ISP or a duopoly market consisting of multiple ISPs, and they derived the Nash equilibrium by modeling the relationship between ISPs and CPs using the two-stage Stackelberg game. Ren et al. assumed a duopoly market of two NSPs (network service providers) with different QoS and modeled the relationship between two NSPs using the Cournot competition to investigate the growth of profit obtained by investing in network technologies [27]. Moreover, Liu et al. investigated how the performance of a search engine affected the profit of search engine providers by modeling the relationship among search engine providers, advertisement providers, and users using a three-stage repeated game in the duopoly market consisting of two search engine providers [18]. Zhang et al. derived the optimum price that maximized the profit of SPs (service providers) and ISPs by modeling the relationship among SPs using the Cournot competition and by modeling the relationship among ISPs using the Bertrand competition [35]. Moreover, using a three-stage infinitely repeated game, Ren et al. proposed a charging method for platform providers that maximized their revenue in the UGC (user-generated content) market [28].

We can also find some works modeling the relationship among ISPs, CPs, and users in content delivery services, and investigating the price at the equilibrium state as a result of the autonomous behavior of these players. For example, Hande et al. investigated the price resulting from each player autonomously maximizing its utility function when both ISPs and CPs charge users a fee proportional to the amount of data transmitted [13]. However, they did not consider a charging method involving a content charge imposed by ISPs on CPs.

Musacchio et al. derived the optimum price at which each player (ISP, CP, and user) maximized revenue at the equilibrium state [24]. Lee et al. investigated the effect of providing CDN services by ISPs on the revenue of ISPs using a four-stage Stackelberg game consisting of two ISPs, with and without CDN service, and CPs [17]. Moreover, Ma et al. proposed rational methods of allocating profit among players based on their contribution by regarding the transit relationship between one CP and multiple ISPs as a kind of coalition and by distributing profit among players based on the Shapley value of a coalitional game [19][20][21]. Dhamdhere et al. analyzed the desirable strategies for access providers to increase revenue assuming three players of access providers, CPs, and transit providers [8]. Park et al. investigated the possibility of revenue sharing between one ISP and one CP based on collaboration to reduce online content piracy [26].

However, the conditions of introducing a content charge were not investigated in any of these works. Moreover, the charging model used by ISPs on CPs in these studies was assumed to be a content charge or usage-based charge that was simply proportional to the total amount of data transmitted. They did not compare the content charge with the usage-based charge of common use in which the increase ratio of the charge decreases as the amount of data transmitted increases, and they did not investigate the effects of the content charge on the revenue of ISPs. Although we previously investigated the conditions necessary to levy a content charge by ISPs [15], the way to optimally set the charging parameter was not analyzed.

III. MODELING CONTENT CHARGE BY ISP

In this section, we describe the models of relationship among players, the amount of traffic generated, the charging models ISPs use with content providers, and the cost to each player. Table I summarizes the semantics of the variables.

A. Structure among Players

The players that provide the content delivery services are CPs, users, and ISPs delivering content from CPs to users. We

TABLE I
SUMMARY OF VARIABLES.

Variable	Semantics
u_y	number of users accommodated by ISP-y ($y = 1$ or 2)
N	number of CPs
$\mathcal{H}$	entire set of N CPs
$\mathcal{H}_k$	set of CPs connecting with no ISPs, ISP-1, ISP-2, and both ISPs for $k = 0$, 1, 2, and 3, respectively
T_{xy}	transit fee paid by CP-x to ISP-y
ϵ_x	ratio of requests for content provided by CP-x
d_{xy}	average request count generated from each user of ISP-y for content of CP-x within one month
d	average request count generated from each user of ISP with transit agreement with CP within one month
γ	degree of quality degradation caused by going through both ISPs
D_{xy}	average number of requests generated from users of ISP-y for content of CP-x within one month
P	fee charged by CPs to user for each content delivery
α	charging parameter of content charge by ISP-1
β	charging parameter of transit charge by both ISPs
L	average content size
V	amount of data transmitted per second
V_{xy}	value of V applied to CP-x by ISP-y
n_t	coefficient of transit fee
F	monthly leased line fee paid by CPs
G	cost of delivering each content issued in each ISP network
$\phi_{x,k}$	monthly revenue obtained by CP-x when using strategy k
z_x	product $epsilon_x$ and d
$C_{x,k}$	condition for α in which CP-x selects strategy k
$\rho_{x,*}$, $\sigma_{x,*}$	threshold of α determining $\mathcal{H}_k$
$\mathcal{A}_1$, $\mathcal{A}_2$	set of CPs classified by magnitude relation among $\rho_{x,*}$
u	total number of users in both ISPs
ξ	ratio of user count of ISP-1
S_k	range of α in which CP-x takes strategy k
R_y	monthly revenue of ISP-y
R_C	sum of monthly revenue of all CPs
Φ	monthly social surplus
θ	parameter determining distribution of ϵ_x

assume that CPs obtain a fee directly from users, i.e., a paid delivery service, and we do not consider the business model based on advertisements. We also assume that there are two ISPs, i.e., ISP-1 and ISP-2, accommodating u_1 and u_2 users. We assume that the price and provided quality are identical in the two ISPs, and that the two ISPs are not competing to acquire users, so u_1 and u_2 are fixed. There are N CPs, and let $\mathcal{H}$ denote the entire set of N CPs. Each CP independently and freely selects ISPs to enter into a transit agreement with; let $\mathcal{H}_1$, $\mathcal{H}_2$, and $\mathcal{H}_3$ denote the set of CPs entering into a transit agreement with only ISP-1, only ISP-2, and both ISPs, respectively. The CPs can also choose not to enter into a transit agreement with either ISP, and let $\mathcal{H}_0$ denote the set of these CPs.

