A Study of ISP Pricing for Networks with Peer-to-peer Users

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The development of P2P technology has facilitated content delivery in the Internet, and may become the next disruptive technology. At the same time, however, P2P traffic is consuming a large amount of network resources and the management of P2P traffic has become a significant problem for ISPs. In the first part of this thesis, we study the idea of using usage-based uplink pricing as the solution. We develop a simple model describing a local market, to explore the effects of uplink pricing on users' P2P usage and ISPs' pricing policies. Our results indicate that under business competition, uplink pricing is expected to be adopted by all profit-seeking ISPs. Additionally, we also derive the optimal pricing strategy if ISPs are to cooperate. Base on the simple model, we further discuss how the accounting cost would affect the adoption of uplink pricing and how uplink pricing would affect the industry of P2P applications. Our study differs from previous studies on usage-based pricing by specifically focusing on the nature of the P2P technology and a network composed of multiple ISPs.

In the second part, we revisit the idea of Paris Metro Pricing, the simplest differentiated services solution. We develop a simple model to assess the viability of this pricing policy compared to one-channel flat-rate pricing. We focus on comparing two-channel identical pricing to one-channel flat-rate pricing in terms of profit and social welfare. Combined with the work in past literature, It is suggested that the form of quality-of-service functions is a key factor in determining the viability of Paris Metro Pricing.

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中文摘要

对等网络技术（或点对点技术）作为一项突破性技术，它的发展推动了互联网内容的传播和用户之间的信息交流。用户频繁使用对等网络应用软件，造成了互联网数据流量的激增，对等网络数据流吞食了大量的网络带宽资源，因此对对等网络数据流的管理成为互联网服务运营商面临的一个严峻的挑战。在这篇论文的前半部分，我们提出通过对上行流量计费的方式来解决这个问题。我们建立了简单的模型来描述一个本地网络，从而探讨这种上行流量计费策略对用户使用对等网络软件的影响，以及网络运营商会如何采取这种计费方式。分析结果指出，在商业竞争中，相比于固定费率定价方式，网络运营商会倾向于采取上行流量计费策略来提高自身的利润。我们还设计并分析了网络运营商的合作策略。基于这个简单的模型，我们进一步讨论了数据流测量引起的额外开销会如何影响这种上行流量计费策略的普及，以及这种计费方式对对等网络技术发展的影响。我们关于这个课题的研究不同于之前关于流量计费的讨论，上行流量计费策略是针对对等网络技术的特性而提出的，同时我们在分析过程中研究了多于两个网络运营商的场景。

这篇论文的另一部分主要讨论了“巴黎地铁”收费策略的可行性问题。“巴黎地铁”收费策略是一种最简单的区分服务收费策略。我们建立了简单的模型，来比较“巴黎地铁”收费策略和固定费率定价策略。我们着重分析比较了两级网络统一定价方式和一级网络固定费率定价方式在利润率和社会福利方面的区别。结合之前其他研究者的工作，我们发现服务质量函数是决定“巴黎地铁”收费策略可行性的关键因素。

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Chapter 1

Introduction

The first dialup Internet Service Provider (ISP) *The World* open up in 1989 brought the network into commerce and the following-up spread of privately run ISPs promoted the commercialization of Internet services. Commercial ISPs connecting non-educational users into Internet leads to a tremendous growth of host number in the Internet (Fig. 1.1). Since then, how to price the Internet services has been a hotly studied topic.

Nowadays, it is no secret that the Internet is *filled* with Peer-to-Peer (P2P) traffic. P2P-based content distribution effectively distributes the load from a single server and its uplink to all the receivers of the content and the rest of the network. The natural question to ask is whether Internet Service Providers (ISPs) will be able to estimate the P2P traffic growth and provision enough bandwidth for P2P users, and if not quite enough, how ISPs will be able to manage the limited resource? Many ISPs, from backbone ISPs to small campus network administrators are all grappling with these questions.

Leaving the practicality issues aside for a moment, it seems a perfectly reasonable approach is by properly applying pricing to reflect the utility of network resource usage. A major part of this thesis is a study on exploring such kind of pricing scheme. Internet users are used to flat-rate pricing. The reasons are mostly psychological - a consumer prefers not to repeatedly spend the

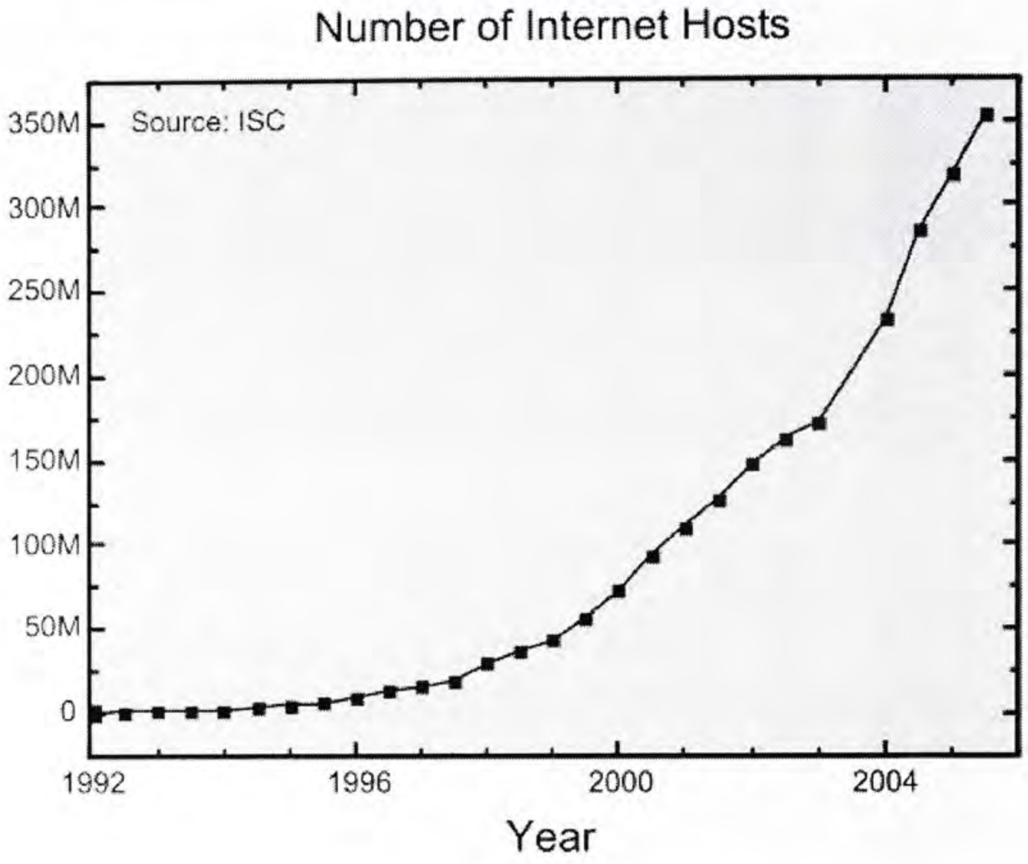

Figure 1.1: Number of Internet hosts

energy making small decisions for incremental network usage. Internet content providers, however, often have to negotiate private deals with their Internet service providers. The pricing is usually based on a combination of bandwidth usage (which costs the ICPs), as well as the value of the ICP content to the ISPs (which costs the ISPs). The use of the P2P technology shifts the bandwidth usage from the ICPs to the users, and at the same time makes all the users little ICPs (by offering content). Arguably, the negotiated ICP pricing must also be shifted to the P2P users. In this thesis, we propose a new pricing method, called *uplink pricing*, which charges users a volume-based fee for uplink traffic and a flat-rate fee for downlink traffic. With this pricing policy, P2P users who help content distribution will incur some costs to themselves. We develop a model describing the scenario where multiple ISPs provide Internet access services. We model the heterogeneity of users by assuming they have different levels of P2P requirement. Game-theoretic analysis is carried out to examine the adoption of uplink pricing in both competitive case and cooperative case. Results show that uplink pricing could be adopted by all ISPs at the equilibrium in a competitive market. Further more, we suggest that by cooperation ISPs could obtain a higher profit and some threat strategy can encourage such cooperation. Extended studies find that when the accounting cost in measuring users' P2P usage is considerable, flat-rate pricing would be adopted in the competitive case. We also present a nice demonstration that uplink pricing can be treated as a promising method on triggering the development of P2P technology.

A study about the viability of Paris Metro Pricing is presented in the other part of this thesis. Paris Metro Pricing is the simplest differentiated pricing scheme. With such pricing scheme, ISPs partition the total capacity into several virtual channels and impose differentiated pricing on them. The expectation is that higher-priced channels accommodate less users, hence provide better quality of service. Intensive studies have been conducted on examining the viability of Paris Metro Pricing [2, 5, 7, 20], particularly its profitability for a monopolist, its capability in bringing higher social welfare and the adoption of Paris Metro Pricing in a competitive market. Among those literature, [2] and [5] focus on comparing two-channel identical pricing with two-channel differentiated pricing. While [7] and [20] compare one-channel flat-rate pricing with two-channel differentiated pricing under some specific congestion functions and interestingly these two papers reach opposite results on profitability of Paris Metro Pricing. In Chapter 4, we revisit this topic and novelly compare the performance between one-channel flat-rate pricing and two-channel identical pricing. We find that there are gaps on revenue and social welfare between one-channel flat-rate pricing and two-channel identical pricing. We characterize these gaps under different kinds of quality-of-service functions. Combined with the result in [2], we present the conditions under which Paris Metro Pricing would win out. Finally, we also manage to explain the reason behind the opposite results demonstrated in [7] and [20].

This thesis has three distinct parts. In Chapter 2, We review the past literature on addressing the Internet pricing policies and the viability of those policies. We also present a qualitative comparison over those pricing policies. After that in Chapter 3, we propose the idea of uplink pricing, present our model in describing networks with P2P users and examine how ISPs would adopt uplink pricing in competitive and cooperative case respectively. We continue to examine the viability of Paris Metro Pricing in Chapter 4. We conclude in Chapter 5 with a brief summary.

□ **End of chapter.**

Chapter 2

A Review of Pricing in Internet Industry

The commercialization of Internet in late 1980s brought ordinary people (educational or non-educational) into the incredibly magical world of Internet. The development of Internet industry is accompanied by continuous studies on pricing policies. Some simple pricing policies, like flat-rate pricing and usage-based pricing are first proposed, since they have been successfully implemented in telephony services. Starting from late 1990s, an unprecedentedly rapid development of Internet applications presents a large variety of services to the users, including video-on-demand services, fast file transfers, voice conferencing, instant messaging, etc. These services lead to a dramatic traffic volume growth, as well as demand of differentiated services for various applications. In this respect, more complicated pricing methods are proposed to control the frequent congestion and to provide differentiated quality of service.

We are going to review most of Internet pricing policies in the following parts and pay special attention to those that have been intensively studied.

2.1 Static Pricing

2.1.1 Flat-rate Pricing

The idea of flat-rate pricing is quite intuitive: one user pays the ISP a rental fee for leasing a certain amount of bandwidth and connecting to the Internet, while his/her usage will incur no extra charge at all. Flat-rate pricing stands out as the most popular pricing policy, adopted by most of the worldwide ISPs, but it also causes constantly hot debate [15], [19].

The objection towards flat-rate pricing is based on the concern that it would encourage wastes, leading to frequent congestion and lower utilization of network resources. Besides, treating all packets equally makes flat-rate pricing incompatible with quality-differentiated services. The Internet Demand Experiment (INDEX) [1] provides an empirical evidence showing that the average number of bytes transmitted under flat-rate pricing is far more than under other pricing methods involving usage metering.

However, although supporters admit that flat-rate pricing has shortcomings theoretically, they still strongly believe this pricing policy would win out because of its simple pricing structure and consumers' strong preference towards simplicity. Consumers' willingness to pay a flat-rate price is also empirically studies in INDEX project. It is shown that the majority of the subjects selected a flat-rate, unlimited-access pricing plan, when they were offered options with different bandwidth-price plans. In particular, many subjects were paying a premium, which is defined as the amount of money one subject chose to pay for his usage minus the the amount of money he would have paid if he makes a expenditure-minimizing choice. The premium reflects the additional benefit users felt from using the bandwidth freely without being metered. This is a psychological reason why users prefer flat-rate pricing - a consumer prefers not to repeatedly spend the energy making small decisions for incremental network usage.

2.1.2 Usage-based Pricing

Simple usage-based pricing is designed as metering users' usage, connecting time or desired bandwidth and charging a certain amount of money per unit. Although several empirical studies have shown that usage-based pricing is not preferred by the users [1], the pressure of increasingly massive traffic and frequent network congestion is so overwhelming that some ISPs consider trying out usage-based pricing.

So as to inherit the simplicity of flat-rate pricing and to cater to users' willingness in buying out bandwidth, the most common form of usage-based pricing is designed as: users are allowed to deliver a certain volume of data for a buyout price, and are charged a volume-based extra fee for the data beyond that allowance. This form of pricing is well adopted in New Zealand and Chile.

The comparison between usage-based pricing and flat-rate pricing has been analyzed empirically and theoretically, [1], [15], [14], etc.. In [15], a practical variation of usage-based pricing is examined, a two-part tariff, which charges a flat-rate price as the fee to get initial access to the Internet plus extra usage-based charge. A Hotelling-type model is developed to examine which pricing method will be adopted in a duopoly competition. Users' demand is assumed to be negatively related to the usage-based price charged; if the usage-based price is p, users' demand would be $1 - p$. The two networks in competition are assumed to be incompatible, so that the total demand from one network D produces a positive network effect, nD, in which n is the network effect parameter and also congestion is interpreted as reduction in n. It is also assumed that an extra cost m would be induced for the ISPs when they charge an extra usage price, which can be viewed as the accounting cost for measuring users' usage. Based on this simple model, game-theoretic analysis shows that when the accounting cost is sufficiently small, two-part tariff is the unique equilibrium, but when the accounting cost is sufficiently large, flat-rate pricing would be the unique equilibrium. For the case with intermediate value of the accounting cost, the equilibrium state is related to the network effect: there would be no equilibrium if network effect is really high, which can be viewed as the situation when networks are perfectly incompatible or less congested; while both pricing policies can be adopted at equilibrium if network effect is sufficiently low, which means networks are more compatible or more congested.

Up till now, usage-based pricing has been proven to be less preferable psychologically [1] but theoretically viable under competition if the cost to implement it is sufficiently small [15]. Clearly, the debate over flat-rate pricing and usage-based pricing is still going to be an open question waiting for further investigation.

2.1.3 Paris Metro Pricing

Concerning the incompatibility of flat-rate pricing with quality-differentiated services, A. Odlyzko [18] proposed Paris Metro Pricing, the simplest differentiated services solution. Paris Metro Pricing is to partition the whole bandwidth into several logically separate channels, which differ only in the price paid to use them. There is no guaranteed service for any channel and pricing is the primary tool to manage traffic. It is expected that the channels with higher prices would attract less packets so that provide better quality of service, in terms of lower congestion cost. Generally, different applications have different requirements on transmission delay, so when a user steps into the network, he needs to make the decision of which channel to send his packets on, based on the delay requirement of his packets and his budgets as well as his observation of the congestion situation in different channels.

