On Multi-Resource Procurement in Internet Access Markets: Optimal Strategies and Market Equilibrium

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ABSTRACT

With the increasing popularity and significance of content delivery services, especially video streaming, stringent Quality of Service (QoS) requirements have been placed upon Internet content providers (CPs). As a result, CPs have strong incentives to pay for resources such as premium peering bandwidth and cache capacity that ameliorate service quality. In this paper, we study an Internet access market with multiple access resources that CPs can purchase to enhance service quality. We build a detailed content delivery model, through which we characterize the traffic throughput and the resulting utilities of CPs and social welfare. We show that a market equilibrium exists for a multi-resource market, at which the optimization problems for individual utilities and social welfare coincide. Furthermore, we characterize the optimal purchasing strategies of CPs as well as how varying parameters are going to change the market equilibrium via sensitivity analysis.

Keywords

premium peering, cache, content provider, ISP, market equilibrium

1. INTRODUCTION

Content delivery services, especially video streaming, have taken a significant portion of the Internet traffic. In this era of contents, the Quality of Service (QoS) perceived by users should be among the primary concerns of content providers (CPs), because long loading time and low feasible resolution could severely reduce a user's willingness to watch a video online. In other words, the service quality can be measured by the traffic delay and the overall throughput, which directly affect users' desire for contents.

As service quality deteriorates due to the network congestion at the bottleneck links, CPs have incentives to pay for additional resources that could address the issues. Although acquiring bandwidth or cache can improve the QoS of content delivery and only require relatively slight modifications to the current network infrastructure, less is known for the scenario of deploying a hybrid of *premium peering* and *cache* resources. We take a unified view of *access resources* available for purchasing from Internet Service Providers (ISPs) in the last-mile access markets. As acquiring more access resources also induces additional expenses, we study how should CPs procure to optimize their *individual utilities*, i.e., the revenue earned from users less the payments to ISPs. From the perspective of the entire market, however, regulators concern about the total revenue that can be generated, i.e., the *social welfare*. In particular, we study an Internet access market consisting of one access ISP and multiple CPs, where CPs determine their *purchasing strategies* on multiple access resources. We exploit the *market equilibrium*, at which the demand and supply are balanced.

We show that a market equilibrium exists, at which the optimization problems for CPs' individual utilities and the social welfare coincide, and the *market-clearing prices* of resources are unique. Our work suggests that CPs may consider purchasing a hybrid of access resources to improve QoS, and demonstrates how to optimally determine their purchasing strategies under a novel content delivery model.

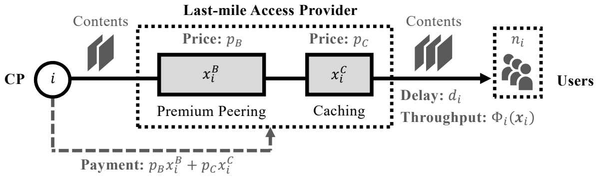

Figure 1: Resource procurement and content delivery of a CP.

2. RESOURCE PROCUREMENT AND CONTENT DELIVERY

2.1 Resource Procurement, Utilities and Social Welfare

Figure 1 illustrates a typical CP i that purchases two types of available resources: *premium peering* bandwidth and *cache* capacity. We denote the unit prices of premium peering bandwidth and cache by $\boldsymbol{p} = (p_B, p_C)^T > \boldsymbol{0}$, specified by the ISP. We denote the *purchasing strategies* of CP i by $\boldsymbol{x}_i = (x_i^B, x_i^C)^T \geq \boldsymbol{0}$, when CP i purchases x_i^B units of bandwidth and x_i^C units of cache capacity, and consequently pays the ISP a total of $\boldsymbol{p}^T \boldsymbol{x}_i = p_B x_i^B + p_C x_i^C$.