Figure 1 illustrates an example of the relationship among players when CP-1, CP-2, and CP-N enters into a transit agreement with only ISP-1, both the ISPs, and only ISP-2, respectively. Each CP-x pays the transit fee T_{xy} to connected ISP-y and delivers content to users through the connected ISPs. There are mainly two types of agreements, i.e., transit and peering agreements, which is when ISPs connect with other ISPs. A transit agreement is mainly used between a regional ISP and a transit ISP; the regional ISP pays the transit fee to the transit ISP based on the amount of generated traffic. In a peering agreement, on the other hand, no transit fee is paid between connected ISPs. We assume that both the two ISPs are connected through a peering agreement. By entering into a transit agreement with at least one ISP, CPs can deliver content to all users accommodated by the two ISPs. As shown in Fig. 2(a), for example, content of CP-1 connecting with only ISP-1 is delivered to users of ISP-1 only through the network of ISP-1, whereas it is delivered to users of ISP-2 through the networks of both ISP-1 and ISP-2. On the other hand, as shown in Fig. 2(b), content of CP-2 connecting with both the ISPs is delivered to users of ISP-1 only through the network of ISP-1, and delivered to users of ISP-2 only through the network of ISP-2.

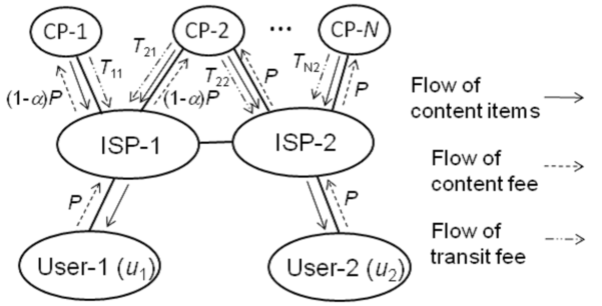
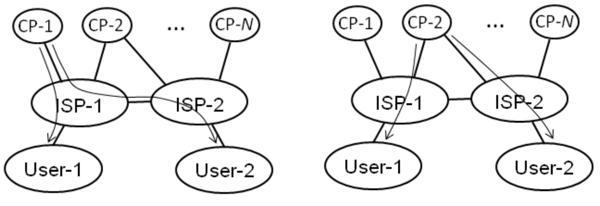


Fig. 1. Relationship between players



(a) Delivery from CP-1 (b) Delivery from CP-2

Fig. 2. Examples of content delivery route

B. Amount of Traffic

We assume that the preference of users for content is identical, and we define ϵ_x as the ratio of requests for content provided by CP-x. Here, ϵ_x satisfies $\sum_{x=1}^{N} \epsilon_x = 1$. Let d_{xy} denote the average number of requests generated from each user accommodated by ISP-y for content of CP-x within one month. d_{xy} depends on various factors, including the link capacities or link load in each network, the connectivity among ISPs, and the capacities and loads of transit or peering links between ISPs, so accurately estimating d_{xy} is difficult. However, we can roughly say that the quality of content delivery, i.e., throughput and stability, is different between users accommodated by an ISP with a direct connection to the CP and those accommodated by an ISP without a direct connection to the CP. Therefore, to investigate the general trend, we ignore the structure of connectivity among ISPs and simply assume that d_{xy} depends only on whether or not ISP-y has a transit agreement with CP-x, and we simply set $d_{xy} = \epsilon_x d$ for ISP-y with a transit agreement with CP-x and $d_{xy} = \gamma\epsilon_x d$ for ISP-y without a transit agreement with CP-x, where d is the average number of requests generated from a user accommodated by the ISP with a transit agreement with the CP within one month. Here, γ is a parameter that takes a real number in the range of $0 < \gamma < 1$, and it represents the degree of quality degradation that results from going through both ISPs. By evaluating the performance with various values of γ, we can investigate the influence of γ on the ISP revenue.

Here, D_{xy} is defined as the average number of content deliveries from CP-x to users of ISP-y within one month. For users accommodated in an ISP without a transit agreement with the CP, content goes through the network of the other ISP, and transit traffic is generated in the other ISP. Therefore, D_{xy} is obtained by

$$D_{x1} = \begin{cases} 0, & x \in \mathcal{H}_0 \cup \mathcal{H}_2, \\ \epsilon_x d(u_1 + \gamma u_2), & x \in \mathcal{H}_1, \\ \epsilon_x d u_1, & x \in \mathcal{H}_3, \end{cases} \tag{1}$$

$$D_{x2} = \begin{cases} 0, & x \in \mathcal{H}_0 \cup \mathcal{H}_1, \\ \epsilon_x d(\gamma u_1 + u_2), & x \in \mathcal{H}_2, \\ \epsilon_x d u_2, & x \in \mathcal{H}_3. \end{cases} \tag{2}$$

C. Charging Model of ISPs for Content Providers

The charging system that many CPs use to charge users is a flat fee, in which users can download as much content as they want at a fixed fee, or a usage-based charge, in which users pay a fee for each content delivery [14]. In this paper, we assume a usage-based charge in which CPs obtain a fixed fee P from users for each content delivery regardless of the type of content. Now, let us consider the case where ISP-1 introduces a content charge, i.e., it obtains part of content fee P from CPs for each content delivery, in addition to the transit fee T_{x1}. Specifically, ISP-1 obtains αP from CPs for each content delivery in addition to T_{x1}, where α is the charging ratio, which takes a real number between zero and unity. In other words, CPs obtain $(1-\alpha)P$ instead of P from users for each content delivery when delivering content via a transit link with ISP-1. We assume that ISP-2 does not introduce a content charge and continues to use only a transit charge. Figure 1 also depicts the money flow among players. We leave the investigation of the case where three or more ISPs exist, or multiple ISPs introduce a content charge as future work.

Next, we model the transit charge. The transit charge is the charging model most commonly used by ISPs with content providers: ISPs charge the content provider based on the amount of data transmitted per second on the transit link. According to an analysis of transit charges of ISPs in 20 areas of the USA in 2004, the transit fee in one month, T, is proportional to the amount of data transmitted per second, V (bps), powered by 0.75, and T can be approximated as $T = 100V^{0.75}$ [4]. For example, $T = 560$ USD when $V = 10$ Mbps, and $T = 100,000$ USD when $V = 10$ Gbps. In this paper, using a real number parameter β, we generalize the transit fee as $T = 100V^{\beta}$. We assume that the parameter of transit charge β is fixed because the Internet transit service, not limited to the content delivery service, affects the transit fee. We have also investigated the case when ISP-2 as well as ISP-1 can configure the charging parameter β in [16].