After A. Odlyzko proposed the idea of Paris Metro Pricing (PMP), some researchers have worked on building mathematical models to address the viability of PMP [2, 5, 7, 20]. We will revisit this topic in detail in Chapter 4.

2.2 Dynamic Pricing

Unlike static pricing, where ISPs set a price according to the market and keep that price constant for a certain period of time, dynamic pricing requires interaction between customers and accounting systems, and the price, either fixed-rate or volume-based, would fluctuate according to the network situation. In this section, we are going to review some of the typical dynamic pricing schemes and examine their viability.

2.2.1 Smart-market Pricing

Smart-market pricing [13] was proposed as early as 1993, so as to reflect the true cost of providing Internet access services, to utilize bandwidth resources more efficiently and to resolve the congestion problem.

In [13], in addition to those monetary costs, including bandwidth cost, management cost, network expansion cost, etc., congestion is also recognized as a social cost, which is induced to those delayed or discarded packets. When the network is not congested, actually the incremental cost to deliver a packet is almost zero, so the packets should not be charged additionally. However when the network is congested, to reflect the higher incremental (social) cost, an extra price should be charged for delivered packets. Smart-market pricing incorporates the Vickrey auction to implement such prices. A "bid" field is added in its header which indicates the highest willingness-to-pay for this packet. The network collects all the bids and calculates a cutoff value, which is the bid of the marginal user and which is lower than the bids of all the delivered packets. This cutoff value reflects the marginal congestion cost to deliver those packets and each delivered packet is charged this price. If we assume the incremental cost of delivering one packet when there is no congestion as zero, this per-packet price is just the congestion price.

As more congestion means less packets admitted, intuitively, the congestion price in smart-market pricing increases as congestion increases, which implies its special feature of reflecting congestion. Besides, with smart-market pricing, only the packets with the highest bids, or say, the packets which are the most valuable, would be admitted, which realizes differentiated services. Unlike traditional differentiated services, in which *networks* treat applications with different QoS requirements differently, smart-market pricing transfers the job of differentiation to the user-end – *customers* are to decide what level of QoS their packets require.

Although smart-market pricing exhibits many desirable features in reflecting congestion and providing differentiated services, some inconvenient limitations still hinder its practical implementation. The process of assigning bids, collecting bids and determing the cutoff value definitely increase the accounting overhead. Higher accounting cost might discourage ISPs to adopt smart-market pricing unless the revenue increment can recover the extra cost. Whether smart-market pricing could bring higher profit to ISPs can be an open question for further investigation. In addition, assigning bids could also bother the customers, because it is no easy job to determine one's highest willingness-to-pay for the packets. Lack of information might lead to false bid, which either causes higher expenditures for users or loss of important packets.

2.2.2 Responsive Pricing

The concept of responsive pricing ([12],[16]) incorporates the feedback scheme, which is a well-established method in improving network efficiency, and exploits users' adaptive nature. Like the traditional TCP congestion control scheme, where a feedback message is sent back to adjust the data input rates, in responsive pricing a component varying with the state of network congestion is transmitted back to the users in the form of a price per packet.

Similar to the smart-market pricing, responsive pricing charges zero when network is not congested. However, when the network is congested and it is observed that some packets are experiencing QoS degradation, the congestion will be measured and converted into a price per packet. The expectation is that users will adapt to per-packet price by reducing the number of packets sent and thereby release the congestion.

The key issue related to responsive pricing is how heterogeneous users would adapt to the feedback. Adaptive users are classified into two types, *elastic* users and *inelastic* users. Elastic users normally possess higher delay tolerance but require minimum loss of the whole file. On sensing the network congestion, elastic users will evaluate their willingness-to-pay under current per-packet price and their loss of utility if delaying the transmission to less congested stage, then decide how many packets to send in current stage. To the contrary, inelastic users cannot tolerate transmission delay but experience smaller QoS degradation with packet loss. One example is the users delivering video with a two-level codec, the first level of which includes the minimum essential information for the video but the second level of which helps enhance the quality of video. On receiving positive packet price, these users could adjust the amount of information related to the video delivered, namely provide different playback rates for the video [12].

One shortcoming with this kind of feedback scheme is that there is at least a one-period lag between the network state the users are informed of and the network state they are going to experience. The congestion level will be different from what users have presumed when they make decisions on the amount of packets to transmit. In this respect, smart-market pricing falls into a special case of responsive pricing with a "tight loop". In smart-market pricing, networks collect users' willingness-to-pay first and only deliver those packets whose "bid" is higher than the cutoff value. Therefore no feedback delay is incurred.

Simulation carried out by MacKie-Mason et al. [12] on comparing priced networks with unpriced networks shows that the average loss percentage is smaller and users' valuation of the delivered packets is larger with responsive pricing. This result implies that responsive pricing could increase the efficiency in utilizing network resources and also provide better QoS experience for users. However, implementing responsive pricing requires extra interaction at the user ends, as well as considerable process overhead. Some viability issues still need careful examination before wide adoption of this pricing scheme, including users' attitude on frequent interaction with ISPs during websurfing activities, and the extra accounting cost for measuring congestion and calculating prices.

2.2.3 Edge Pricing

Most literature about Internet pricing have focused on achieving optimal social welfare, which requires charging marginal congestion cost for usage, like what we have reviewed above. [22]

redirects the research on Internet pricing away from optimality paradigm to a new paradigm: the edge pricing.

It is argued that optimality issues should not dominate the research agenda about Internet pricing. Charging based on marginal congestion cost probably cannot recover the total facility cost needed in building and operating the networks, especially with rapid development in networking technology. Therefore, marginal congestion cost is no longer relevant to the pricing issue. Even though marginal cost pricing is enough in recovering the facility cost, it is argued in [22] that the marginal congestion costs are however inaccessible. Normally congestion cost is defined as the QoS degradation of users incurred by network congestion, but how the congestion would influence users' utility is actually complicated. Unknown users' utility functions make this problem even more difficult. Congestion might lead to packets delay or even packet loss, which affect different applications in different degrees. For example, occasional packet loss might cause tremendous trouble for email senders or receivers, but could have negligible effect on online video-on-demand experience. Besides, the evaluation of congestion along the entire transmission path requires computation at each hop, like smart-market pricing, which entails considerable complexity. Therefore, if not impossible, it is practically difficult to measure the congestion cost. Based on the above criticism, [22] advocates to shift attention from optimal pricing issue to some architectural issues, including the possibility to price locally, how to price multicast and the ability to charge receivers.

A new paradigm called edge pricing supports a wide variety of locally implemented pricing schemes other than uniform pricing policy to achieve the optimal welfare. To approximate the congestion cost, the current congestion condition is replaced by the expected congestion condition, which is essentially QoS-sensitive time-of-day pricing. This pricing does not reflect instantaneous congestion fluctuations, but encourages users to shift their usage to less-congested (low-priced) hours. To approximate the congestion cost, the cost of the actual path is also replace by the cost of the *expected* path, which only depends on the source and destination. The price related to the expected congestion on the expected path therefore can be determined *locally* at access points (or edges). S. Shenker et al. have not proposed any scheme on the detailed nature of charging, like flat-rate pricing or usage-based pricing, but they believe that since pricing is determined completely locally, ISPs would figure out the most appropriate policies through the interaction with subscribers and the market competition. Fig. 2.1 illustrates one example of this edge pricing. The packet originating from network A is charged according to network A's local charging policy. If this packet ends inside network A, it is only charged once. However, if this packet leaves network A for network B, when it enters network B, it will be charged against network A's bill according to network B's local pricing policy. This example also implies that the implementation of edge pricing requires bilateral agreements among ISPs and falls into local pricing afterwards.

S. Shenker et al. also discuss the non-local issues, like the challenges of pricing multicast applications and charging the receivers. All these issues are open for further researches.

2.3 Comparisons

In previous sections, we have reviewed several typical Internet pricing policies, from flat-rate pricing to Paris Metro Pricing, from smart-market pricing to edge pricing. We will identify each of them with its unique features and carry out a qualitative comparison in the following part.

Flat-rate pricing stands out as the simplest, the most popular pricing policy of all, and probably the most preferable one from

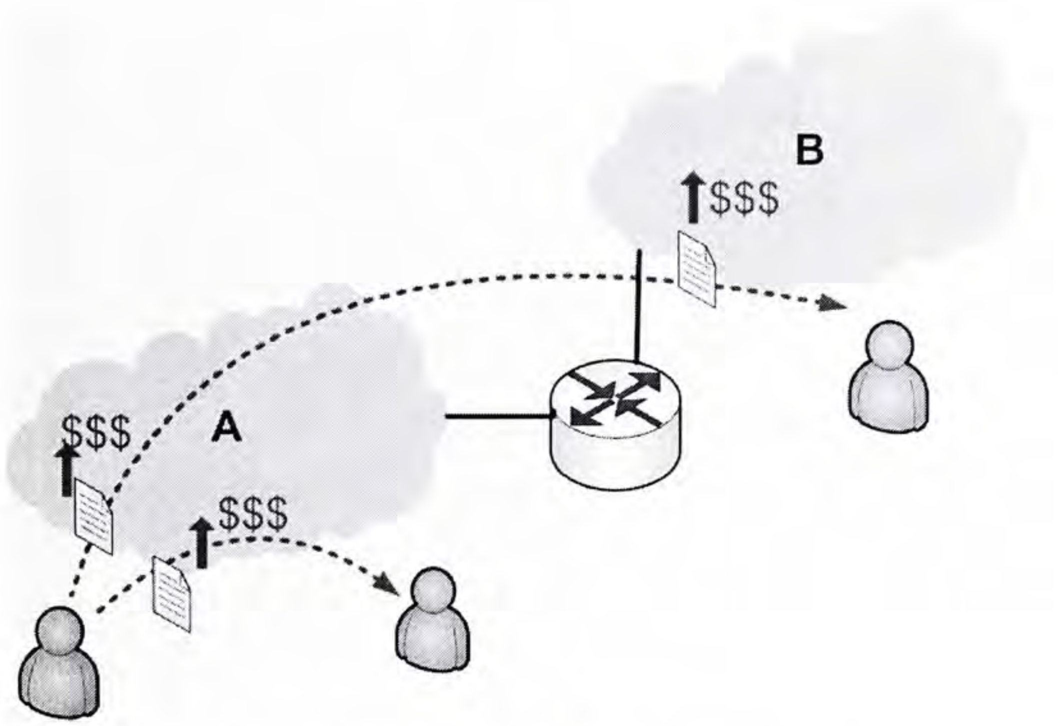

Figure 2.1: An example of edge pricing

customers' viewpoint. It has been critiqued for its inefficiency in utilizing network resources, and its lack of differentiated services. Usage-based pricing arises to improve the efficiency in utilizing network resources. Flat-rate pricing versus usage-based pricing has been the hottest debate in Internet pricing area. Paris Metro Pricing falls into a multi-class flat-rate pricing, which realizes differentiated services with the least complexity. The static price setting in the above three pricing policies is incapable of tuning the price to reflect the congestion fluctuations inside the networks. Smart-market pricing and responsive pricing both tune the per-packet price according to the network conditions, therefore provide dynamic pricing to release the congestion. Edge pricing is a pricing policy which deviates from the traditional research track and novelly addresses the architectural issues related to network pricing.

On the one hand, dynamic pricing incorporates the interaction with customers and the price is adaptive to the network condition, therefore it is respectively more complicated than static pricing. On the other hand, at the cost of complexity, dynamic pricing helps allocate network capacity more efficiently and provides differentiated services, which are the central issues in designing network pricing policies. However, due to psychological reasons, simpler pricing is always more favorable to the customers, which makes the practical implementation of dynamic pricing uneasy. In summary, Table 2.3 demonstrates a qualitative comparison over all the pricing policies we have reviewed.

	Price flexibility	Service differentiation	Usage constrain	Customer interaction	Complexity
Flat-rate pricing	Low	No	No	No	Low
Usage-based pricing	Low	No	Yes	No	Low
PMP	Low	Yes	No	Yes	Medium
Smart-market pricing	High	Yes	Yes	Yes	High
Responsive pricing	High	Yes	Yes	Yes	High
Edge pricing	Medium	Yes	Yes	No	High

Table 2.1: Comparisons among different pricing policies

2.4 Concluding Remarks

When people talks about Internet pricing, the most heated topic they could discuss is the debate over flat-rate pricing versus usage-based pricing. Apart from that, past literature also proposed some other more complicated pricing policies. In the above parts, we review the most widely-researched pricing policies, which can be classified into two types, static pricing and dynamic pricing. Dynamic pricing enables more efficient utilization of the capacity resources by charging according to the congestion level and providing differentiated services, at the cost of considerable complexity. Customers' preference towards simplicity and transparency forces simpler pricing ways, like flat-rate pricing and usage-based pricing, to stand out as the most popular ones. Comparisons in Section 2.3 show that no pricing policy is perfect, therefore, further study on how to implement a trade-off scheme that could capture the strengths of those pricing policies is essential in study on Internet pricing.

□ **End of chapter.**

Chapter 3

Uplink Pricing

3.1 Introduction

An important recent trend in Internet's development and evolution is the increasing use of Peer-to-Peer (P2P) technology for content distribution. This development has the effect of *flattening* the Internet, and leading to a new data transfer architecture for the Internet in the next ten years [25]. Whether these new network technologies and mechanisms will be adopted and used will be resolved by the "tussle among the stakeholders" in the Internet [3]. In this sense, this chapter is a study of the "tussle" rather than the technology itself.

At some level of abstraction, the important stakeholders of the Internet are: the ISPs, the users, and the content providers (ICPs). Furthermore, the ISPs can be categorized according to their distinct roles: (a) *access ISPs* (also referred to as "eyeball" ISPs) connect users to the Internet; (b) *content ISPs* allow content to be accessed from the Internet; and (c) *transit ISPs* provide the conduit connecting users to content. These ISPs connect with each other via *bilateral* peering agreements to form the Internet. Figure 3.1 illustrates the situation.

