Pricing Broadband: Survey and Open Problems

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***Abstract*—Driven by the emerging directions from the FCC and the broadband market, this paper aims at answering the fundamental question of how to use pricing as a lever to enable universal broadband coverage and effective network management in the United States. We address differential pricing as a network management tool, i.e., what to charge, how to charge, and how much to charge. We also outline research towards multi-platform two-sided pricing focusing on ISP that charges both content and application providers. Open problems are highlghted. As a next step, through collaboration we will combine the access to large-scale empirical data with rigorous modeling and analysis; we will go all the way from data collection through mathematical analysis to practical impact on policy decisions and ISP business decisions, thus closing the loop in the study of network economics for universal broadband coverage.**

I. Introduction

This paper is a short survey of pricing strategies in networks to understand the dynamics between Internet service providers (ISPs) and end users. Study of pricing strategies can help maximize ISPs' revenue and/or manage network traffics. In the case of broadband access networks, it can also help ISPs deploy access networks considering investment cost and returns on investment. This paper is also motivated from recent regulatory trends in the United States and focuses on a particular dimension of network economics: *how to provide pricing mechanisms conducive to universal broadband coverage?* It is driven by two timely and important questions: (1) Who will pay for the estimated cost of $55B-350B in the next decade to enable universal coverage of broadband services? How much can rural area consumers, content providers, and tier-1 ISPs contribute, in addition to taxpayers money? (2) Can pricing mechanisms be leveraged as a new and practical approach to network management that is net-neutrality compatible, and yet generates sufficient revenue to incentivize network expansion for universal broadband? There is no point in creating a network management structure to support an economic model that cannot be sustained. In this paper, we address both the "what" and the "how" of network management: the "what" is forensics to identify economic models that can be sustained, and the "how" is to identify the information and develop methodology essential to support them.

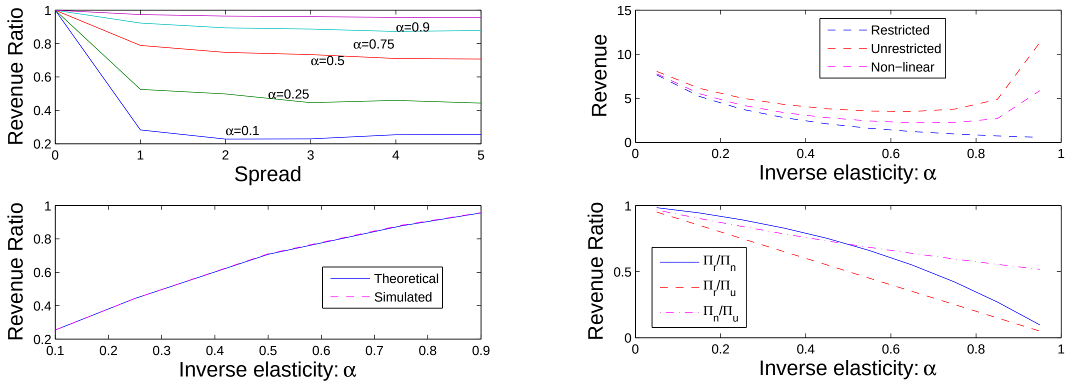
This paper serves as a short survey on state of the art of pricing in access networks and highlights some of the open problems. Throughout this paper we will explore the cases and opportunities where network economics help to understand: (1) how to make access to broadband services universally available and (2) how to manage demand in broadband services that is network neutrality compatible.

II. Differential Pricing as Network Management

One can view the value propositions of the telecommunication industry today as an *inverted* triangle. There is a top layer representing telecom and Internet applications and services. There is a middle transport layer where the focus is operations at massive scale. At the tip there is infrastructure and what we might think of as traditional communications research. Twenty-five years ago we would also have used a triangle to represent the value proposition in the industry, but it would not be inverted. The dilemma is that the old triangle still describes the industry cost structure. A sustainable ISP pricing structure is therefore essential to further the value accrued from applications and services while managing the infrastructure cost incurred.

The economics of pricing, if done properly, offers a new lever to achieve network management goals by ISPs, including rural ISPs serving the under-priviledged consumers, often in more user-transparent ways and thus less heated under net neutrality debates. Among related works, [32] investigated how end-user and network operators economic-driven behavior influence the network performance. Many research works studied revenue maximization in congestible networks: [5], [17], [20], [21], [28] focused on the network revenue maximization by using usage-price and flat-price, [29] studied the similar problem but considered incomplete network information. Dynamic pricing, which is rooted in yield management [30], was proposed for telecommunication networks to reap revenue [22] [26]. Time-dependent pricing is considered in [16], where the authors propose a model with time-dependent consumer utilities and analyze the revenue loss to a monopoly ISP due to insufficient information about consumer utilities.