CPs generate revenues by providing contents. Regardless of the sources, a CP's revenue increases when its users request for more contents and generate more traffic. Thus, we denote any CP i's average per-unit traffic revenue by v_i and aggregate throughput by Φ_i, and define its utility as

$$U_i(\boldsymbol{x}_i) = V_i(\boldsymbol{x}_i) - \boldsymbol{p}^T \boldsymbol{x}_i,$$

where $V_i(\boldsymbol{x}_i) = v_i\Phi_i(\boldsymbol{x}_i)$ defines the revenue of CP i. The *utility* of a CP is defined as its profit, i.e., revenue less the payment to the ISP. We define overall throughput $\Phi_i(\boldsymbol{x}_i)$ as a function of $\boldsymbol{x}_i$, since $\boldsymbol{x}_i$ determines the QoS that can be achieved, which further influences how much users desire for the contents.

We denote the set of CPs that provide content to the end-users through the ISP by $\mathcal{N}$, and define the *social welfare* as the aggregate revenue of all CPs, i.e.,

$$\sum_{i\in\mathcal{N}} V_i(\boldsymbol{x}_i) = \sum_{i\in\mathcal{N}} v_i\Phi_i(\boldsymbol{x}_i).$$

2.2 Content Delivery Model

Less congestion and better QoS are indeed two sides of the same coin, as service degradation is often caused by congestion. Because longer delays are induced by more congested links, we model the congestion level of the route between CP i and users by the average delay of traffic, denoted by d_i. Accordingly, we measure the QoS of CP i's service by its aggregate *throughput* ϕ_i. On the one hand, under a given congestion level, the route can accommodate certain amount of throughput $\phi_i(d_i)$. On the other hand, the throughput also influences the congestion level.

We denote the number of users of CP i by n_i, which represents the user population that requests for contents from CP i under its best achievable QoS. Some users may stop using CP i with degrading QoS. Under less congestion, the proportion of users who use CP i grows, and these users also have stronger desire for contents. On average, each user of the total population n_i desires more from CP i. We characterize the users' desire by the *desirable throughput*, and denote the average per-user desirable throughput by $\Lambda_i(d_i)$.

Definition 1 (Steady-State) *For any CP i, the content delivery enters a steady-state if and only if ϕ_i satisfies*

$$\phi_i = n_i\Lambda_i(d_i). \tag{1}$$

As mentioned before, the average traffic delay d_i is influenced by throughput ϕ_i. Under certain assumptions with intuitive and reasonable explanation, there exists a unique $\phi_i > 0$ that satisfies Equation (1). Since the *steady-state throughput* uniquely exists given the purchasing strategies $\boldsymbol{x}_i$, we can denote it by a function $\phi_i = \Phi_i(\boldsymbol{x}_i)$.

3. ANALYSES OF MARKET EQUILIBRIUM

We study the market equilibrium at which resource supply balances the demands from CPs. We will show that the multi-resource market equilibrium is optimal with respective to social welfare.

3.1 Market Equilibrium and Optimality

We denote the ISP's capacities of premium peering bandwidth and cache by X_B and X_C, i.e., the *supply.* When the prices vary, buyers will respond with their *demand*, characterized as a demand function $\boldsymbol{\chi}_i(\boldsymbol{p})$ of the prices. The market tends to reach an equilibrium at which the supply and demand are balanced, i.e., the prices $\boldsymbol{p}$ *clear the market.*

Definition 2 (Market Equilibrium) *A pair $(\boldsymbol{p};\mathbf{x})$ of price vector and demand matrix is a market equilibrium if and only if the demand matrix $\mathbf{x} = (\boldsymbol{x}_1,\ldots,\boldsymbol{x}_N)$ satisfies*

$$\boldsymbol{x}_i = \boldsymbol{\chi}_i(\boldsymbol{p}),\ \forall i\in\mathcal{N}, \quad \textit{and} \sum_{i\in\mathcal{N}} x_i^B = X_B,\ \sum_{i\in\mathcal{N}} x_i^C = X_C.$$

In particular, $\boldsymbol{p}$ is referred to as the market-clearing prices.