Many ISPs use the 95th percentile of the data transmission rate every 5 minutes as V, and we assume that the 95th percentile of the data transmission rate is three times the average data transmission rate [8]. Let L (Mbytes) denote the average content size and let us assume that the number of days within one month is 30 days; then V_{xy}, the value of V applied to CP-x by ISP-y, is

$$\begin{aligned} V_{xy} &= \left\{ \frac{3 \times 8LD_{xy}}{30 \times 24 \times 3600} \right\} \\ &= 1.08 \times 10^{-5} L D_{xy}. \end{aligned} \tag{3}$$

Hence, T_{xy}, the monthly transit fee paid by CP-x to ISP-y, is obtained by

$$T_{xy} = n_t D_{xy}^{\beta}, \tag{4}$$

where we define n_t as $n_t \equiv 100 \times (1.08 \times 10^{-5})^{\beta} L^{\beta}$.

D. Cost Model

Next, we model the cost on each CP and ISP. CPs need to pay the fee of a leased line between content servers and the access point of ISPs in addition to the transit fee and content delivery fee mentioned in Section III-C. We assume a fixed charge for the leased line fee and set F as the monthly charge when any CP-x connects with any ISP-y. Based on the price of the ATM Mega Link Service provided by NTT East under the conditions of 30 km, dual class, and 100 Mbps, we set F = 40,000 USD [25].

By contrast, ISPs need to consider the cost of delivering content. As shown in Fig. 2, for each request from users of ISP-1 for content of CP-x ($x \in \mathcal{H}_1 \cup \mathcal{H}_3$), ISP-1 delivers content from the access point with CP-x to users. ISP-1 also delivers content from the access point with CP-x of $x \in \mathcal{H}_1$ to the peering point with ISP-2 for each request from users of ISP-2 for content of CP-x. Moreover, for each request from users of ISP-1 for content of CP-x ($x \in \mathcal{H}_2$), ISP-1 delivers content from the peering point with ISP-2 to users. We assume that identical cost G arises from each of these content deliveries. We also apply cost G for ISP-2.

It is difficult to accurately estimate G. Therefore, for example, Valancius et al. analyzed the effect of setting the price according to distance on the revenue of ISPs by simply assuming that the transmission cost of traffic obeyed a convex function of distance or a function of roughly classified distance categories, i.e., metro, domestic, and international [32]. In this paper, we set G based on the monthly transit fee between ISPs. The current average transit fee per 1 Mbps in the USA in 2013 is 1.57 USD [10], and it was reported that the amount of demand at peak hours was about 1.8 times larger than the average in a commercial VoD service [34], so we set G as

$$G = \frac{1.57 \times 1.8 \times 8L}{30 \times 24 \times 3600} = 8.72 \times 10^{-6} L \tag{5}$$

IV. ANALYSIS OF EFFECT OF CONTENT CHARGE

In this section, the optimum strategies of each CP and ISP are analyzed and the conditions required to implement a content charge and the effect of the content charge on the revenue of an ISP are investigated. As mentioned in Section III-C, we assume that the parameter of transit charge β is fixed. In contrast, ISP-1 can freely set the parameter of content charge α, and each CP determines the ISPs with which they enter into a transit agreement after determining the setting value of α. Therefore, the behavior of CPs and ISPs consists of two stages: ISP-1 sets α in the first stage, and each CP determines the ISPs with which it enters into a transit agreement. We assume that each player is rational, i.e., they select the optimum strategy to maximize their own revenue. The relationship between ISP-1 and CPs can be modeled by a Stackelberg game, so the equilibrium state is the subgame perfect Nash equilibrium (SPE), and we can derive the equilibrium state by a backward induction [23]. That is, we can obtain the SPE by first deriving the optimum strategy of each CP for a given α and then deriving the optimum strategy of ISP-1 when setting α.

A. Optimum Strategy of CPs

Let k denote the strategy of each CP as it enters into a transit agreement with no ISPs ($k = 0$), only ISP-1 ($k = 1$), only ISP-2 ($k = 2$), and both ISPs ($k = 3$). We define $\phi_{x,k}$ as the monthly revenue obtained by CP-x when using strategy k, and it is obtained by

$$\phi_{x,1} = Pz_x(u_1 + \gamma u_2)(1-\alpha) - n_t z_x^{\beta}(u_1 + \gamma u_2)^{\beta} - F, \tag{6}$$
$$\phi_{x,2} = Pz_x(\gamma u_1 + u_2) - n_t z_x^{\beta}(\gamma u_1 + u_2)^{\beta} - F, \tag{7}$$
$$\phi_{x,3} = Pz_x\left\{(1-\alpha)u_1 + u_2\right\} - n_t z_x^{\beta}(u_1^{\beta} + u_2^{\beta}) - 2F, \tag{8}$$

where z_x is defined as $z_x = \epsilon_x d$. For strategy $k = 0$, $\phi_{x,0} = 0$. For the condition that determines the behavior of CPs, the following proposition is formed.