Our own work [13] investigated the pricing of Internet connectivity services in the context of a monopoly or competitive ISP market selling broadband access to consumers. It provided a systematic framework to analyze revenue maximization for a monopoly ISP operating a single bottleneck link with fixed capacity. Flat pricing is generally viewed as consumer friendly [1], but it could also be a significant factor in loss of consumer net-utility when the consumers have low price sensitivity. At the same time, access ISPs face a mismatch between their revenue from total usage and cost incurred from peak usage of networks. Our analysis in [13] revealed that the ISP can manage the mismatch and retain the revenue through a combination of *low usage fee* and *a high flat fee*, and by dropping packets of consumer demanded data that exceed available capacity. However, ISPs face regulatory hurdles, including "network neutrality" concerns [24], [33], that do not encourage congestion management through packet drops.



(a) (b)

Fig. 1. (a): Revenue loss from pricing based congestion management plotted against spread of consumer utility levels over time, and inverse of consumer price elasticity; (b): ISP revenue under uniform pricing (Π_r) and non-linear pricing (Π_n) compared to unrestricted pricing (Π_u)

An alternative approach for the ISP is to manage congestion through sufficiently high usage component in access prices. We show in [13] that this results in a revenue loss that is higher if the consumers are highly price sensitive as demonstrated in Figure 1(a).

Regulatory attention further discourages ISPs from practicing price discrimination across consumers. We show in [13] that the revenue loss from imposing uniform pricing across flows is higher if consumers are less price sensitive. The revenue loss can be mitigated if the ISP can offer prices non-linear in data-volume or data-rate consumption, with discount on higher data-rate demand. The choice of data consumption is left to the consumer, thus preventing explicit price discrimination among consumers. We use methods related to “second-degree price discrimination” in economics to design the non-linear price and show that the recovery is less when consumer price sensitivity is low. The results are demonstrated in Figure 1(b).

In the following three subsections, we outline the research direction on differential pricing that is net-neutrality compatible, from three aspects: *What* to charge, *How* to charge, and *How much* to charge.

A. *What to Charge?*

With Internet applications and content increasingly driven by consumer demand and third-party developers’ offerings, ISPs are beginning to reposition the focus on their network assets. To better monetize their networks, ISPs can offer a wider variety of services other than the traditional bit-pipe connectivity.

The following is a listing of some of the services that ISPs can provide by leveraging their network assets:

- *Connectivity Service Differentiation*: The commonly provisioned best-effort service works well in the absence of congestion. When network capacity is limited, some forms of Internet content require differentiated connectivity options to assure a reasonable level of end-user experience.
- *Receipt Service*: ISPs can provision receipt services by indicating status of content delivery to the sending transmitter. The receipt service could be in the form of a feedback on average thruput rate and delay as in Real-Time-Control-Protocol (RTCP) or even a per packet delivery status. The transmitter can use the receipt service to adapt content for efficient utilization of the available connectivity service.
- *Package Service*: ISPs can offer a service where they take the ultimate responsibility for the delivery of content to the end-users. ISPs can resort to both content manipulation (e.g. Transcoding) and enhanced connectivity service provisioning to ensure good end-user experience of the content.
- *Network Information Service*: ISPs can offer generic network information service where they can share network related information enabling content providers and distributors to better judge the use of network resources for their content. The network related information could be macroscopic (e.g. network load, network topology) or microscopic (e.g. predicting channel conditions).

The discussion in the rest of the section will focus on connectivity service differentiation.

Quality of service (QoS) and differentiated connectivity service are concepts that are seemingly as old as the Internet. Several sophisticated resource provisioning mechanisms, including packet classification and scheduling algorithms, have been designed into networks in general and access networks in particular, enabling fairly elaborate service differentiation. While ISPs have pursued service differentiation as one way to avoid the “dump-pipe” or “bit-pipe” categorization of their networks, and researchers have pursued service differentiation for the rich variety of complex problems offered, there has been little adoption of service differentiation in practice. Service differentiation in practical access networks is typically limited to providing different peak data-rates. One reason for lack of wider adoption of service differentiation has been the economics of the service offering. Driven by the need to simplify end-user pricing, ISPs have rarely been able to extract differentiated payments for differentiated services from end-users.

A recent trend is an increasing ISP interest in generating revenue from an additional source by charging content and application providers under the two-sided pricing model [12]. Application and content providers have a stake in end-users' broadband connectivity service to ensure good end-user experience. In addition, they can better understand the need for differentiated connectivity, tailor-made to the requirements of their application and content. Further, content providers can better absorb the pricing complexities compared to end-users. The trend can facilitate adoption of service differentiation provided the pricing of differentiated services does not cause undue disruption in content economics.

A second trend is increasing expansion of Internet applications to the traditionally congested wireless access networks. Although availability of wireless capacity has considerably expanded over the past decade, so has the availability of wireline capacity. As Internet applications evolve to assimilate the expanded wireline capacities, providing an equivalent service over wireless requires service differentiation to ensure reasonable end-user experience. However, the need for service differentiation cannot translate into adoption unless due consideration is provided to the pricing of such differentiated services.