Roughly speaking, both access ISPs and content ISPs pay transit ISPs according to volume of traffic. The content ISPs also tend to charge ICPs according to traffic volume to cover

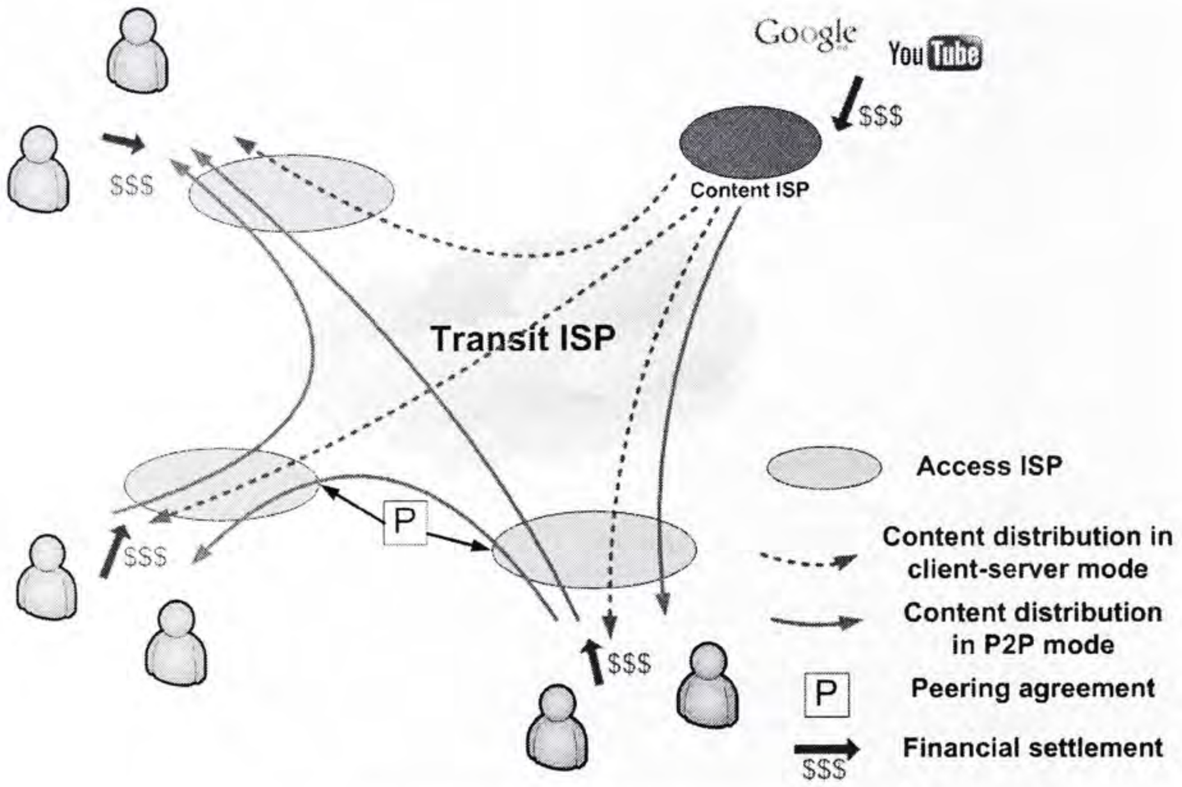

Figure 3.1: Structure of Internet industry

transit costs[1]. Due to a variety of reasons, however, access ISPs usually charge users (eyeballs) only a flat fee, independent of traffic sent or received. The P2P technology, however, has blurred the difference between ICPs and users, in terms of the traffic they generate. In the *flattened* Internet, the peers are both users as well as content servers. The volume of traffic from the ICPs is shifted and distributed to the peers. This in turn results in dramatic shifts in traffic patterns in the entire Internet. It is therefore no longer consistent to apply the same flat-rate pricing to both P2P users and non-P2P users.

In the world of bilateral peerings and flat-rate pricing by ac-

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[1] The relationship between ICPs and ISPs is generally more complicated since content can also help ISPs increase their business. Therefore ICPs may be able to negotiate with ISP according to other factors than just traffic volumes.

cess ISPs, many access ISPs are concerned about whether they are fairly compensated for the traffic they are carrying. On the one hand, they don't welcome the increased traffic volume due to P2P(except the content ISPs); but on the other hand, they know the P2P technology is helping content delivery and availability, and hence will likely bring new customers. This tussle between ISPs and P2P content distribution has been studied in some recent papers [4], [26].

As a solution, some ISPs have tried to cap the P2P traffic. Longer term, ISPs are working to localize P2P traffic [29]. We postulate that the best solution is to introduce more consistent pricing and let the market forces deal with it. We propose a new pricing scheme called *uplink pricing*, where one user is charged a fixed-rate price for the downlink bandwidth, but is charged a different fee based on its uplink traffic volume. With this pricing policy, P2P users who help content distribution will incur some costs to themselves. Most importantly, uplink pricing is designed to price consistently for services as they are delivered.

Fig. 3.2 shows a simplistic representation of the ISP market, in which one content ISP and M access ISPs are connected to the transit ISP and there is no bilateral peering agreement between any two access ISPs. Among all possible varieties of workload models, we address one specific case to compare different pricing models. The workload is simply that, besides some background traffic, there is respectively one end-user in each ISP requesting the same unit of data, which is initially stored at the server. The traffic flow with and without P2P distribution can be different:

- Client-server mode (Fig.3.2(a)): The server respectively uploads this unit of data to *each* end-user, therefore uploads M units in total.
- P2P mode (Fig.3.2(b)): The server uploads this unit of data to *some* of those requesting end-users and the data is

also distributed among end-users.

Access ISPs have three options to charge the end-users, flat-rate pricing, usage-based pricing and uplink pricing. In the following part, we study the charge of access ISPs, as well as the cost induced for all ISPs under different pricing models in both client-server mode and P2P mode.

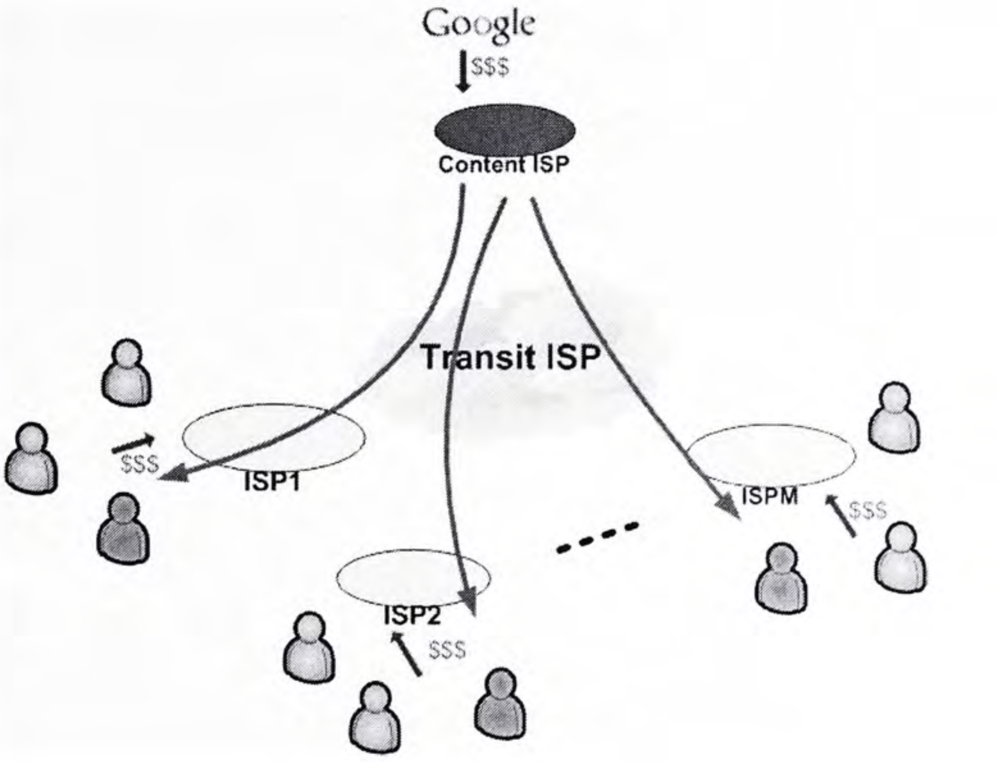
A. Client-server Mode

Without P2P's help in distributing the content, the server would inject the content M times into the content ISP who forwards the data to each end-user through the transit ISP. The content ISP charges the server for uploading M units of data and pays the transit ISP for those data as well. If we assume that content ISP charges p_{cu} per data unit and transit ISP charges p_t per data unit, the cost induced by this specific workload for the content ISP would be $M * p_t$, while the charge from server is $M * p_{cu}$. At the end of access ISPs, each one is charged $1 * p_t$ by transit ISP for downloading one unit of data, but the access ISP's revenue relies on it pricing strategy.

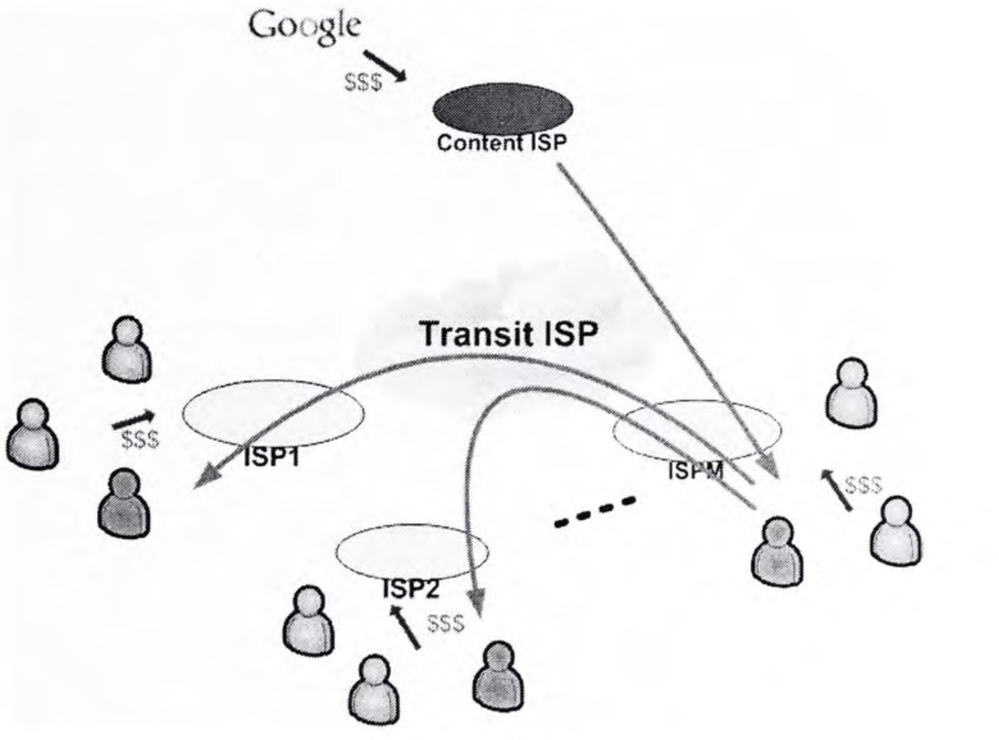
- Flat-rate pricing: The access ISP charges its subscribers the same price p_f for leasing the bandwidth for a certain time interval, so the revenue is $n * p_f$ if the number of users in each ISP is n.

- Usage-based pricing: Suppose the access ISP charges a fee based on *downloading volume*, the end-user who requests the data pays $1 * p_u$ and the others pay nothing, so the ISP's revenue is $1 * p_u$, in which p_u is the price for per unit of downloading volume.

- Uplink pricing: If we denote the flat-rate price for downlink as p and the volume-based price for uplink as q, all the users are only charged p for downloading and the revenue is $n * p$.



(a) Client-server



(b) Peer-to-Peer

Figure 3.2: Workload models in client-server mode and P2P mode

The second column of Table 3.1 sums up the above analysis.

B. Peer-to-Peer Mode

With the help of P2P technology, the data requested directly from the server will be less than in the client-server mode and extra flows of traffic will be generated between end-users. We are going to address one extreme case of workload with P2P data distribution. One end-user, say the user inside ISP_M without loss of generality, first downloads this unit of data from the server and then uploads it to all the other $M-1$ users who request this data. In this extreme case, the cost of content ISP decreases to $1*p_t$ and its revenue decreases to $1*p_{cu}$ accordingly. In those access ISPs other than ISP_M (denoted by ISP_{-M}), the traffic flow remains the same as under the client-server mode, so do the revenue and costs. In ISP_M, $M-1$ units of outgoing data and one unit of incoming data would incur a transit fee of $(M-1)*p_t$. If flat-rate pricing is adopted, each user inside ISP_M is nevertheless charged p_f for accessing the Internet, because this pricing strategy is insensitive to the traffic volume, so ISP_M's revenue remains as $n*p_f$. If usage-based pricing is adopted, as the user's downloading volume remains unchanged, he is charged p_u and ISP_M's revenue is still p_u. However, if ISP_M adopts uplink pricing, the user who distributes data will be charged an additional fee of $(M-1)*q$ for its uploading traffic and ISP_M's revenue goes to $n*p+(M-1)*q$. The third column of Table 3.1 demonstrates the analysis for the P2P traffic mode.

			Client-server Mode	Peer-to-Peer Mode
content ISP	Cost		$M * p_t$	$1 * p_t$
	Revenue		$M * p_{cu}$	$1 * p_{cu}$
ISP_{-M}	Cost		$1 * p_t$	$1 * p_t$
	Revenue	Flat-rate	$n * p_f$	$n * p_f$
		Usage-based	$1 * p_u$	$1 * p_u$
		Uplink pricing	$n * p$	$n * p$
ISP_M	Cost		$1 * p_t$	$(M - 1) * p_t$
	Revenue	Flat-rate	$n * p_f$	$n * p_f$
		Usage-based	$1 * p_u$	$1 * p_u$
		Uplink pricing	$n * p$	$n * p$ +(M-1)*q

Table 3.1: Cost and revenue of each ISP with different workload models

We make the following observations from the above table:

- P2P traffic distribution shifts part of the cost from the server end to the access ISPs, flattening the Internet. In either flat-rate pricing or usage-based pricing, this shift of cost is not reflected in the charging method.

- If we view the data originated from end-users in P2P mode as same as the data input by servers, uplink pricing is consistent with the pricing model in traditional client-server mode, where servers are charged based on usage regarding the traffic injected into the Internet and clients are charged a flat-rate price regardless of the traffic downloaded by them.

- Uplink pricing only imposes a flat-rate fee on the user who does not upload data. In other words, users will be charged a flat-rate price for their *end-user* behavior and a usage-based price for their *server* behavior. The dissatisfaction incurred by usage-based charge would be reduced to the lowest degree so that only the users acting like servers are bothered. This difference from usage-based pricing makes us believe if ISPs want to control the increasingly massive volume of P2P traffic by adopting pricing policy, uplink pricing would be better than usage-based pricing on the grounds that it only penalizes the users who actually cause the massive traffic.

The main contribution of the work in this chapter is to create a plausible model of user behavior (with different requirements on P2P usage) and ISP costs, so that the adoption of usage-based uplink pricing can be analyzed, both in the context of a competitive market as well as a cooperative setting for ISPs. Initially, in Section 3.2, we start with the description of our model, in which users' different preference towards P2P applications is reflected by their different P2P demands. The market equilibria are derived in Section 3.3 and Section 3.4, for competitive and cooperative cases respectively. Then in Section 3.5, we make further discussion on accounting cost and P2P locality. Related works and conclusions are give in Section 3.6 and 3.7.