Proposition 1. When we define $C_{x,1}$, $C_{x,2}$, and $C_{x,3}$ as the condition for α in which CP-x selects strategy $k = 1$, $k = 2$, and $k = 3$, respectively, we obtain them as

$$C_{x,1}: \qquad \alpha < \min(\rho_{x,a}, \rho_{x,b}, \sigma_{x,a}), \tag{9}$$
$$C_{x,2}: \qquad \alpha > \max(\rho_{x,a}, \rho_{x,c}), \tag{10}$$
$$C_{x,3}: \qquad \rho_{x,b} < \alpha < \min(\rho_{x,c}, \sigma_{x,b}), \tag{11}$$

where $\rho_{x,a}$, $\rho_{x,b}$, $\rho_{x,c}$, $\sigma_{x,a}$, and $\sigma_{x,b}$ are defined as

$$\begin{aligned}\rho_{x,a} &= \frac{(1-\gamma)(u_1-u_2)}{u_1+\gamma u_2} + \frac{n_t}{Pz_x^{1-\beta}(u_1+\gamma u_2)} \\ &\quad \left\{(\gamma u_1+u_2)^{\beta} - (u_1+\gamma u_2)^{\beta}\right\}, \end{aligned} \tag{12}$$

$$\begin{aligned}\rho_{x,b} &= 1 - \frac{1}{\gamma} - \frac{n_t}{Pz_x^{1-\beta}\gamma u_2}\left\{(u_1+\gamma u_2)^{\beta} - u_1^{\beta} - u_2^{\beta}\right\} \\ &\quad + \frac{F}{Pz_x\gamma u_2}, \end{aligned} \tag{13}$$

$$\begin{aligned}\rho_{x,c} &= 1 - \gamma + \frac{n_t}{Pz_x^{1-\beta}u_1}\left\{(\gamma u_1+u_2)^{\beta} - u_1^{\beta} - u_2^{\beta}\right\} \\ &\quad - \frac{F}{Pz_x u_1}, \end{aligned} \tag{14}$$

$$\sigma_{x,a} = 1 - \frac{n_t}{Pz_x^{1-\beta}(u_1+\gamma u_2)^{1-\beta}} - \frac{F}{Pz_x(u_1+\gamma u_2)}, \tag{15}$$

$$\sigma_{x,b} = 1 + \frac{u_2}{u_1} - \frac{n_t(u_1^{\beta}+u_2^{\beta})}{Pz_x^{1-\beta}u_1} - \frac{2F}{Pz_x u_1}. \tag{16}$$

Proof. Only when all three conditions, $\phi_{x,1} > \phi_{x,2}$, $\phi_{x,1} > \phi_{x,3}$, and $\phi_{x,1} > 0$ are satisfied, CP-x selects strategy $k = 1$. These three conditions are satisfied when $\alpha < \rho_{x,a}$, $\alpha < \rho_{x,b}$, and $\alpha < \sigma_{x,a}$, so the condition for α for CP-x to select strategy $k = 1$ is given by (9). Similarly, only when $\phi_{x,2} > \phi_{x,1}$, $\phi_{x,2} > \phi_{x,3}$, and $\phi_{x,2} > 0$ are satisfied, CP-x selects strategy $k = 2$. Because $\phi_{x,2}$ is independent of α, the condition for α for CP-x to select strategy $k = 2$ is given by (10). Moreover, only when $\phi_{x,3} > \phi_{x,1}$, $\phi_{x,3} > \phi_{x,2}$, and $\phi_{x,3} > 0$ are satisfied, CP-x selects strategy $k = 3$, and its condition for α is given by (11). ☐

We note that the condition $\phi_{x,2} > 0$ is not included in $C_{x,2}$, and the strategy $k = 2$ is selected only when both $\phi_{x,2} > 0$ and $C_{x,2}$ are satisfied.

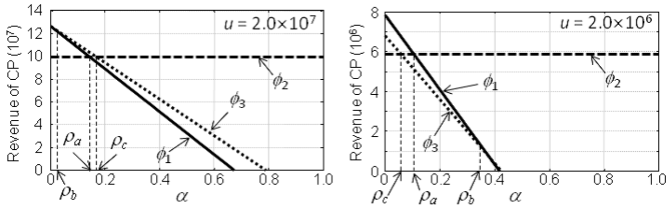
1) Derivation of Set of CPs in Each Strategy: For the magnitude relation among $\rho_{x,a}$, $\rho_{x,b}$, and $\rho_{x,c}$, the following proposition is formed.

Proposition 2. There are $3 \times 2 = 6$ patterns that exist for the magnitude relation among $\rho_{x,a}$, $\rho_{x,b}$, and $\rho_{x,c}$. However, only two patterns, $\rho_{x,b} \le \rho_{x,a} \le \rho_{x,c}$ or $\rho_{x,c} \le \rho_{x,a} \le \rho_{x,b}$ are realized.

Proof. Assuming $\rho_{x,a} < \rho_{x,b} < \rho_{x,c}$ results in a contradiction because $\phi_{x,2} > \phi_{x,1}$, $\phi_{x,1} > \phi_{x,3}$, and $\phi_{x,3} > \phi_{x,2}$ are satisfied simultaneously when $\rho_{x,a} < \alpha < \rho_{x,b}$. Similarly, assuming $\rho_{x,a} < \rho_{x,c} < \rho_{x,b}$, $\rho_{x,b} < \rho_{x,c} < \rho_{x,a}$, or $\rho_{x,c} < \rho_{x,b} < \rho_{x,a}$ results in a contradiction in the range of α. Therefore, only $\rho_{x,b} \le \rho_{x,a} \le \rho_{x,c}$ or $\rho_{x,c} \le \rho_{x,a} \le \rho_{x,b}$ is satisfied. ☐

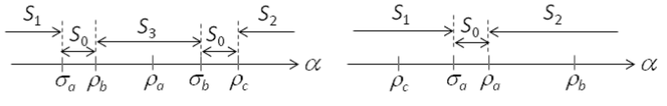
Therefore, all CPs are included in either $\mathcal{A}_1$ or $\mathcal{A}_2$, where $\mathcal{A}_1$ and $\mathcal{A}_2$ are defined as $\mathcal{A}_1 \equiv \{x \in \mathcal{H} : \rho_{x,b} \le \rho_{x,a} \le \rho_{x,c}\}$ and $\mathcal{A}_2 \equiv \{x \in \mathcal{H} : \rho_{x,c} \le \rho_{x,a} \le \rho_{x,b}\}$.