Theorem 1 (Optimality of Market Equilibrium) *If any CP i's throughput $\Phi_i(\boldsymbol{x}_i)$ is differentiable, strictly increasing and concave, there exists a market equilibrium $(\boldsymbol{p};\mathbf{x})$, at which*

(1) $\boldsymbol{x}_i$ maximizes the utility $U_i(\boldsymbol{x}_i)$ for any CP i;

(2) $\mathbf{x}$ maximizes the social welfare $\sum_{i\in\mathcal{N}} V_i(\boldsymbol{x}_i)$;

(3) The market-clearing price vector $\boldsymbol{p}$ is unique.

Furthermore, if $\Phi_i(\boldsymbol{x}_i)$ is strictly concave for all $i\in\mathcal{N}$, the market equilibrium demand matrix $\mathbf{x}$ is also unique.

Theorem 1 generalizes Kelly's results [1] for a market with both bandwidth and cache resources. The market equilibrium is shown to achieve various objectives of the different market participants.

Definition 3 (Hazard Rate) *For a differentiable function $f(x)$, the hazard rate of f with respect to x is defined by*

$$H_f(x) \triangleq -\frac{1}{f}\frac{\partial f}{\partial x} = -\frac{\partial f/f}{\partial x}.$$

The hazard rate measures the rate of decrease in function f with respect to variable x.

Theorem 2 (Intra-CP and Inter-CP Demand) *At the market equilibrium, for CPs $i\neq j$ with $\boldsymbol{x}_i,\boldsymbol{x}_j > \mathbf{0}$, we have*

$$\frac{H_{\Phi_i^B}(x_i^B)}{H_{\Phi_i^C}(x_i^C)} = \frac{p_B}{p_C}, \quad \textit{and} \quad \frac{H_{\Phi_i^B}(x_i^B)}{H_{\Phi_j^B}(x_j^B)} = \frac{H_{\Phi_i^C}(x_i^C)}{H_{\Phi_j^C}(x_j^C)} = \frac{V_j(\boldsymbol{x}_j)}{V_i(\boldsymbol{x}_i)}.$$

Theorem 2 states how CPs' equilibrium demands $\boldsymbol{x_i}$ are related to the prices $\boldsymbol{p}$ and their revenues V_i. The ISP and CPs can gain deeper understanding on how they should choose the resource prices and purchasing strategies.

3.2 Generalization for Multiple Resources

Our model and results could be generalized for a multi-resource market. We assume that the ISP provides L types of resources, with supply and price vectors denoted by $\boldsymbol{X} = (X_1,\ldots,X_L)^T$ and $\boldsymbol{p} = (p_1,\ldots,p_L)^T > \mathbf{0}$. CPs choose purchasing strategies $\mathbf{x} = (\boldsymbol{x}_1,\ldots,\boldsymbol{x}_N)$, where $\boldsymbol{x}_i = (x_i^1,\ldots,x_i^L)^T$ denotes the strategies of CP i. Similarly, a market equilibrium $(\boldsymbol{p};\mathbf{x})$ is a pair of price vector and demand matrix that satisfies $\mathbf{x}\mathbf{1} = \boldsymbol{X}$ and $\boldsymbol{x}_i = \boldsymbol{\chi}_i(\boldsymbol{p})$ for any CP i.

4. CONCLUSION

We study a novel Internet access market where CPs can procure multiple types of access resources. We build a detailed content delivery model, and characterize the traffic throughput, which has a unique closed form at steady-state. We show that for a multi-resource market, a market equilibrium exists, at which the optimization problems for individual utilities and social welfare coincide. Moreover, the market-clearing prices are unique. Our work provide insights for the thriving market of content delivery services, such as video streaming, where CPs are willing to provide better experience for their users at a reasonable cost.

5. REFERENCES

[1] Kelly, F. Charging and rate control for elastic traffic. *European transactions on Telecommunications 8*, 1 (1997), 33–37.