The following is a summary of the main conclusions:

- If ISPs do not cooperate but compete through pricing, eventually they will all adopt uplink pricing and they will set a price that can merely cover the ISP's operation cost, and each ISP's profit is zero at equilibrium.
- ISPs can always achieve higher profit by cooperating on uplink pricing, and the threat strategy can encourage such cooperation.
- When users' marginal utility from P2P usage cannot cover the cost induced by outbound P2P traffic, in either compet-

itive case or cooperative case, ISPs set a sufficiently high price for uplink traffic to block the P2P usage.

- If the accounting cost is taken into consideration, the eventual equilibrium is either for all ISPs adopting flat-rate pricing, or all uplink pricing, depending on the P2P traffic demand in the network and the accounting cost.
- The global adoption of uplink pricing will trigger the improvement on P2P locality.

Usage-based network pricing has been proposed and studied before [9, 11, 15]. The basic treatment models how user's utility is affected by congestion, and how usage-based pricing can increase social welfare. The reason that usage-based pricing is seldom adopted has also been explained by Clark (1997) and others: (a) users' resistance to unpredictable charges; (b) flat rate tends to help business growth; (c) accounting costs. Furthermore, [9] derives a very helpful general observation from their analytical model about when flat-rate (or usage-based) pricing is preferred: depending on whether the network resources are abundant (or congested). In comparison to these previous works, our model includes multiple ISPs. We are able to avoid modeling congestion by assuming the usage-based charge by transit ISPs reflects the effect of increased traffic. In this sense, we feel our model is better able to represent the complicated tussle between the Internet stakeholders.

3.2 Model Description

We consider the simplest representation of a competitive ISP market, consisting of M homogeneous ISPs competing for a population of N subscribers. The homogeneity of ISPs presents as identical operation cost function, to be detailed later in this section. Initially, all ISPs adopt *flat-rate* pricing, with the same price p_o. Therefore, each ISP has a subscriber population of $\frac{N}{M}$, and shares a portion $\frac{1}{M}$ of the total profit generated in this market.

The idea of *uplink pricing* is to divide the user subscription price into two parts: (a) a flat-rate charge p for regular usage, like web-surfing, sending and receiving emails, or online-chatting, etc.; and (b) a usage-based component q designed to charge the user for P2P usage, with which the user is behaving as a server (or ICP). Under uplink pricing, the subscription price $\tilde{p}$, can be expressed as

$$\tilde{p} = p + vq. \tag{3.1}$$

The parameter v represents the uplink traffic volume generated by a user, and q is the charge per volume of traffic.

We are interested in modeling the user behavior due to uplink pricing, and in turn how the multi-ISP market scenario affects the eventual adoption of uplink pricing by ISPs. We make a number of assumptions on stakeholders involved in the model, traffic, ISP costs and user behavior (utility function and P2P usage).

A. Stakeholders

The Internet is complicated by potentially conflicting goals of many different stakeholders. In our model, we assume that the relationship between content providers and ISPs is given. What will be considered in our model is only the ISP-ISP and ISP-user part. For simplicity, we assume that the only way of inter-ISP communication is through transit ISPs, and there is no bilateral agreement between any two access ISPs.

B. Traffic

In the client-server mode, a downloading user in the access network generates a larger volume of downlink traffic but practically no uplink traffic. The situation is the reverse for the servers (or ICPs). As a result, traffic at the peering link of the transit ISP is different depending on whether its downstream is predominantly access ISPs or content ISPs. In the former case, the peering traffic is mostly outbound for the transit provider (inbound for the access ISP); whereas in the latter case, the traffic is mostly inbound for the transit provider. When the downstream has both access and content ISPs, the peering link can have more balanced traffic. This is illustrated in Fig. 3.3.

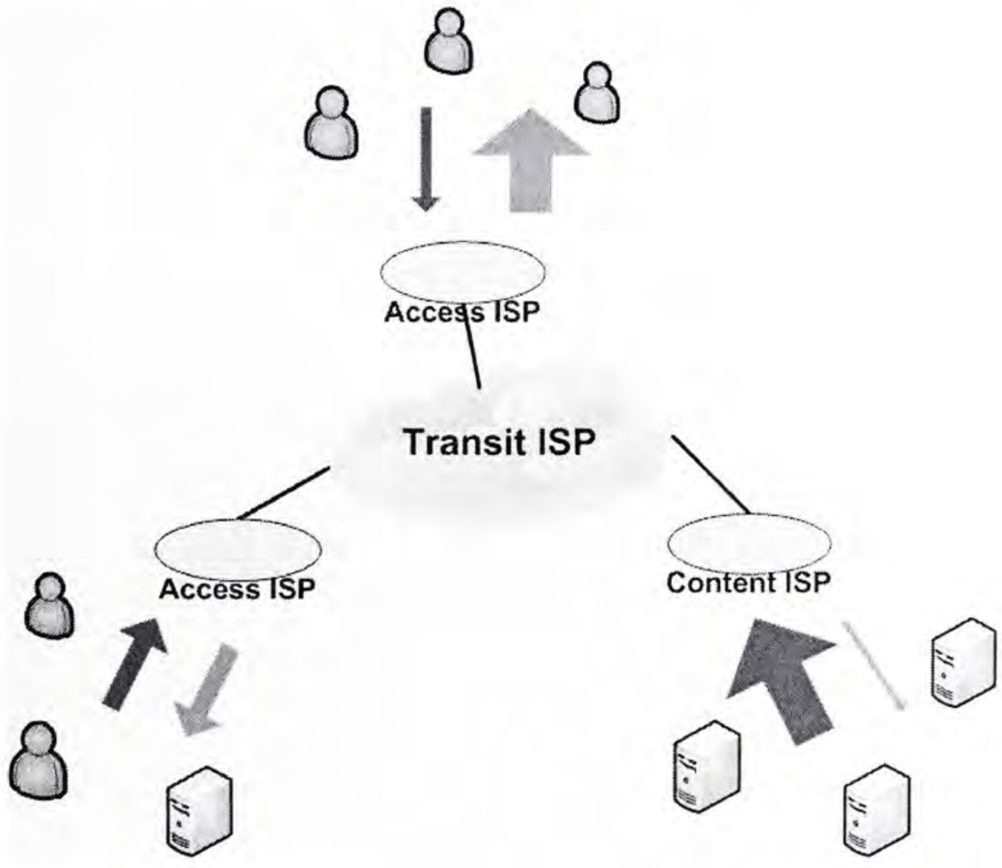


Figure 3.3: Traffic at the peering link of the transit ISP

With the advent of P2P technology, P2P users in access networks may also upload a large volume of traffic, which changes the traffic characteristics at the peering links between access ISPs and transit ISPs. To simplify our model, we assume that even with P2P traffic, the downlink traffic between one access ISP and its transit ISP is always larger than the uplink traffic. This assumption does not stray too far from the reality. For example, in the client-server mode, an access ISP with no ICP subscriber uploads v_u to its transit ISP and downloads v_d. v_u is smaller than v_d as we explained in the previous paragraph. With P2P traffic, we can expect that the extra downlink traffic due to P2P $v_{d(P2P)}$ is comparable to the extra uplink traffic $v_{u(P2P)}$, that is

$$v_{d(P2P)} \approx v_{u(P2P)}.$$

As a whole,

$$v_d + v_{d(P2P)} > v_u + v_{u(P2P)},$$

and this is what we have assumed, that an access ISP always downloads more than uploading.

Up till now, traffic locality of P2P applications is still an open question [24], [27]. In [27], J.H. Wang et al. managed to suggest a function describing the inter-ISP traffic when there is no peering link between two access ISPs,

$$t_i^r = \frac{(1 - r(\alpha_i))G(c_i^r - t_i^r)}{(1 - r(\alpha_i))G(c_i^r - t_i^r) + r(\alpha_i)} n\rho\alpha_i \tag{3.2}$$

In (3.2), t_i^r denotes the private traffic traversing the transit ISP. $r(\alpha)$ is defined as a caching function, a non-decreasing function of α, the market share (or population size) of the ISP. $G(\cdot)$ is defined as the performance sensitivity function, which describes the sensitivity of the routing to the link performance, and $G(\cdot) = 1$ means routing is not affected by link performance. c_i^r represents the capacity of this private link (the link to the transit ISP), and $n\rho\alpha_i$ can be simply viewed as the total traffic generated inside the ISP_i.

We borrow function (3.2) for our model. In our model, the link between access ISP and transit ISP is never saturated, which means the link performance is always good enough for transmitting outbound traffic. Therefore, in our model, $G(c_i^r - t_i^r)$ in (3.2) is equal to 1, and then original function becomes

$$t_i^r = (1 - r(\alpha_i))n\rho\alpha_i. \tag{3.3}$$

Given the total volume of traffic generated inside the network, the fraction of outbound traffic is simply $1 - r(\alpha_i)$, which is solely related to ISP_i's market share. For web traffic, $r(\alpha)$ is the probability that a subscriber's request can be satisfied by its ISP's local network when the subscriber's ISP is with a market share of α, and this caching function depends on the location of servers. For P2P traffic, $r(\alpha)$ is related to neighbor selection algorithms of P2P applications or caching strategies implemented by ISPs. Therefore, this caching function can be different for regular traffic and P2P traffic. We distinguish them by denoting the caching function as $r_r(\cdot)$ for regular traffic and $r_p(\cdot)$ for P2P traffic. Besides, the difference of market share between ISPs in a local market is negligible compared to the huge size of global market. On this ground, we assume that the caching function is identical for all ISPs, but we do distinguish the caching functions between regular traffic and P2P traffic, r_r and r_p respectively.

C. ISP Costs

Each ISP has sufficient funds for capital investments to support all users in the market if necessary, so we do not explicitly consider capital costs, but only an ISP's operating cost. We assume there are four components to the operating cost:

$$C(n, X) = C_f + C_m n + C_t r_r \bar{d} n + C_t r_p X. \tag{3.4}$$

The first component C_f is a fixed cost, which includes the cost for device maintenance, the personnel salaries, and other costs that are independent from user base or user behavior. This fixed cost captures a simple form of *economies of scale*, namely, the more subscribers (or remote traffic), the less the per user (or per traffic volume) cost. The second component depends on the number of users, where n is the subscriber population size and C_m is the management cost per additional subscriber; the third and the fourth components are the peering cost induced by the external traffic. On charging an access ISP for the transit service, the upper level ISPs compare the downlink traffic volume with uplink traffic and charge the larger direction of traffic based on usage[2]. Given the traffic assumption that downlink traffic is no smaller than uplink traffic, it means the peering cost depends on the inbound traffic of an access ISP. The third component is the peering cost induced by the inbound *regular* traffic. $\bar{d}$ denotes the average regular traffic. The P2P users would generate an extra P2P downloading traffic X, which contributes to the fourth component. In this cost function and the following part, so as to match the notations for the other parts of cost, we use C_t instead of p_t to denote the price a transit ISP charges for one unit of external traffic.

D. User Behavior

We introduce a utility function to describe users' benefit from accessing the Internet. The user's utility is defined as the combination of utility from regular usage and P2P usage. To focus on P2P usage, we represent the utility from regular usage by an average value $\bar{U}_r$, which is the same for all the users, and we

---

[2] In real operation, transit ISPs take 5-minute samples of the traffic volume and charge based on the 95^{th} percentile value, the higher of uplink and downlink. To simplify the cost function, we simply assume the payment is proportional to the traffic volume, the higher of uplink and downlink.

also denote users' downloading volume of regular traffic by an average value $\bar{d}$. This can be extended to other utility value or other downlink regular traffic. For the utility of P2P usage, we represent it as the following,

$$U_p(x) = u(x), x \leq \tilde{x}$$

in which, x represents the volume of downloading P2P traffic, and $\tilde{x}$ denotes the maximum P2P traffic volume one user can download in a time unit when P2P usage incurs no extra charge. We denote by $\tilde{x}$ users' *P2P requirement*. To represent users' variation on using P2P, $\tilde{x}$ is modeled as a random variable following an exponential distribution with parameter λ. We make a further assumption that $u(x)$ is a nondecreasing, concave, continuously differentiable function, and $u(0) = 0$. As we have assumed, a user's downloading volume of P2P traffic is identical to the uploading volume of P2P traffic, so x can represent either user's uploading or downloading P2P volume. When user i is charged in the uplink pricing way, his payoff function is

$$S(x_i; p, q) = \bar{U}_r + U_p(x_i) - (p + qx_i), \tag{3.5}$$

in which x_i is user i's P2P usage. Given the price p and q, user i makes the decision of whether to subscribe to a network and how much P2P traffic to download (x_i^*), based on the following constraints:

- *Optimality constraint*:

$$S(x_i^*; p, q) \geq S(x; p, q), \forall x \neq x_i^*.$$

- *Rationality constraint*:

$$S(x_i^*; p, q) \geq 0.$$

- *Feasibility constraint*:

$$x_i^* \leq \tilde{x}_i.$$

Given p and q, user i maximizes his payoff (3.5). The objective function (3.5) is obviously a concave function. Doing the first-order derivative of the objective function, we have

$$S'(x_i; p, q) = u'(x_i) - q.$$

Let the above formulation to be zero,

$$u'(x_i) = q, \tag{3.6}$$

and the solution is denoted by $\hat{x}$. As the function $u(x)$ is the same for all users, $\hat{x}$ is identical for users. Comparing $\hat{x}$ with users' heterogeneous P2P requirement, we determine users' payoff-maximizing volume of P2P usage.

- If $\hat{x} \leq 0$, which means $u'(0) - q \leq 0$, then $x_i^* = 0$. User i stops using P2P because P2P usage would incur reduction in payoff.

- If $0 \leq \hat{x} \leq \tilde{x}_i$, then $x_i^* = \hat{x}$. User i whose P2P requirement is larger than $\hat{x}$ lowers the downloading volume to $\hat{x}$.

- If $\hat{x} > \tilde{x}_i$, then $x_i^* = \tilde{x}_i$. User i whose P2P requirement is smaller than $\hat{x}$ sticks to his original usage level.

For the network, if $S(\hat{x}; p, q) < 0$, which means even the optimized payoff is negative, users would all leave the network. If $S(\hat{x}; p, q) \geq 0$, the payoff is then to be checked to see whether x_i^* satisfies the *rationality constraint*.

For the case when $\hat{x} \leq 0$, $x_i^* = 0$ and the payoff is $\bar{U}_r - p$. If $\bar{U}_r \geq p$, user i would subscribe to the network but use no P2P; otherwise, user i opts out. Therefore, if $\bar{U}_r \geq p$, all users subscribe to the network because they could get non-negative payoffs with or without P2P requirement. Otherwise, users with small enough P2P requirement would gain negative payoffs and opt out. In this case, there would be a threshold, users with P2P requirement smaller than which will leave the network. We denote this threshold by $\hat{x}_1$.