Figure 3 plots the monthly revenue of ISP-1, ϕ_1, ϕ_2, and ϕ_3, obtained by (6)-(8) against α when setting $N = 1$ ($\epsilon_1 = 1$),



(a) Case of A_1 (b) Case of A_2

Fig. 3. Revenue of CP against α



(a) Case of $\rho_b < \rho_a < \rho_c$ (b) Case of $\rho_c < \rho_a < \rho_b$

Fig. 4. Ranges of α in each CP strategy

$d = 10$, $P = 1$, and $\gamma = 0.7$[1]. We set the total number of users in both ISPs, $u = u_1 + u_2$, at a fixed value, and we gave the user count of each ISP as $u_1 = \xi u$ and $u_2 = (1-\xi)u$, where ξ is a parameter that takes a real number between zero and unity. We set $u = 2\times10^7$ or 2×10^6, and $\xi = 0.8$. In the figures, $\alpha = \rho_a$ at the crossing point of ϕ_1 and ϕ_2. Similarly, $\alpha = \rho_b$ and $\alpha = \rho_c$ at the crossing point of ϕ_1 and ϕ_3, or ϕ_2 and ϕ_3. Figures 3(a) and 3(b) correspond to the case of $x \in \mathcal{A}_1$ and $x \in \mathcal{A}_2$, respectively.

For CP-x of $x \in \mathcal{A}_1$, the revenue obtained using the strategy $k = 0$ agrees with that obtained using the strategy $k = 1$ when $\rho_{x,b} > \sigma_{x,a}$ and $\alpha = \sigma_{x,a}$, and the revenue obtained using the strategy $k = 1$ agrees with that obtained by the strategy $k = 3$ when $\rho_{x,b} < \sigma_{x,a}$ and $\alpha = \rho_{x,b}$. Therefore, we cannot uniquely determine the strategy taken by CP-x when α is at these boundaries. However, we assume that CP-x selects $k = 3$ at these boundaries. Similarly, although the strategy taken by CP-x of $x \in \mathcal{A}_1$ is not uniquely determined when $\alpha = \rho_{x,c}$ or $\sigma_{x,b}$, we assume that CP-x selects $k = 1$ at these boundaries. Moreover, although the revenue obtained by CP-x of $x \in \mathcal{A}_2$ using strategy $k = 1$ agrees with that using strategy $k = 0$ ($k = 2$) when $\rho_{x,a} > \sigma_{x,a}$, $\alpha = \sigma_{x,a}$ ($\rho_{x,a} < \sigma_{x,a}$, $\alpha = \rho_{x,b}$), we assume that CP-x selects $k = 1$ at these boundaries. For the set of CPs that take each strategy, we obtain the following theorem.

Theorem 1. The CP set of each strategy, $\mathcal{H}_0$, $\mathcal{H}_1$, $\mathcal{H}_2$, and $\mathcal{H}_3$, is obtained by

$$\mathcal{H}_0 = \mathcal{H} \setminus (\mathcal{H}_1 \cup \mathcal{H}_2 \cup \mathcal{H}_3), \tag{17}$$

$$\begin{aligned}\mathcal{H}_1 = {} & \{x \in \mathcal{A}_1 : \alpha \le \min(\rho_{x,b}, \sigma_{x,a})\} \\ & \cup \{x \in \mathcal{A}_2 : \alpha \le \min(\rho_{x,a}, \sigma_{x,a})\},\end{aligned} \tag{18}$$

$$\begin{aligned}\mathcal{H}_2 = {} & \{x \in \mathcal{A}_1 : \alpha \ge \max(\rho_{x,c}, \sigma_{x,b}),\ \phi_{x,2} > 0\} \\ & \cup \{x \in \mathcal{A}_2 : \alpha \ge \rho_{x,a},\ \phi_{x,2} > 0\},\end{aligned} \tag{19}$$

$$\mathcal{H}_3 = \{x \in \mathcal{A}_1 : \rho_{x,b} \le \alpha \le \min(\rho_{x,c}, \sigma_{x,b})\}. \tag{20}$$

Proof. CP-x of $x \in \mathcal{A}_1$ can maximize its revenue by selecting strategy $k = 1$, $k = 0$, $k = 3$, $k = 0$, and $k = 2$ when $\alpha \le \min(\rho_{x,b}, \sigma_{x,a})$, $\min(\rho_{x,b}, \sigma_{x,a}) < \alpha < \rho_{x,b}$, $\rho_{x,b} \le \alpha \le \min(\rho_{x,c}, \sigma_{x,b})$, $\min(\rho_{x,c}, \sigma_{x,b}) < \alpha < \rho_{x,c}$, and $\rho_{x,c} \le \alpha$, respectively. Therefore, S_k, the range of α in which CP-x of $x \in \mathcal{A}_1$ takes strategy k, is given by the areas shown in Fig. 4(a). Thus, $\rho_{x,a}$ does not affect the behavior of CP-x.

Similarly, CP-x of $x \in \mathcal{A}_2$ can maximize its revenue by selecting strategy $k = 1$, $k = 0$, and $k = 2$ when $\alpha \le \min(\rho_{x,a}, \sigma_{x,a})$, $\min(\rho_{x,a}, \sigma_{x,a}) < \alpha < \rho_{x,a}$, and $\rho_{x,a} \le \alpha$, respectively. In this case, S_k is given by the areas shown in Fig. 4(b), and $\rho_{x,b}$ and $\rho_{x,c}$ do not affect the behavior of CP-x. Thus, strategy $k = 3$ is never selected by CP-x of $x \in \mathcal{A}_2$. ☐

Therefore, when ISP-1 sets the charging parameter α, the strategies of CPs and the revenue of each player are uniquely determined.

2) Numerical Example of Optimum Strategy of CP: The influence of each parameter on the optimum strategy of a CP is investigated in Fig. 5, which plots the five boundaries for α, i.e., ρ_a, ρ_b, ρ_c, σ_a, and σ_b, as well as ϕ_2 when changing each of the six parameters with setting $N = 1$ ($\epsilon_1 = 1$). Except for the parameter that is changed, we set $u = 2\times10^7$, $d = 10$, $P = 1$, $\gamma = 0.3$, and $\xi = 0.9$. S_k is also illustrated in Fig. 5. In the entire range of γ and ξ, ϕ_2 was greater than unity. However, ϕ_2 suddenly increased or decreased, and the area of S_0 existed because $\phi_2 \le 0$ when u, L, ϵ, and d were changed. Moreover, ρ_a, ρ_b, and ρ_c intersected at a single point, and the left or right area of this matching point corresponded to $x \in \mathcal{A}_1$ or $x \in \mathcal{A}_2$.

By setting α in the area of S_1 or S_3, ISP-1 can introduce the content charge. For example, as shown in Fig. 5(a), ISP-1 can introduce the content charge because S_1 or S_3 exists in the entire range of γ. In contrast, as shown in Fig. 5(b), both S_1 and S_3 do not exist, and ISP-1 cannot introduce the content charge when $\xi \le \xi_{\rho c}$, where $\xi_{\rho c}$ is defined as the value of ξ where $\rho_c = 0$. However, when $\xi > \xi_{\rho c}$, ISP-1 can introduce the content charge by setting α in the area of S_1 or S_3, because the revenue of the CP that increased through entering into a transit agreement with ISP-1 was greater than the increased cost of the CP, and the transit agreement with ISP-1 was therefore advantageous for the CP.

As γ increased, the advantage to the CPs of connecting with both ISPs decreased, and the competitive power of ISP-2 against ISP-1 increased. Consequently, the areas of S_1 and S_3 decreased, whereas that of S_2 expanded. On the contrary, as ξ increased, the advantage to the CPs of connecting with ISP-1 increased, so S_3 or S_1 expanded in the small-region or large-region of α, respectively. As u increased, the income of CPs increased compared with the fixed cost F, and the range

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[1] Because $N = 1$, we simply describe $\phi_{x,k}$, $\rho_{x,*}$, and $\sigma_{x,*}$ as ϕ_k, ρ_*, and σ_*.

of α in which the CP selected the strategy $k = 3$ grew. When u was too small, it was difficult for CPs to obtain sufficient profit when ISP-1 introduces the content charge.

With the increase in L, the amount of transmitted traffic grew, and the transit fee that CPs paid to ISPs increased, so S_3 decreased whereas S_2 expanded. When L was too large, the CPs that had entered into a transit agreement with ISP-1 lost revenue, so ISP-1 cannot introduce the content charge. Moreover, as ϵ or d increased, the income of CPs also increased compared with F, and the range of α in which CPs selected the strategy $k = 3$ expanded.

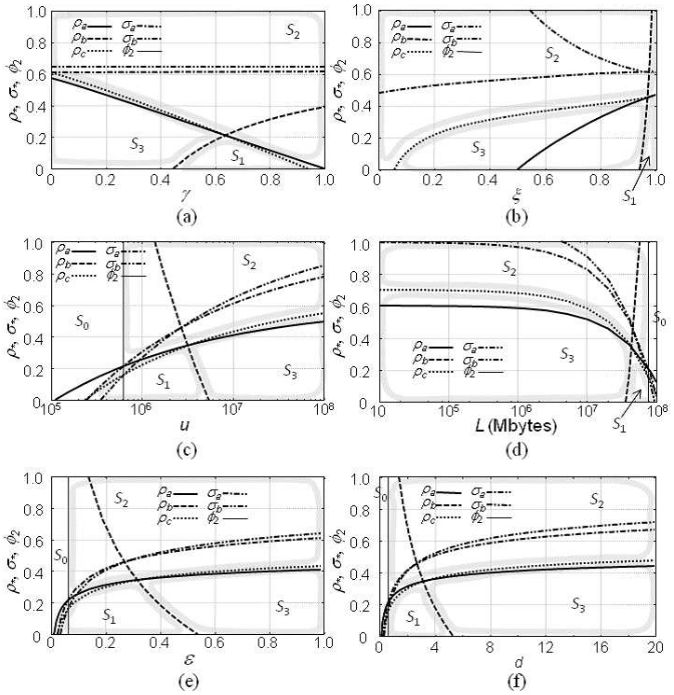

Fig. 5. Optimum strategy of CP against various parameters

B. Optimum Strategy of ISP-1

In this section, we analyze the optimum strategy of ISP-1 in setting the charging parameter α based on the estimates of $\mathcal{H}_k$ derived in Section IV-A. For R_1, the monthly revenue of ISP-1, we obtain the following proposition.

Proposition 3. The monthly revenue of ISP-1, R_1, was obtained by

$$\begin{aligned} R_1 \;=\; & \sum_{x\in\mathcal{H}_1} \left\{(\alpha P - G) z_x (u_1 + \gamma u_2) + n_t z_x^{\beta} (u_1 + \gamma u_2)^{\beta}\right\} \\ & - \sum_{x\in\mathcal{H}_2} G z_x \gamma u_1 \\ & + \sum_{x\in\mathcal{H}_3} \left\{(\alpha P - G) z_x u_1 + n_t z_x^{\beta} u_1^{\beta}\right\}. \end{aligned} \tag{21}$$

Proof. ISP-1 obtains the transit fee and content fee from the contracted CPs as mentioned in Section III-C; at the same time, ISP-1 pays delivery cost G as mentioned in Section III-D. In other words, by delivering content from CP-x of $x \in \mathcal{H}_1$, ISP-1 obtains the revenue of $(\alpha P - G) z_x (u_1 + \gamma u_2) + n_t z_x^{\beta} (u_1 + \gamma u_2)^{\beta}$ within one month. Moreover, by delivering content from CP-x of $x \in \mathcal{H}_3$, ISP-1 obtains the revenue of $(\alpha P - G) z_x u_1 + n_t z_x^{\beta} u_1^{\beta}$ within one month. Although ISP-1 cannot obtain the revenue by delivering content of CP-x of $x \in \mathcal{H}_2$, ISP-1 needs to pay delivery cost G, so ISP-1 obtains the revenue of $-G z_x \gamma u_1$ within one month. Therefore, R_1 is obtained by (21). ☐

The optimum strategy of ISP-1 is to set α so that R_1 is maximized, and R_1 will discontinuously change at the points where $\mathcal{H}_k$ changes. Therefore, we obtain the following theorem for the optimum strategy of ISP-1.