We denote by $\hat{x}_1$ the *rationality threshold* and by $\hat{x}_2$ the *optimality threshold*, in which $\hat{x}_2 = \hat{x}$, if $\hat{x} > 0$; and $\hat{x}_2 = 0$, if $\hat{x} \leq 0$. The following proposition concludes users' behavior when they are charged by uplink pricing with given price p and q.

Proposition 3.2.1 *Users are charged by uplink pricing. Price p and q are given, and $\hat{x}_1$ and $\hat{x}_2$ are determined.*

1. *When $\hat{x}_2 \geq 0$ and $S(\hat{x}_2; p, q) < 0$, all the users leave the network.*
2. *When $\hat{x}_2 \geq 0$ and $S(\hat{x}_2; p, q) \geq 0$, for one user i,*
   - *If $\tilde{x}_i < \hat{x}_1$, user i leaves the network.*
   - *If $\hat{x}_1 \leq \tilde{x}_i \leq \hat{x}_2$, user i stays in the network and uses P2P at the volume of $\tilde{x}_i$.*
   - *If $\tilde{x}_i > \hat{x}_2$, user i stays in the network and users P2P at the volume of $\hat{x}_2$.*

Above all, if $\hat{x}_2 \geq \hat{x}_1 > 0$, we relate prices p, q to thresholds $\hat{x}_1$ and $\hat{x}_2$,

$$p = u(\hat{x}_1) + \bar{U}_r - q\hat{x}_1, \tag{3.7}$$

$$q = u'(\hat{x}_2). \tag{3.8}$$

Then, the profit of ISP is

$$P = Ne^{-\lambda\hat{x}_1}(p - C_m - C_t r_r \bar{d}) + X(q - C_t r_p) - C_f. \tag{3.9}$$

To sum up, we list all the notations for our model in Table 3.2.

Symbol	Explanation
N	Total number of users in this market
M	Total number of ISPs in this market
n	Number of users in one ISP
C_f	Fixed operation cost
C_m	Marginal cost per additional subscriber
C_t	Marginal cost per external traffic volume
$\tilde{p}$	Subscription price under uplink pricing
p	Flat-rate price for downlink traffic in uplink pricing
q	Price for per uplink traffic volume in uplink pricing
p_f	The charge per user under flat-rate pricing
p_u	The charge per unit of traffic under usage-based pricing
p_{cu}	The price the content ISP charges the content servers for per unit of traffic
p_t	The price the transit ISP charges lower-level ISPs for per unit of traversing traffic. It is the same as C_t.
P	Profit of ISP
$\bar{d}$	Average downlink regular traffic volume
r_r	Fraction of inbound external *regular* traffic
r_p	Fraction of inbound external *P2P* traffic
$\bar{U}_r$	Average utility from regular web services
$U_p(x)$	Utility gained from x volume of P2P downlink traffic
x	Downlink P2P traffic volume
$\tilde{x}$	P2P requirement
x^*	The P2P traffic volume a user downloads to maximize his payoff
$\hat{x}_1$	Rationality threshold. Users with P2P requirement lower than $\hat{x}_1$ will leave the network.
$\hat{x}_2$	Optimality threshold.
X	Total volume of downlink P2P traffic
θ	The discount factor in the repeated game
v_u	The outbound traffic volume of one ISP
v_d	The inbound traffic volume of one ISP

Table 3.2: Notations 1

3.3 Uplink Pricing in a Competitive Market

From ISPs' perspective, whether to adopt a new pricing strategy depends on the possible outcome of this adoption, which depends on the action/strategy of other ISPs. When equilibrium strategies exist, they can help us understand the effects of uplink pricing.

In this section, we are going to study the adoption of uplink pricing in a competitive market. We look at a specific case where the utility function is $u(x) = w\log(1+x)$, which obviously conforms to our assumption about the properties of $u(x)$. With this specific utility function, prices are related to thresholds as

$$p = w\log(1+\hat{x}_1) + \bar{U}_r - q\hat{x}_1, \tag{3.10}$$

$$q = \frac{w}{1+\hat{x}_2}. \tag{3.11}$$

To be precise, in the following sections we are going to remove the fixed cost C_f by assuming it is negligible compared to other costs. In practice, the assumption of negligible fixed cost may not be that unreasonable. The fixed costs may be reducible (making it almost a variable cost); and it may also be shared by other business operations, if the ISP is engaged in more than only data networking services.

In the following part, we are going to explore the equilibrium of price setting after uplink pricing is introduced. $\bar{U}_r$ and w are two parameters identical for all users. $\bar{U}_r$ is one user's utility from regular usage and w can be viewed as the marginal utility from P2P usage. Respectively, $\bar{U}_r$ can be larger or smaller than $C_m + C_t r_r \bar{d}$, the cost induced by one user's regular web usage, and w can be larger or smaller than $C_t r_p$, the marginal cost induced by P2P traffic. Therefore, the following four cases are analyzed respectively.

Case 1: $\bar{U_r} \geq C_m + C_t r_r \bar{d}$, $w \geq C_t r_p$

Users' utility from Internet services (P2P and non-P2P traffic) exceeds the cost incurred by their usage for ISPs; namely, the effort ISPs have put into providing services is recognized by users and users are willing to pay for the services they receive. In this setting, we prove the existence of a symmetric pure-strategy equilibrium of the pricing game among multiple ISPs.

Lemma 3.3.1 *When $\bar{U_r} \geq C_m + C_t r_r \bar{d}$, $w \geq C_t r_p$, there exists a symmetric pure-strategy equilibrium that all ISPs adopt uplink pricing and the price setting is identically*

$$
\begin{aligned}
p^* &= C_m + C_t r_r \bar{d}, \qquad (3.12)\\
q^* &= C_t r_p. \qquad (3.13)
\end{aligned}
$$

The proof for Lemma 3.3.1 is similar to the one for Lemma 3.3.2 (Appendix A.1), but the latter one is more general, so we just omit the proof for Lemma 3.3.1 here.

At the equilibrium presented in Lemma 3.3.1, ISPs would get symmetric number of users and the distribution of users' P2P requirement $\tilde{x}$ can be viewed as the same in all ISPs. In this price setting, the two thresholds are $\hat{x}_1 = 0$ and $\hat{x}_2 = \frac{w}{C_t r_p} - 1$. Therefore, ISPs grab all potential subscribers and the P2P usage is upper bounded by $\frac{w}{C_t r_p} - 1$. The profit of each ISP is zero.

Case 2: $\bar{U_r} < C_m + C_t r_r \bar{d}$, $w \geq C_t r_p$

Unlike Case (1), in Case (2) users' utility from regular web usage is lower than the cost incurred by that usage. While utility from P2P usage still can compensate the cost for delivering P2P traffic. Lemma 3.3.2 demonstrates the equilibrium in this situation.

Lemma 3.3.2 *When $\bar{U}_r < C_m + C_t r_r \bar{d}$, $w \geq C_t r_p$, there exists a symmetric pure-strategy equilibrium that all ISPs adopt uplink pricing and the price setting is identically*

$$\begin{aligned} p^* &= C_m + C_t r_r \bar{d}, && (3.14) \\ q^* &= C_t r_p. && (3.15) \end{aligned}$$

Detailed proof is presented in Appendix A.1.

The equilibrium in Lemma 3.3.2 appears the same as the one in Lemma 3.3.1. However, at the former equilibrium, the rationality threshold $\hat{x}_1$ is positive, which means some users with lower P2P requirement do not subscribe to the network, because their loss of payoff in regular traffic cannot be made up by the gain in P2P traffic.

Case 3: $\bar{U}_r \geq C_m + C_t r_r \bar{d}$, $w < C_t r_p$

This is an opposite case to Case (2): utility from regular traffic exceeds the cost induced but marginal utility from P2P traffic is lower than the marginal cost for delivering that traffic.

Lemma 3.3.3 *When $\bar{U}_r \geq C_m + C_t r_r \bar{d}$, $w < C_t r_p$, all ISPs adopt uplink pricing at equilibrium and the stable price setting is*

$$\begin{aligned} p^* &= C_m + C_t r_r \bar{d}, && (3.16) \\ q^* &> w. && (3.17) \end{aligned}$$

Proof: If one ISP unilaterally decreases its charge for uplink as lower than w but keeps price for downlink unchanged, it is straightforward that this ISP will run a deficit because the charge from P2P usage cannot compensate the costs for delivering that traffic.

An interesting question is that whether one ISP, say ISP_k, who charges a price q_k lower than w but a price p_k higher than p^*, can get a positive profit. We assume that $p_k = C_m + C_t r_r \bar{d} + \delta_1$. Let the optimality threshold of ISP_k be $\hat{x}_2^k$, so $\hat{x}_2^k = \frac{w}{q_k} - 1 > 0$. The rationality threshold in ISP_k is denoted by $\hat{x}_1^k$. Any user whose P2P requirement is smaller than $\hat{x}_1^k$ will subscribe to ISPs other than ISP_k. For the other users with requirements higher than $\hat{x}_1^k$, they compare their payoffs in different ISPs and make the decision of which ISP to subscribe to. When subscribing to any ISP other than ISP_k, the payoff just comes from regular usage

$$S_{-k} = \bar{U_r} - C_m - C_t r_r \bar{d}. \tag{3.18}$$

While the payoff of subscribing to ISP_k is

$$S_k = \bar{U_r} + w \log(1 + x) - (C_m + C_t r_r \bar{d} + \delta_1) - q_k x. \tag{3.19}$$

Only when $S_{-k} \leq S_k$ will that user subscribe to ISP_k, which also means when $w \log(1 + x) - \delta_1 - q_k x \geq 0$, that user will subscribe to ISP_k. Therefore, the profit of ISP_k is

$$\begin{aligned} P_k &= \sum_{i \text{ in } ISP_k} (p_k + q_k x_i - (C_m + C_t r_r \bar{d} + C_t r_p x_i)) \\ &= \sum_{i \text{ in } ISP_k} (\delta_1 + q_k x_i - C_t r_p x_i) \\ &\leq \sum_{i \text{ in } ISP_k} (w \log(1 + x_i) - C_t r_p x_i) \\ &< 0 \end{aligned}$$

Therefore, ISP_k cannot get a positive profit if it encourages P2P usage in this case. ∎

At this equilibrium, $\hat{x}_1 = \hat{x}_2 = 0$. Intuitively, when users' marginal utility from P2P usage cannot reach the cost induced for delivering that P2P traffic, ISPs have the incentive to charge a sufficiently high price for uplink traffic, in order to block P2P traffic away.

Case 4: $\bar{U_r} < C_m + C_t r_r \bar{d}$, $w < C_t r_p$

In this situation, ISPs have only two options, (1) charge a higher price and lose all the users, (2) charge a lower price and run a deficit. When facing this kind of market where users' utility from network services is lower than the cost induced to provide those services, ISPs should improve their ability in satisfying users' requests by the local network so as to decrease r_r and r_p, consequently to decrease the operation cost. When the cost decreases to a level that any of the previous cases is satisfied, ISPs could run their business then.

Combing the above four cases, we reach the following proposition.

Proposition 3.3.4 *When $w \geq C_t r_p$, there exists a symmetric pure-strategy equilibrium that all ISPs adopt uplink pricing and set the price as*

$$\begin{aligned} p^* &= C_m + C_t r_r \bar{d}, && (3.20) \\ q^* &= C_t r_p. && (3.21) \end{aligned}$$

When $\bar{U_r} \geq C_m + C_t r_r \bar{d}$ and $w < C_t r_p$, there exists an equilibrium that all ISPs adopt uplink pricing and the price is set as

$$\begin{aligned} p^* &= C_m + C_t r_r \bar{d}, && (3.22) \\ q^* &> w. && (3.23) \end{aligned}$$

However, when $\bar{U_r} < C_m + C_t r_r \bar{d}$ and $w < C_t r_p$, ISPs should cut their operation cost to maintain the business.

3.4 The Cooperative Strategy with Uplink Pricing

In this section, we are going to explore the optimal cooperative strategy for all ISPs adopting uplink pricing. We simply define this cooperation as ISPs setting the same price to maximize the total profit generated in this local market and obtaining equal part of the profit, though we are aware of other forms of cooperation like setting different prices and directly paying each other money as a profit return.

3.4.1 The Cooperative Case

We continue using p and q to denote respectively the fixed rate price for downlink and the volume-based price for uplink. Similarly, the prices and the two thresholds are related as

$$\begin{aligned} p &= w\log(1+\hat{x}_1) + \bar{U}_r - q\hat{x}_1, \qquad (3.24)\\ q &= \frac{w}{1+\hat{x}_2}. \qquad (3.25) \end{aligned}$$

Recall that $\hat{x}_1$ is the turnover point of subscribing to the network or not and $\hat{x}_2$ is the upper-bound limiting per user's P2P downloading volume. According to the user behavior described in Proposition 3.2.1, we formulate the total profit generated in this local market when all ISPs adopt uplink pricing and set the price as p and q.

$$P = NP(\tilde{x} \geq \hat{x}_1)(p - C_m - C_t r_r \bar{d}) + X(q - C_t r_p),$$

in which

$$X = NP(\tilde{x} > \hat{x}_2)\hat{x}_2 + NP(\hat{x}_1 \leq \tilde{x} \leq \hat{x}_2)E(\tilde{x}|\hat{x}_1 \leq \tilde{x} \leq \hat{x}_2).$$

After some derivation, we have

$$\begin{aligned} P &= Ne^{-\lambda\hat{x}_1}(p - C_m - C_t r_r \bar{d})\\ &+ N(q - C_t r_p)((\hat{x}_1 + \frac{1}{\lambda})e^{-\lambda\hat{x}_1} - \frac{1}{\lambda}e^{-\lambda\hat{x}_2}). \end{aligned}$$

Applying (3.24) and (3.25), we have

$$\begin{aligned} P &= Ne^{-\lambda\hat{x}_1}(w\log(1+\hat{x}_1) - C_t r_p \hat{x}_1 + \bar{U}_r - C_m - C_t r_r \bar{d})\\ &+ N\frac{1}{\lambda}(\frac{w}{1+\hat{x}_2} - C_t r_p)(e^{-\lambda\hat{x}_1} - e^{-\lambda\hat{x}_2}), \qquad (3.26) \end{aligned}$$

ISPs can optimize their profit by choosing $\hat{x}_1$ and $\hat{x}_2$. We formulate the following optimization problem

$$\begin{aligned} max_{\hat{x}_1,\hat{x}_2} \quad & P \\ s.t. \quad & \hat{x}_1 \le \hat{x}_2 \\ & \hat{x}_1 \ge 0, \quad \hat{x}_2 \ge 0 \end{aligned} \tag{3.27}$$

Doing the first-order partial derivative of P over $\hat{x}_1$ and $\hat{x}_2$ respectively, we have

$$\begin{aligned} \frac{\partial P}{\partial \hat{x}_1} &= e^{-\lambda\hat{x}_1}(\lambda(C_t r_p \hat{x}_1 - w\log(1+\hat{x}_1) - \bar{U}_r - C_m - C_t r_r \bar{d}) \\ &+ \frac{w}{1+\hat{x}_1} - \frac{w}{1+\hat{x}_2}) \end{aligned} \tag{3.28}$$

$$\begin{aligned} \frac{\partial P}{\partial \hat{x}_2} &= -\frac{w}{(1+\hat{x}_2)^2}\frac{1}{\lambda}(e^{-\lambda\hat{x}_1} - e^{-\lambda\hat{x}_2}) \\ &+ (\frac{w}{1+\hat{x}_2} - C_t r_p)e^{-\lambda\hat{x}_2} \end{aligned} \tag{3.29}$$

Case 1: $w < C_t r_p$

When $w < C_t r_p$, which means users' marginal utility from P2P usage is smaller than the marginal cost induced by P2P traffic, according to (3.29), it follows that $\frac{\partial P}{\partial \hat{x}_2} < 0$. Therefore, the optimal value of $\hat{x}_2$ is set to be $\hat{x}_1$. We equate $\hat{x}_2$ to $\hat{x}_1$ in (3.26) and have

$$P = Ne^{-\lambda\hat{x}_1}(w\log(1+\hat{x}_1) - C_t r_p \hat{x}_1 + \bar{U}_r - C_m - C_t r_r \bar{d}) \tag{3.30}$$

It is obvious that when $w < C_t r_p$, $\frac{\partial P}{\partial \hat{x}_1} < 0$, so P reaches its maximum point when $\hat{x}_1 = \hat{x}_2 = 0$. As a result, the optimal price setting should be

$$\begin{cases} p^* = \bar{U}_r \\ q^* > w \end{cases}$$

The total profit in this local market is

$$P = N(\bar{U}_r - C_m - C_t r_r \bar{d}),$$

which is nonnegative if $\bar{U}_r \geq C_m + C_t r_r \bar{d}$, and negative otherwise. Two implications can be perceived from the cooperative strategy in this case.