Theorem 2. When the boundary set of α is defined as

$$\begin{aligned} \mathcal{M}_1 &\equiv \{\rho_{x,b}, \rho_{x,c} : x \in \mathcal{A}_1\}, & (22)\\ \mathcal{M}_2 &\equiv \{\sigma_{x,a} : x \in \mathcal{A}_1, \sigma_{x,a} < \rho_{x,b}\}, & (23)\\ \mathcal{M}_3 &\equiv \{\sigma_{x,b} : x \in \mathcal{A}_1, \sigma_{x,b} < \rho_{x,c}\}, & (24)\\ \mathcal{M}_4 &\equiv \{\rho_{x,a} : x \in \mathcal{A}_2\}, & (25)\\ \mathcal{M}_5 &\equiv \{\sigma_{x,a} : x \in \mathcal{A}_2, \sigma_{x,a} < \rho_{x,a}\} & (26) \end{aligned}$$

and $\mathcal{M}$ is defined as

$$\mathcal{M} \equiv \mathcal{M}_1 \cup \mathcal{M}_2 \cup \mathcal{M}_3 \cup \mathcal{M}_4 \cup \mathcal{M}_5, \tag{27}$$

it is sufficient for ISP-1 to consider only $\alpha \in \mathcal{M}$ as the candidate for the setting value of α, and ISP-1 can maximize R_1 by calculating R_1 from (21) when setting α to each member of $\mathcal{M}$ and selecting α that maximizes R_1 as the optimum value of α, α^*.

Proof. As mentioned in Section IV-A1, for CP-x of $x \in \mathcal{A}_1$, $\mathcal{H}_k$ discontinuously changes at $\alpha = \rho_{x,b}$ and $\alpha = \rho_{x,c}$. Moreover, $\mathcal{H}_k$ also discontinuously changes at $\alpha = \sigma_{x,a}$ in the case of $\sigma_{x,a} < \rho_{x,b}$ and at $\alpha = \sigma_{x,b}$ in the case of $\sigma_{x,b} < \rho_{x,c}$. On the other hand, for CP-x of $x \in \mathcal{A}_2$, $\mathcal{H}_k$ discontinuously changes at $\alpha = \rho_{x,a}$, and $\mathcal{H}_k$ discontinuously changes at $\alpha = \sigma_{x,a}$ in the case of $\sigma_{x,a} < \rho_{x,a}$. Therefore, only when α takes a value of the elements of $\mathcal{M}$ defined by (27), $\mathcal{H}_k$ can change.

When the behavior of CPs at the boundaries of α is assumed as described in Section IV-A1, R_1 monotonically increases with the increase in α at the boundaries where $\mathcal{H}_k$ changes, so R_1 is constant when changing α in the range of $m_1 < \alpha \leq m_2$, where m_1 and m_2 are any two consecutive elements of $\mathcal{M}$. Therefore, it is enough to consider only m_2 as the setting value of α in the range of $m_1 < \alpha \leq m_2$ because R_1 is maximized at $\alpha = m_2$ in this range of α. Therefore, as the candidate for the setting value of α, it is enough to consider only the elements of $\mathcal{M}$ defined by (27). ☐

The monthly revenue of ISP-2, R_2, is obtained by

$$\begin{aligned} R_2 &= -\sum_{x\in\mathcal{H}_1} Gz_x\gamma u_2 + \sum_{x\in\mathcal{H}_2}\left\{n_t z_x^{\beta}(\gamma u_1+u_2)^{\beta}\right. \\ &\quad \left. -Gz_x(\gamma u_1+u_2)\right\} + \sum_{x\in\mathcal{H}_3}\left(n_t z_x^{\beta}u_2^{\beta} - Gz_x u_2\right), \end{aligned} \tag{28}$$

independently of the strategy of ISP-1 in setting α. Moreover, we define R_C as the sum of the monthly revenue of all the CPs. Using $\phi_{x,1}$, $\phi_{x,2}$, and $\phi_{x,3}$ obtained by (6)-(8), we can derive R_C as

$$R_C = \sum_{x\in\mathcal{H}_1}\phi_{x,1} + \sum_{x\in\mathcal{H}_2}\phi_{x,2} + \sum_{x\in\mathcal{H}_3}\phi_{x,3}. \tag{29}$$

Let Φ denote the monthly social surplus, i.e., the sum of the revenue of all the players; it is obtained by

$$\begin{aligned} \Phi &= R_1 + R_2 + R_C, \\ &= \sum_{x\in\mathcal{H}_1}\{(P-G)z_x(u_1+\gamma u_2) - Gz_x\gamma u_2 - F\} \\ &\quad + \sum_{x\in\mathcal{H}_2}\{(P-G)z_x(\gamma u_1+u_2) - Gz_x\gamma u_1 - F\} \\ &\quad + \sum_{x\in\mathcal{H}_3}\{(P-G)z_x(u_1+u_2) - 2F\}. \end{aligned} \tag{30}$$

The money flow caused by the content charge is offset between ISP-1 and the CPs, so Φ is independent of α.

V. NUMERICAL EVALUATION

A. Evaluation Conditions

In this section, we evaluate what effect the content charge has on the revenue of each player. Here, we describe the baseline setting of parameters in the evaluation. We set P, the fee that CPs obtain from users for each content delivery, at 1 USD [14]. It was reported that the average number of views within one month per user when charged a flat fee was 10 [3], and we can regard this number as the upper limit of the view count determined by various constraints, e.g., the amount of free time. Consequently, we set d, the average number of requests generated from each user accommodated by an ISP with a transit agreement with a CP within one month, at 10. Moreover, we set γ, the degree of quality degradation caused by going through both ISPs, at 0.3, and we set β, the charging parameter of the transit charge, at 0.75.