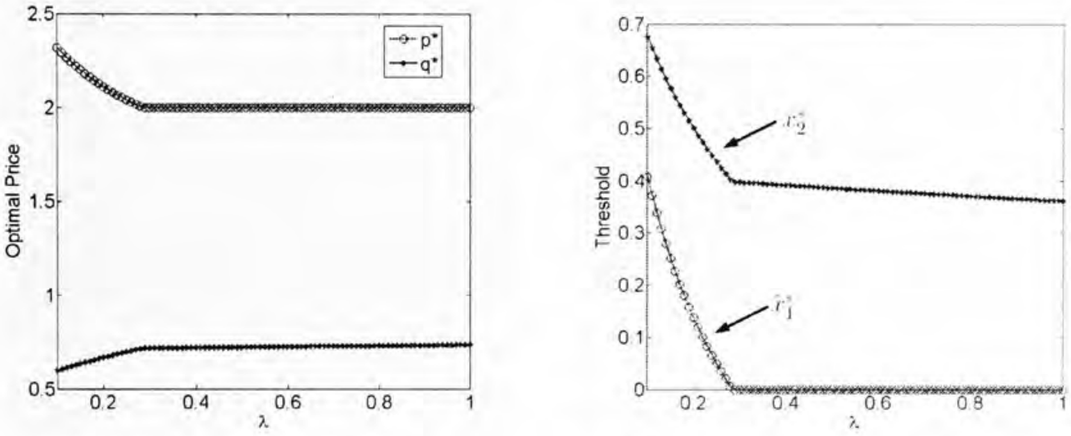
1. When $w < C_t r_p$ and $\bar{U}_r \geq C_m + C_t r_r \bar{d}$, compared to the same case in competitive situation, ISPs can get a higher profit by cooperation as expected. Besides, like Case (3) in competitive market, ISPs choose to charge a sufficiently high price for uplink traffic to block P2P.
2. When $w < C_t r_p$ and $\bar{U}_r < C_m + C_t r_r \bar{d}$, cooperation between ISPs still cannot save ISPs' business. ISPs have to pursue improvement in technology to reduce the operation cost.

Case 2: $w \geq C_t r_p$

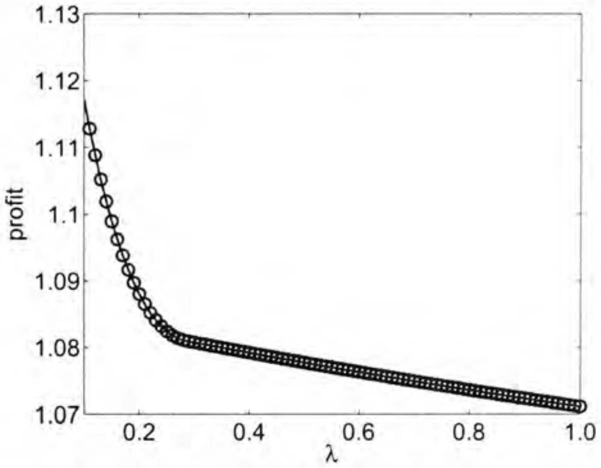
When user's marginal utility from P2P is no smaller than the marginal costs P2P traffic could incur, the optimization problem becomes much more complicated and seems intractable, so we are going to find some insights through numerical results. In finding the numerical results, the default value we use are: $N = 1$, $\bar{U}_r = 2$, $C_m + C_t r_r \bar{d} = 1$, $w = 1$, $C_t r_p = 0.5$. We vary λ, the parameter for distribution of P2P requirement, from 0.1 to 1. The following figures (Fig. 3.4) illustrate the optimal price setting to maximize total profit as λ increases, the according threshold pair $(\hat{x}_1^*, \hat{x}_2^*)$ and ISPs' profit as well.

We make the following observations from the figures:

- As we increases λ, the turnover point $\hat{x}_1^*$ and the price for downlink traffic p^* decrease. We have assumed the distribution of users' P2P requirement follows an exponential distribution, so larger λ means more users assemble at lower P2P requirement region and the average P2P requirement is smaller. Therefore, when λ increases, p^* is decreased to grab those users with smaller P2P requirement, otherwise



(a) The optimal price as λ changes (b) The optimal thresholds as λ changes



(c) The profit each ISP could obtain as λ changes

Figure 3.4: Optimal cooperative strategy and profit

ISPs would lose too many users to obtain an optimal profit. Especially when λ increases to a certain level, $\hat{x}_1$ goes down to zero to admit all the users into the network. After that, p^* would not change and it is equal to $\bar{U}_r$.

- As we increase λ, the price for uplink traffic q^* increases to reach the optimality. As λ increases, more people assemble at the lower P2P requirement region, so if q^* is increased moderately, only a smaller part of subscribers would reduce their P2P usage, therefore the total volume of P2P usage would not decrease too much. Meanwhile, as ISPs increase the price q^*, the per-volume profit would be increased. Therefore, the total profit (per-volume profit times total volume) after increasing q^* would be higher than not increasing it.

Particularly, compared to the part where $\hat{x}_1$ is zero, q^* increases more rapidly before $\hat{x}_1^*$ hits zero. This is because in the first half part, as λ increases, $\hat{x}_1^*$ goes down to attract the users with smaller P2P requirement (Fig. 3.4(c)), which makes the average P2P requirement decrease even more sharply. Therefore, q^* is increased more rapidly to increase the per-volume profit so as to get an optimal profit. While after $\hat{x}_1$ hits zero, the user number is fixed, so the change of average P2P requirement is only related to λ and it is less rapid compared to the first half part, therefore, q^* increases less rapidly.

As $q^* = \frac{w}{1+\hat{x}_2^*}$, $\hat{x}_2^*$ decreases as λ increases, and it decreases more rapidly in the first half part.

- It can be seen from Fig. 3.4(c) that the profit each ISP could obtain through cooperation decreases as λ increases, which means if the P2P requirement in this market is smaller, the profit one ISP could gain with optimal strategy would be smaller. The reason is because when P2P requirement decreases, users' utility from P2P usage would also decrease, so the utility that could be "squeezed" out by cooperative ISPs gets smaller.

3.4.2 The Threat Strategy

Analysis shows that ISPs can obtain a higher profit through cooperation compared to the profit under competition (Fig. 3.4(c)). However, there is no incentive for ISPs to cooperate. Some threat strategy is applicable here to encourage the cooperation.

We denote the cooperation strategy described in previous part by $s_{cooperate}$ and denote the strategy described in Proposition 3.3.4 by s_{threat}. The pricing game is viewed as an infinitely repeated game with many stages, at which each ISP evaluates its own profit, reviews others' strategies, and adjusts its strategy if necessary. The following proposition states the subgame-perfect equilibrium of this game.

Proposition 3.4.1 *The strategy profile "Play $s_{cooperate}$ until some ISP deviates and play s_{threat} since then" is a subgame-perfect equilibrium for the repeated pricing game among these ISPs under the condition that*

$$\theta > 1 - \frac{1}{M}, \tag{3.31}$$

in which θ is the discount factor of the repeated game.

Discount factor is a critical factor in the theory of repeated game. This discount factor represents the rate of inflation that makes future profit less valuable when compared to current returns. The equilibrium of a repeated game requires comparing two strategies involving future profits as well as current returns, so it is necessary to include this factor in the comparison.

Proposition 3.4.1 implies that whether the proposed strategy is a subgame-perfect equilibrium or not depends on the discount fact θ, which is explicitly negatively related to the number of ISPs in the market. In reality, the discount factor is fairly fixed in the short run, so if the number of ISPs increases, $(1 - \frac{1}{M})$ might get so large that θ cannot catch up with it, and the condition (3.31) fails, then the proposed strategy profile would be no longer subgame perfect. As cooperation can bring ISPs higher profit, one possible way to encourage cooperation is that some large companies take over small companies to decrease the number of ISPs in the market to the extent that condition (3.31) can be satisfied. At that time it will be less beneficial to break the cooperation agreement, so all the ISPs can be expected to stay in the cooperative agreement and get a higher profit.

3.5 Further Discussion

3.5.1 Accounting Cost

In the above analysis, the management cost in ISPs' cost function is always assumed to be identical in both flat-rate pricing and uplink pricing. In fact,we should not neglect the extra cost incurred by the measurement of traffic volume. This accounting cost consists of the cost for the measurement devices, the extra database to store users' volume record, etc.. To address this factor, we assume that with the adoption of uplink pricing, the management cost per user is increased by C_a, which denotes the accounting cost per user. Therefore, when adopting uplink pricing, ISPs cost function becomes

$$C(n, X) = C_f + (C_m + C_a)n + C_t r_r \bar{d} n + C_t r_p X, \qquad (3.32)$$

in which n is the number of subscribers inside this network, and X is the total P2P traffic volume.

The incorporation of accounting cost does not affect the cooperation strategy a lot, since we just need to substitute the original C_m with $C_m + C_a$, and carry out the same derivation. However the non-cooperative equilibrium is no longer what it used to be. Uplink pricing may be too costly to implement if the accounting cost is considerable compared to the peering cost. Normally accounting cost C_a depends on the latest technology, and it is not related to users' behavior. Therefore, if the peering cost for P2P in the market is relatively small, it would be nonprofitable to invest money for adopting uplink pricing and flat-rate pricing is favorable; while if the peering cost induced by P2P is considerable in the network, ISPs would be better off by adopting uplink pricing.

3.5.2 Peer-to-Peer Locality

Most P2P applications nowadays are designed to pick up peers randomly from the neighbor list that trackers have provided. This randomness on the one hand balances the traffic flow among the Internet, but on the other hand also leads to insufficient use of local sources and considerable peering cost.

With the uplink pricing policy, users are charged based on their P2P usage volume, which would inevitably decrease their P2P usage. This might be a bad news for the P2P application developers. However, if P2P software are designed to be more ISP-friendly, which means the fraction of external P2P traffic is much smaller than now, ISPs' peering cost is expected to decline. Once the peering cost is lower, the usage-based part q of uplink pricing will go down accordingly. As a result, lower q will lead to higher users' P2P usage, which is also better for P2P application developers' business.

To sum up, if uplink pricing is adopted by all the ISPs, there should be incentive for P2P software designers to improve the P2P locality when designing the applications.

3.6 Related Works

Many researchers have worked on the pricing policies inside the Internet industry, but as this industry involves so many stake holders and thus the complicated relationship in between, researchers mostly focused on part of the relationship.

[21] demonstrates a solid analysis over the interaction among ISPs, and figures out how the retail ISPs would behave on setting prices for access services, how the backbone ISPs choose the price for transit services, and how ISPs would decide on peering. This paper covers the three levels of backbone ISPs, access ISPs and end-users, but ignores the content providers and

the influence content would have on ISPs' behavior. [10] makes up with this part. It reveals how the profit should be reallocated between content ISP and "eyeball" ISP linking together. Besides, quite a lot of papers have worked on the peering relationship between ISPs, focusing on different aspects of this issue [6, 8, 17, 23, 26, 28], whether two ISPs should peer, how they should peer, whether they should set a "bill-and-keep" peering contact or a normal peering with mutual payment, how the payment is decided, etc.. A great part of the papers mentioned above have examined the general case in Internet industry. With the development of P2P technology, researchers might need to incorporate the P2P factor into the study on Internet pricing. [26] then has worked on the peering relationship when P2P traffic is taken into account.

3.7 Concluding Remarks

Recent reports and studies have apparently shown that Internet Service Providers are under a dilemma on how to view P2P traffic and make it controllable. The pervasion of P2P being wider makes ISPs more conscious before carrying out any new policy related to P2P applications, otherwise users might be bothered and ISPs' own business is ruined at the same time. We believe in current Internet where P2P traffic dominates, a targeted pricing policy could help resolve the conflict between ISPs and P2P traffic.

In this chapter, we took a game-theoretic approach towards examining the effect of uplink pricing on ISPs' business and the whole Internet market. Results arising from the analysis show that uplink pricing can be adopted by all the ISPs at the equilibrium in a competitive market. It is also proven that ISPs can get higher profit by cooperation, and some threat strategy is presented to encourage such cooperation. We also present a nice demonstration that uplink pricing can be treated as a promising method on triggering the development of P2P technology.

□ **End of chapter.**

Chapter 4

Viability of Paris Metro Pricing

Paris Metro Pricing is borrowed from the charging scheme imposed on Paris metro, where carriages are classified into higher-class and regular-class and different classes of carriages are charged different prices. Paris Metro Pricing in Internet partitions the whole network capacity into several virtual channels and imposes different prices for different channels. The expectation for Paris Metro Pricing is that higher-priced channels seize less users, therefore perform higher level of quality-of-service compared to lower-priced channels. Paris Metro Pricing realizes a simple form of differentiated service pricing.

Whether Paris Metro Pricing could bring higher profit for a monopolist or bring better social welfare for social planners has been intensively studied [2, 5, 7, 20]. [5] also contributes in examining the adoption of Paris Metro Pricing in a competitive market. Interestingly, with different models, [7] and [20] reach different conclusions about whether Paris Metro Pricing could bring higher profit for a monopolist, compared to one-class flat-rate pricing.

In both [2] and [5], it has been proven that when the quality-of-service(QoS) function satisfies some constraints, ISPs could get a higher profit by differentiating the prices of two channels than assigning the same prices for them. Besides, for a social planner, identical pricing for both channels is always inferior to differentiated pricing, in terms of social welfare. However, there is no reason to argue that imposing p on the network could bring the same profit or social welfare as partitioning the network into two virtual channels and imposing p identically on them. Therefore, to compare one-channel flat-rate pricing with Paris Metro Pricing, it is urgent to clarify the relationship between one-channel flat-rate pricing and two-channel identical pricing.

Our major contributions in this chapter include determining the sufficient conditions under which there is a gap between one network with price p and two virtual channels with identical price p, as well as providing explanations for the opposite results in [7] and [20]. The following parts are organized as follows: In Section 4.1, we develop a simple model to describe the problem. In Section 4.2, we further analyze the model to characterize the gap between one network with price p and two virtual channels with identical price p. Case studies are carried out in Section 4.3 to explain the reason why the two papers [7] and [20] find opposite results. Finally, we summarize this chapter.

4.1 The Model

We build a similar model to the one in [2]. We consider the scenario where one monopolist ISP possesses a total capacity of C, and users in the market have different preferences for quality of service. The preference is characterized by θ, which is a random variable at the region of $[\underline{\theta}, \bar{\theta}]$, following the probability distribution function $f(\theta)$ (and also the cumulative distribution function $F(\theta)$). The network quality of service is described by a function $K(C, J)$, which is related to the network capacity C and user demand J. The user demand J can be either user number inside the network or packet arrival rate at the entrance of the network, depending on the granularity of the model. If the ISP divides the capacity into m channels, then $K(C_i, J_i)$

Symbol	**Explanation**
C	Capacity of the network
C_i	Capacity of channel i
θ_j	User j's preference on quality of service
$K(C,J)$	Quality-of-service function when network capacity is C and user demand is J
$\boldsymbol{p}$	Price vector charged over all channels
p_i	Price charged for channel i
J	User demand, can be either user number or packet arrival rate
J_i	User demand in channel i
J_f	Total user demand with flat-rate pricing
R_f	Total revenue with flat-rate pricing
W_f	Social welfare with flat-rate pricing
J_{2c}	Total user demand with two-channel identical pricing
R_{2c}	Total revenue with two-channel identical pricing
W_{2c}	Social welfare with two-channel identical pricing

Table 4.1: Notations 2

denotes the quality of service of channel i and p_i denotes the price imposed on class i. We look at a certain class of functions $K(C,J)$, which subject to the following constraints:

1. $K(C,J)$ is positive, strictly increasing with C, strictly decreasing with J and differentiable;
2. There exists a permutation of $(1,\ldots,m)$, say $(x_1,\ldots,x_m)$, such that $J_{x_1} \geq \cdots \geq J_{x_m} \Longrightarrow k(C_{x_1},J_{x_1}) \leq \cdots \leq k(C_{x_m},J_{x_m})$ and k denotes the partial derivative of K over J.

The first constraint implies the nature of quality of service. The quality of service would be better if the capacity is larger or the user demand is lower. The second constraint eliminates those irregular QoS functions.

Given the set of QoS functions over all channels $\{K(C_i,J_i)\}$, users' preference θ and the price vector $\boldsymbol{p} = \{p_1,p_2,\ldots,p_m\}$, user j's utility function in channel i would be

$$U(\theta_j, i) = \theta_j K(C_i, J_i) - p_i \tag{4.1}$$

Table 4.1 sums up all the notations used in this model and the following analysis.

4.2 Flat-rate Pricing versus Paris Metro Pricing

When ISPs make decisions on which pricing policy to adopt, profitability is one of the most important factors to evaluate. While from a social planner's point view, social welfare is the first priority. Therefore, on examining the viability of Paris Metro Pricing, revenue and social welfare are both addressed. We explicitly split the comparison between one-channel flat-rate pricing and Paris Metro Pricing into two steps: (1) comparing one-channel flat-rate pricing with two-channel identical pricing; (2) comparing two-channel identical pricing with two-channel differentiated pricing. The second step has been well studied in [2]. It is proven that compared to two-channel identical pricing, ISPs can always get better revenue and social planners can always achieve higher social welfare by differentiating the prices for those two channels, under the condition that QoS function $K(C, J)$ satisfies the constraints in previous section. However, as to our knowledge, no past literature has ever studied the first step explicitly. Therefore, in this section, we first study the change of revenue and social welfare as the network is partitioned into two channels and the channels are priced identically. Then we combine the two steps together to reach a conclusion on the comparison between flat-rate pricing and Paris Metro Pricing.

4.2.1 One-channel Flat-rate Pricing

Consider the scenario where one ISP charges each subscriber a flat-rate price p and the capacity of the network is C, then only the users whose utility is non-negative would subscribe to the network. That is

$$U_j = \theta_j K(C, J_f) - p \geq 0,$$

so we have

$$\theta_j \geq \frac{p}{K(C, J_f)}.$$

Let $\hat{J}$ be the potential user demand in the market, then

$$\hat{J} P(\theta_j \geq \frac{p}{K(C, J_f)}) = J_f, \tag{4.2}$$

in which J_f denotes total user demand.

Lemma 4.2.1 *There is a unique solution J_f for the equation (4.2).*

Proof: The right side of (4.2) is strictly increasing with J_f and the left side is strictly decreasing with J_f. When $J_f = 0$, the left side is positive and the right side is zero, while when J_f goes to infinity, the left side goes to zero but the right side goes to infinity, therefore there must a unique intersection between those two curves. ■

The revenue of the ISP is

$$R_f = pJ_f, \tag{4.3}$$

and the social welfare is

$$W_f = \int_{\frac{p}{K(C,J_f)}}^{\bar{\theta}} \theta K(C, J_f) f(\theta) d\theta \tag{4.4}$$

4.2.2 Two-Channel Identical Pricing

Let us assume the ISP partitions the whole capacity into two channels, with capacity $C\alpha$ and $C(1-\alpha)$ respectively, and charges both channels the price p as in one-channel flat-rate pricing.

Lemma 4.2.2 *The quality of service at equilibrium is the same for both channels, which means the following equation holds*

$$K(C\alpha, J_1) = K(C(1-\alpha), J_2), \tag{4.5}$$

where J_i denotes user demand in channel i at equilibrium.

Proof: Suppose that (4.5) does not hold at equilibrium, without loss of generality, we assume

$$K(C\alpha, J_1) > K(C(1-\alpha), J_2),$$

then there is always incentive for users in channel 2 to switch to channel 1. As users transferring from channel 2 to channel 1, $K(C\alpha, J_1)$ decreases and $K(C\alpha, J_2)$ increases. Eventually, the equilibrium is reached when the quality of service is the same in both channels. ∎

If we denote the total user demand in this two-channel case as J_{2c}, then

$$J_{2c} = J_1 + J_2 = \hat{J}P(\theta_j \geq \frac{p}{K(C\alpha, J_1)}). \tag{4.6}$$

The revenue in this case is

$$R_{2c} = pJ_{2c},$$

and the social welfare is

$$W_{2c} = \int_{\frac{p}{K(C\alpha,J_1)}}^{\bar{\theta}} \theta K(C\alpha, J_1) f(\theta) d\theta$$

4.2.3 Flat-rate Pricing versus Two-Channel Identical Pricing

Let R_G be the *revenue gap*, the difference on revenue between the above two cases, and let R_W be the *welfare gap*, the difference on social welfare. Therefore,

$$R_G = R_f - R_{2c},$$

$$W_G = W_f - W_{2c}.$$

The following proposition characterizes the above gaps with different types of QoS functions.

Proposition 4.2.3 *The relationship between QoS function $K(C, J)$ and performance gaps J_G, W_G is shown as follows:*

1. $K(C\beta, J\beta) = K(C, J), \quad \forall\beta > 0$
   $\Longrightarrow R_G = 0, W_G = 0.$
2. $K(C\beta, J\beta) \geq K(C, J)$, *when* $\beta \geq 1, \forall\beta > 0$
   $\Longrightarrow R_G > 0, W_G > 0.$
3. $K(C\beta, J\beta) \leq K(C, J)$, *when* $\beta \geq 1, \forall\beta > 0$
   $\Longrightarrow R_G < 0, W_G < 0.$

Proof: For one-channel flat-rate pricing case, J_f is the solution of the following equation

$$\hat{J}P(\theta_j \geq \frac{p}{K(C, J_f)}) = J_f. \tag{4.7}$$

For two-channel identical pricing case, J_1 and J_2 are the solution of the following equation groups

$$\begin{cases} K(C\alpha, J_1) = K(C(1-\alpha), J_2) \\ J_1 + J_2 = \hat{J}P(\theta_j \geq \frac{p}{K(C\alpha, J_1)}) \end{cases}$$

If the QoS function satisfies the condition that $K(C\beta, J\beta) = K(C, J), \forall\beta > 0$, then we have

$$K(C\alpha, J_1) = K(C, \frac{J_1}{\alpha}) = K(C(1-\alpha), J_2) = K(C, \frac{J_2}{(1-\alpha)}).$$

It follows that

$$\frac{J_1}{\alpha} = \frac{J_2}{(1-\alpha)}.$$

Therefore,

$$J_{2c} = J_1 + J_2 = \frac{J_1}{\alpha} = \hat{J}P(\theta_j \geq \frac{p}{K(C\alpha, J_1)}) = \hat{J}P(\theta_j \geq \frac{p}{K(C, \frac{J_1}{\alpha})}).$$

Lemma 4.2.1 makes sure that $J_f = \frac{J_1}{\alpha}$, so $J_f = J_{2c}$, and $R_f = R_{2c}$. Similarly, we have $W_f = W_{2c}$.

If the QoS function satisfies the condition that $K(C\beta, J\beta) \geq K(C, J)$, when $\beta \geq 1, \forall\beta > 0$, and if we assume $\alpha > 0.5$ without loss of generality, then we have

$$K(C(1-\alpha), J_2) = K(C\alpha, J_1) > K(C(1-\alpha), \frac{J_1(1-\alpha)}{\alpha}),$$

As $K(C, J)$ is decreasing with J, it follows that $J_2 < \frac{J_1(1-\alpha)}{\alpha}$, so $J_{2c} = J_1 + J_2 < \frac{J_1}{\alpha}$. Therefore,

$$K(C\alpha, J_1) < K(C, \frac{J_1}{\alpha}) < K(C, J_{2c}).$$

Then, we have that

$$J_{2c} = \hat{J}P(\theta_j \geq \frac{p}{K(C\alpha, J_1)}) < \hat{J}P(\theta_j \geq \frac{p}{K(C, J_{2c})}).$$

It follows that $J_{2c} < J_f$. As a result, we have $R_{2c} < R_f$ and $W_{2c} < W_f$.

Similar analysis could also find that if $K(C\beta, J\beta) \leq K(C, J)$, when $\beta \geq 1, \forall\beta > 0$, then $R_{2c} > R_f$ and $W_{2c} > W_f$.

■

- If user demand is interpreted as number of subscribers in the network, Proposition 4.2.3 implies that as long as the QoS function is solely dependent on $\frac{C}{J}$, namely per-user bandwidth, switching from one-channel pricing to two-channel identical pricing incurs no gap on revenue or social welfare. However, if users with the same per-user bandwidth prefer larger networks, which captures positive network externalities, partitioning network would cause degradation on revenue as well as social welfare; otherwise, revenue and social welfare would increase after capacity partition.

- Let the user demand be the packet arrival rate at the entrance of network, it is found that when packets merely evaluate congestion from the busy probability of the network, there would be no gap between one-channel flat-rate pricing and two-channel identical pricing. However, given the same busy probability, if packets prefer higher service rate to lower service rate, which is similar to the case when congestion is evaluated from the average response time, revenue and social welfare get worse after channel partitioning.

4.2.4 Flat-rate Pricing versus Paris Metro Pricing

In [2], Chau presents solid analysis on comparing two-channel identical pricing to two-channel differentiated pricing. It is proven that differentiated pricing could always reach higher revenue and social welfare. Combining the result in [2] with our findings in Proposition 4.2.3, we reach the following corollary.

Corollary 4.2.4 *For one QoS function* $K(C, J)$,

- *If* $K(C\beta, J\beta) = K(C, J), \quad \forall \beta > 0$, *or* $K(C\beta, J\beta) \leq K(C, J)$, *when* $\beta \geq 1, \forall \beta > 0$, *Paris Metro Pricing could always bring higher revenue for a monopolist and higher social welfare for a social planner.*

- *If $K(C\beta, J\beta) \geq K(C, J)$, when $\beta \geq 1, \forall \beta > 0$, it is possible that Paris Metro Pricing cannot help in getting higher revenue or higher social welfare.*

In corollary 4.2.4, we provide the sufficient conditions under which Paris Metro Pricing is viable compared to flat-rate pricing. We also suggest the condition which *probably* leads to worse performance with Paris Metro Pricing. Further studies could focus on exploring the sufficient conditions under which Paris Metro Pricing is not viable.

4.3 Case Studies

Two of the former papers also study the viability of Paris Metro Pricing compared to flat-rate pricing [7], [20] . In both papers, congestion functions are specified and the utility functions of users are in the following form

$$U'(\theta'_j, i) = V - \theta'_j K'(C_i, J_i) - p_i, \tag{4.8}$$

which is slightly different from our definition (4.1). In (4.8), V denotes the benefit one user could get from this network, θ'_j denotes users' congestion sensitivity, and K' is a congestion function which is strictly increasing with the user demand J_i. As a matter of fact, these two utility functions are compatible, since either $V - \theta'_j K'(C_i, J_i)$ or $\theta_j K(C_i, J_i)$ can represent the net benefit. Besides, in (4.8), higher θ'_j means lower delay sensitivity or lower QoS preference, while in (4.8), higher θ_j means higher QoS preference.

Case 1: $K(C, J) = V - \frac{J}{C}$

In [7], $K'(C_i, J_i) = \frac{J_i}{C_i}$, so we can convert the utility function in [7] into $U_1(\theta_j, i) = \theta_j(V - \frac{J_i}{C_i}) - p_i$, which is in the form of (4.1). Therefore, the QoS function is $K(C, J) = V - \frac{J}{C}$.

It is straightforward that this function satisfies the constraint (1). If we divide the whole capacity into two channels, $C\alpha$ and $C(1-\alpha)$ ($\alpha > 0.5$), then the QoS function for each channel is $K_1(J_1) = V - \frac{J_1}{C\alpha}$ and $K_2(J_2) = V - \frac{J_2}{C(1-\alpha)}$. Doing the first-order derivative of K over J, we find $k_1 = -\frac{1}{C\alpha}$ and $k_2 = -\frac{1}{C(1-\alpha)}$, so $k_1 > k_2$ for all J_1, J_2. Therefore, this specific QoS function conform to our constraint (2). According to [2], with this QoS function, a monopolist could get a higher profit by differentiating the prices for both channels.