The number of CPs was set at $N = 10$, and ϵ_x, the ratio of requests for content provided by CP-x, obeyed the Zipf distribution with parameter θ, i.e., $\epsilon_x = c/x^{\theta}$ ($c = 1/\sum_{x=1}^{N} 1/x^{\theta}$). The number of users of ISP-y, u_y, is given by $u_1 = \xi u$ and $u_2 = (1-\xi)u$, and we set $u = 1.0\times 10^7$ and $\xi = 0.6$. Moreover, we set L, the average content size, at 30 Gbytes, which corresponds to content encoded by the DVB-S2 at an encoding rate between 40 and 60 Mbps and with a length of 100 min.

Two cases of charging methods used by the two ISPs were compared. In the first case, denoted as *TR*, both ISP-1 and ISP-2 use the transit charge. In the second case, denoted as *CC*, ISP-1 uses both a transit charge and a content charge, whereas ISP-2 uses only a transit charge.

B. Influence of Content Charge on Revenue of Each Player

To investigate the influence of introducing a content charge on each player, $\hat{R}_1$ defined as $\hat{R}_1 \equiv R_{1,CC} - R_{1,TR}$ was evaluated, where $R_{1,CC}$ and $R_{1,TR}$ are R_1 in CC and in TR, respectively. Similarly, $\hat{R}_2$, $\hat{R}_C$, and $\hat{\Phi}$ are also defined as the differences in R_2, R_C, and Φ between the two charging model patterns for ISPs. Figure 6 plots $\hat{R}_1$, $\hat{R}_2$, $\hat{R}_C$, and $\hat{\Phi}$ against each parameter.

In the entire range of all the parameters, $\hat{\Phi}$ was zero, and it was confirmed that the social surplus was sustained after the introduction of a content charge by ISP-1[2]. With the increase in γ, the number of CPs contracting with ISP-1 was kept constant; whereas α^* increased in the small region of γ, and α^* decreased in the large region of γ. Therefore, $\hat{R}_1$ had a similar tendency as α^*. Moreover, as ξ or u increased, the competitive strength of ISP-1 grew, so α^* and $\hat{R}_1$ increased. With the increase in L, α^* decreased, so $\hat{R}_1$ also decreased.

With the increase in γ, the advantage for CPs to enter into a transit agreement with only ISP-1 increased, so $\hat{R}_2$ drastically decreased as γ increased. However, in the entire range of all the other parameters, $\hat{R}_2$ was close to zero, and we confirmed that ISP-2 was not affected by the introduction of a content charge by ISP-1. Because part of the profits of CPs moved to ISP-1 in CC, $\hat{R}_C$ showed the reverse tendency of $\hat{R}_1$.

In summary, it was confirmed that part of the profit shifted from CPs to ISP-1 while sustaining the revenue of ISP-2 and the social surplus as a result of ISP-1 introducing a content charge.

VI. CONCLUSION

This paper reported the results of analyzing the required conditions for ISPs to levy a content charge on CPs and the effect the content charge had on the revenue of each player. The analysis was done by modeling the competition among players using the two-stage Stackelberg game. The main findings were obtained through numerical evaluation and are summarized as follows.

1) ISPs can always introduce a content charge while sustaining the same number of contracted CPs by setting the charging ratio α to a value below the upper limit determined by the contribution to the CPs.
2) As the number of users of an ISP increases, the superiority of that ISP against other competing ISPs increases for CPs, so the effect of introducing a content charge on

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[2] At some points, e.g., $\gamma = 0.5$, nine CPs were in contract with only ISP-1 in TR, and just one CP was in contract with both ISPs; by contrast, two CPs were in contract with both ISPs in CC. Therefore, $\hat{\Phi}$ suddenly increased at these points.

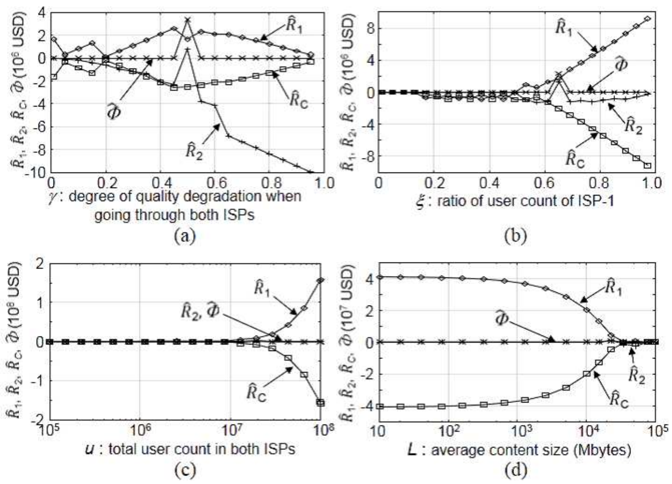

Fig. 6. Difference in revenue of each player before and after introducing content charge

the revenue improves through the growth of the setting value of α.

3) The influence of γ, the degree of quality degradation caused by going through both ISPs, or ξ, the user count ratio, on the social surplus is small, and affects only the profit distribution among players. As γ or ξ increases, the revenue of ISP introducing a content charge increases, and the revenue of ISP charging only a transit fee decreases. Moreover, R_C, the total revenue of all CPs, increases or decreases with the increase in γ or ξ, respectively.
4) In a wide range of average content size L, ISPs can dramatically increase their revenue by introducing a content charge. However, when L is extremely large, the revenue of all the players rapidly decreases because it is difficult for CPs to obtain a profit, and the number of CPs that have not entered into a transit agreement with both the ISPs rapidly increases. There are two possible factors accounting for the traffic growth: the increase in the number of content deliveries and the increase in the size of content. Although introducing a content charge is effective for dealing with the former factor, ISPs need to cover the cost of investing in networks by using methods other than levying a content charge in order to deal with the latter factor.
5) The result of introducing a content charge by ISPs is that part of the revenue of CPs moves to the ISPs that introduce the content charge.

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