Furthermore, the function $K(C, J)$ is only related to $\frac{J}{C}$, so according to Corollary 4.2.4, with this QoS function, a monopolist could gain higher profit with Paris Metro Pricing than with one-channel flat-rate pricing. This conclusion matches the numerical results presented in [7].

Case 2: $K(C, J) = V - \frac{1}{C-J}$

Similarly, we can convert the utility function in [20] into $U_2(\theta_j, i) = \theta_j(V - \frac{1}{C_i - J_i}) - p_i$, so the case in [20] applies another QoS function $K(C, J) = V - \frac{1}{C-J}$. We could check that this function conforms to our constraints for QoS functions, so with such a function, a monopolist could get higher revenue through differentiating the prices for different classes.

Closer examination finds that $K(C\beta, J\beta) \geq K(C, J)$, when $\beta \geq 1, \forall \beta > 0$, so with such form of QoS function, corollary 4.2.4 suggests that Paris Metro Pricing probably brings lower profit for the monopolist. The numerical results in [20] validate our conjecture.

Based on the above case studies, we argue that different forms of QoS functions (or congestion functions) is the key factor that leads to the opposite conclusions about the profitability of Paris Metro Pricing in [7] and [20].

4.4 Concluding Remarks

In this chapter, we explicitly split the study on viability of Paris Metro Pricing into two steps: from one-channel flat-rate pricing to two-channel identical pricing, then to two-channel differentiated pricing. Most of the past literature either solely study the second step [2], [5] or directly compare one-channel flat-rate pricing with two-channel differentiated pricing [7],[20]. Our contribution is to characterize the performance gap between one-channel flat-rate pricing and two-channel identical pricing. Combined with the work in [2], we also present some preliminary results about the viability of Paris Metro Pricing. It is found that only when the QoS functions satisfy some constraints will the Paris Metro Pricing bring higher revenue and higher social welfare, otherwise it is possible that Paris Metro Pricing could not help.

□ **End of chapter.**

Chapter 5

Conclusion

The Internet pricing problem - how ISPs charge the subscribers for the Internet access services to better utilize capacity resources and earn higher profit - is an important problem in the commercialized Internet industry. In this thesis, we present our work on this problem.

When you talk to people who work for ISPs, large or small, you quickly realize that all ISPs are grappling with the P2P problem, which ironically is also an opportunity to ISPs as P2P can be viewed as a renewed content provider technology. ISPs have tried different methods, such as P2P traffic blocking, and rate limiting, which sometimes have led to negative sentiments by their customers. In the first part of this thesis, we revisit pricing as a possible mechanism to manage ISP networks in the P2P era. We suggest a usage-based uplink pricing, which imposes an extra usage-based charge on users' uplink traffic. Game-theoretic analysis is taken to examine the adoption of uplink pricing in the competitive case as well as the cooperative case. Results arising from analysis show that uplink pricing could be adopted by all ISPs in competition. It is also proven that cooperation could bring higher profit for ISPs and a threat strategy could encourage such cooperation. Further discussions find that when the accounting cost to measure users' usage is considerable, flat-rate pricing would outperform uplink pricing in the competitive case. We also argue that uplink pricing could trigger the improvement of P2P technology in utilizing local resources.

The other part of this thesis is a study about the viability of Paris Metro Pricing. We build a simple model to evaluate the gap on revenue and social welfare between one-channel flat-rate pricing and two-channel identical pricing. In particular, it is found that the gap is tightly related to the forms of quality-of-service functions. Combined with former results in [2], we argue that only if QoS functions satisfy some constraints, Paris Metro Pricing could bring higher revenue and social welfare. Finally, we also provide an explanation of the opposite results on the profitability of Paris Metro Pricing in [7] and [20].

□ **End of chapter.**

Appendix A

Equation Derivation

A.1 Proof for Lemma 3.3.2

Proof: We first prove that if all ISPs adopt uplink pricing, p^* and q^* is the stable price setting. We need to show that no ISP can get higher profit by deviating from this price setting. At this price setting, the two thresholds are involved as

$$\begin{aligned} p^* &= w\log(1+\hat{x}_1) + \bar{U}_r - q\hat{x}_1 \\ q^* &= \frac{w}{1+\hat{x}_2} \end{aligned}$$

Without loss of generality, we assume that ISP_k deviates from this price setting. It is straightforward that ISP_k cannot get a better profit by increasing or decreasing the price of only one link. For example, if $q_k = q^* - \delta$ and $p_k = p^*$, it is obvious that ISP_k can attract all the users because of its lower price but get a negative profit; while if ISP_k merely increases q^* a little, it would definitely lose all the users. Therefore, the way of deviation that is more likely to bring higher profit is to increase the price for one link and decrease the other.

Case 1

The number of users admitted is kept unchanged, but the price for uplink is decreased and the price for downlink is increased. In other words, $q_k = q^* - \delta$ and $\hat{x}_1$ is kept unchanged.

In this situation, $\hat{x}_2$ is changed to

$$\hat{x}_2' = \frac{w}{q^* - \delta} - 1.$$

As $\hat{x}_1$ is unchanged,

$$p_k = w\log(1+\hat{x}_1) + \bar{U}_r - q_k\hat{x}_1 = p^* + \delta\hat{x}_1.$$

When there is one ISP charging in a different way from the others, users would evaluate their payoffs in each ISP and choose the one that brings the highest payoff.

(1) For the user i that $\hat{x}_1 \le \tilde{x}_i \le \hat{x}_2$, he can download P2P traffic at the volume of $\tilde{x}_i$ in all ISPs but its payoff in ISP_k and the other ISPs might be different. We use S_i^k to denote the payoff of user i in ISP_k and S_i^{-k} to denote the payoff of user i in ISPs other than ISP_k.

$$S_i^k = w\log(1+\tilde{x}_i) + \bar{U}_r - (p_k + q_k\tilde{x}_i),$$
$$S_i^{-k} = w\log(1+\tilde{x}_i) + \bar{U}_r - (p^* + q^*\tilde{x}_i).$$

Comparing the profit, we have

$$S_i^k - S_i^{-k} = \delta(\tilde{x}_i - \hat{x}_1) \ge 0.$$

Therefore, user i would subscribe to ISP_k.

(2) For the user i that $\hat{x}_2 < \tilde{x}_i \le \hat{x_2'}$, it can download volume $\tilde{x}_i$ in ISP_k but download volume $\hat{x}_2$ in the other ISPs.

$$S_i^k = w\log(1+\tilde{x}_i) + \bar{U}_r - (p_k + q_k\tilde{x}_i)$$
$$S_i^{-k} = w\log(1+\hat{x}_2) + \bar{U}_r - (p^* + q^*\hat{x}_2)$$

Comparing the profit, we have

$$\begin{aligned} S_i^k - S_i^{-k} &> (w\log(1+\hat{x}_2) + \bar{U}_r - (p_k + q_k\hat{x}_2)) - (S_i^{-k}) \\ &= (p^* - p_k) + (q^* - q_k)\hat{x}_2 \quad \text{(A.1)} \\ &= -\delta\hat{x}_1 + \delta\hat{x}_2 \ge 0 \quad \text{(A.2)} \end{aligned}$$

(3) For the user i that $\tilde{x}_i > \hat{x}'_2$, it can download volume $\hat{x}'_2$ in ISP_k but $\hat{x}_2$ in the other ISPs. Similarly, we compare the user's payoff in different ISPs and we have

$$S_i^k - S_i^{-k} \geq 0$$

Combining the above three items together, we can conclude that when ISP_k deviates by setting a lower price than q^* and keeping $\hat{x}_1$ unchanged, it can obtain all the users. In this situation, its profit is

$$\begin{aligned} P_k &= Ne^{-\lambda \hat{x}_1}(p_k - C_m - C_t r_r \bar{d}) \\ +N(e^{-\lambda \hat{x}'_2}\hat{x}'_2 &+ (\frac{1}{\lambda} + \hat{x}_1)e^{-\lambda \hat{x}_1} - (\frac{1}{\lambda} + \hat{x}'_2)e^{-\lambda \hat{x}'_2})(q_k - C_t r_p) \\ &= N\frac{1}{\lambda}(e^{-\lambda \hat{x}_1} - e^{-\lambda \hat{x}'_2})(-\delta) < 0. \end{aligned}$$

Therefore, in this way of deviation, ISP_k gets a worse profit.

Case 2

ISP_k sets a lower price for uplink, $q_k = q^* - \delta$, and increases the price for downlink in the way so that $\hat{x}_1$ decreases. If we denote the rationality threshold in ISP_k by $\hat{x}'_1$, we have,

$$\hat{x}'_1 < \hat{x}_1 \leq \hat{x}_2 < \hat{x}'_2.$$

In this case,

$$p_k - p^* < \delta \hat{x}'_1.$$

Applying the methodology in Case (1), we manage to prove that all the users would subscribe to ISP_k but the ISP_k's profit is still negative.

Case 3

If ISP_k sets a lower price for uplink $q_k = q^* - \delta$ and increases the price for downlink in the way so that

$$\hat{x}_1 < \hat{x}'_1 \leq \hat{x}_2 < \hat{x}'_2.$$

Therefore

$$p_k = w\log(1+\hat{x}_1') + \bar{U}_r - q_k\hat{x}_1' > p^* + \delta\hat{x}_1'. \tag{A.3}$$

For one user i, if $\hat{x}_1 \leq \tilde{x}_i < \hat{x}_1'$, he does not subscribe to ISP_k.

If $\hat{x}_1' \leq \tilde{x}_i < \hat{x}_2$, similar to previous analysis, user i could download $\tilde{x}_i$ in all ISPs. User i would subscribe to ISP_k is

$$S_k - S_{-k} = (p^* - p_k) + (q^* - q_k)\tilde{x}_i > 0.$$

It follows that

$$\tilde{x}_i > \frac{p_k - p^*}{\delta}.$$

Clearly $\frac{p_k-p^*}{\delta} > \hat{x}_1'$. If $\frac{p_k-p^*}{\delta} \leq \hat{x}_2$, then users who satisfy that $\frac{p_k-p^*}{\delta} < \tilde{x}_i \leq \hat{x}_2$ would subscribe to ISP_k. If $\tilde{x}_i > \hat{x}_2$, the payoff of user i in ISP_k continues increasing until $\tilde{x}_2$ hits $\hat{x}_2'$, but the payoff of user i in ISP_{-k} would remain as when usage is $\hat{x}_2$. Therefore, users who satisfy $\tilde{x}_i > \hat{x}_2$ subscribe to ISP_k. To sum up, users who satisfy $\hat{x}_i > \frac{p_k-p^*}{\delta}$ subscribe to ISP_k. We could calculate the profit of ISP_k,

$$\begin{aligned}
P_k &= e^{-\lambda\frac{p_k-p^*}{\delta}}(p_k - C_m - C_t r_r \bar{d}) \\
&+ (q_k - C_t r_p)((\frac{p_k - p^*}{\delta} + \frac{1}{\lambda})e^{-\lambda\frac{p_k-p^*}{\delta}} - \frac{1}{\lambda}e^{-\lambda\hat{x}_2'}) \\
&= \frac{1}{\lambda}\delta(e^{-\lambda\hat{x}_2'} - e^{-\lambda\frac{p_k-p^*}{\delta}}) < 0
\end{aligned}$$

However, if $\frac{p_k-p^*}{\delta} > \hat{x}_2$, then users who satisfy $\hat{x}_1' \leq \tilde{x}_i \leq \hat{x}_2$ do not subscribe to ISP_k. We further examine the users with higher P2P requirement to see whether they would subscribe to ISP_k. For user i, if $\hat{x}_2 < \tilde{x}_i \leq \hat{x}_2'$, he could download $\tilde{x}_i$ in ISP_k but $\hat{x}_2$ in ISP_{-k}. Therefore,

$$\begin{aligned}
S_k - S_{-k} &= (w\log(1+\tilde{x}_i) - p_k - q_k\tilde{x}_i) - (w\log(1+\hat{x}_2) - p^* - q^*\hat{x}_2) \\
&= (w\log(1+\tilde{x}_i) - q_k\tilde{x}_i) - (w\log(1+\hat{x}_2) - q^*\hat{x}_2) - (p_k - p^*) \\
&= (w\log(1+\tilde{x}_i) - q^*\tilde{x}_i) - (w\log(1+\hat{x}_2) - q^*\hat{x}_2) - (p_k - p^*) + \delta\tilde{x}_i \\
&= -\Delta_1 - (p_k - p^*) + \delta\tilde{x}_i,
\end{aligned}$$

in which $-\Delta_1 < 0$ denotes the negative value of $(w\log(1+\tilde{x}_i)-q^*\tilde{x}_i)-(w\log(1+\hat{x}_2)-q^*\hat{x}_2)$. It follows that when $S_k - S_{-k} > 0$, $\tilde{x}_i > \frac{p_k - p^* + \Delta_1}{\delta}$. If $\frac{p_k - p^* + \Delta_1}{\delta} \le \hat{x}'_2$, then users who satisfy $\tilde{x}_i > \frac{p_k - p^* + \Delta_1}{\delta}$ would subscribe ISP_k. Similarly, we could formulate the profit of ISP_k and prove that it is negative.

If $\frac{p_k - p^* + \Delta_1}{\delta} > \hat{x}'_2$, we know that users who satisfy $\tilde{x}_i \le \hat{x}'_2$ do not subscribe to ISP_k. For users with higher P2P requirement than $\hat{x}'_2$, they could download $\hat{x}'_2$ in ISP_k but $\hat{x}_2$ in ISP_{-k}. They all get the same payoff as the user whose P2P requirement is $\hat{x}'_2$, so they all subscribe to ISP_{-k} and ISP_k would get no subscribers.

Above all, under some condition ISP_k could get certain number of subscribers but its profit is negative.

Case 4

If ISP_k sets a lower price for uplink $q_k = q^* - \delta$ and increases the price downlink in the way so that

$$\hat{x}_1 \le \hat{x}_2 < \hat{x}'_1 \le \hat{x}'_2.$$

We could apply the same methodology as in Case (3) and prove that under some condition ISP_k could get certain number of subscribers but its profit is negative.

Up till now, we have proven that if ISP_k sets a lower price for uplink and a higher price for downlink, it could not get more benefit.

Symmetrically, there are other four cases where ISP_k sets a higher price for uplink and a lower price for downlink. Applying the same methodology as in previous cases, we could prove that it is also not beneficial.

Above all, we have exhausted all the possible ways for one ISP to deviate from the equilibrium, and the analysis shows that it is not beneficial for one ISP to deviate from the equilibrium price setting while the other ISPs set the equilibrium prices.

We also need to prove that no ISP can get a better profit by adopting flat-rate pricing when the others are using uplink pricing. Suppose ISP_k adopts flat-rate pricing with price p_k, and the other ISPs adopt uplink pricing with price p^* and q^*, the stable price setting as in Lemma 3.3.2. ISP_k could attract user i only if $p_k \leq p^* + q^*\tilde{x}_i$, under which condition ISP_k would run a deficit.

■

☐ **End of chapter.**

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