Previous works on the economics of service differentiation have focused more on simplification of pricing rather than of the complexities of service differentiation for ISP revenue maximization. One way to do away with the complexities of service differentiation is to assume equal rate allocation across users who share the available capacity. This problem is considered with zero usage fee in [4] under a wireless access link with variable capacity, where the transmission power allocation provides an additional degree of freedom to the ISPs. A modified version of the problem is analyzed in [28] for a specialized set of utility functions and fixed capacity under zero usage fee. A more complicated service differentiation is the "generalized metro-pricing" service in [28], where the available capacity is logically divided into many parts, and flat prices are announced for each class. Customers choose the class to join, and the capacity is equally divided between customers in a given class. The connectivity quality is implicitly better in service classes that are priced higher, as fewer users opt into such service classes.

One way to consider the economics of service differentiation is to first define the service classes without consideration of the economics, and then look into the appropriate pricing of the service classes. This has been the traditional approach in many of the existing works on pricing of connectivity services. Such an approach, however, can lead to unattractive economics, making the service unacceptable to either the ISP or the customers or both. We propose to consider optimization of key parameters of service differentiation *jointly*, with pricing with the economic objectives of both the ISP and the consumers directly taken into account.

The approach can be demonstrated by considering an illustrative example of creating a menu of strict priority connectivity service. Consumers are likely to obtain the service, provided that the net-utility, utility of the service taking into account the price paid, is non-negative. The economic incentive for an ISP is to maximize the overall revenue derived. Further, policy consideration dictates that consumers be given the option to join one of the service classes instead of the ISP categorizing the consumers. Consumers who join service class j are strictly prioritized over customers who join service classes $\{j+1, j+2, \cdots\}$. Data requirements of consumers in higher priority service classes are satisfied before lower priority service class customers are served. Let $\mathcal{F}_j(\{g_k, h_k\})$ be the set of consumer data flows in class j, as a function of the all service classes of flat fee $\{g_k\}$ and usage fee $\{h_k\}$. Consumers choose class j if the net utility from data consumption in class j is higher than that in all other classes. We have

$$\begin{aligned} \mathcal{F}_j(\{g_k, h_k\}) = \{f : u_f(x_f^j) - g_j - h_j x_f^j \geq 0, \\ u_f(x_f^j) - g_j - h_j x_f^j \geq u_f(x_f^k) - g_k - h_k x_f^k, k \neq j\} \end{aligned} \quad (1)$$

where $u_f(x)$ is the utility of consumer data flow f, and $x_f^k = {u'_f}^{-1}(h_k)$ is the data demand that maximizes consumers net utility at the price charged by the ISP for service class k. The problem of jointly determining pricing and service parameters for strict priority pricing can then be modeled:

$$\begin{array}{ll} \text{maximize} & \sum_j \sum_{f \in \mathcal{F}_j} (g_j + h_j x_f) \\ \text{subject to} & x_f = {u'_f}^{-1}(h_j), f \in \mathcal{F}_j \\ & \sum_{f \in \mathcal{F}_j} x_f \leq C - \sum_{f \in \mathcal{F}_1 \cup \mathcal{F}_2 \cup \cdots \cup \mathcal{F}_{j-1}} x_f, \forall j \\ \text{variables} & \{g_j, h_j, x_f\} \end{array} \quad (2)$$

where we have dropped the dependency of $\mathcal{F}_j$ on prices $\{g_j, h_j\}$ for notational simplicity. The ISP incentive of revenue maximization is incorporated into the objective, and the consumer net-utility is accounted for in the constraints. In addition to pricing of service categories, the capacity allocation to different service classes is derived from the problem solution. The ISP is assumed to have complete pricing power in the formulation above. The other extreme would be a competitive ISP market where the problem formulation is game-theoretic instead of an a single optimization problem. The problem formulation can be generalized to other forms of service differentiation, including relative priority and probabilistic delay assurance, to answer the following key questions:

Q1: Can feasible prices and optimal service parameters be determined in practice through the data collection outlined in Introduction? What are the feasible prices for a given form of service differentiation (e.g., strict priority, weighted priority, relative priority) under given ISP market conditions (e.g., monopoly, oligopoly, competitive)?

Q2: What are the optimal service parameters (e.g., number of classes, capacity partitioning etc.) as a function of consumer utility functions and ISP cost structure that result in compatibility of ISP and consumer economic incentives?

B. How to Charge?

The ISP can charge the consumers in a variety of ways. We consider four different kinds of pricing schemes: metered, flat price, flat up to a cap, and cap then metered. "Metered" implies that a user is charged in proportion to the usage (e.g., [17], [32]). "Flat rate" is a fixed amount of charge irrespective of the usage (e.g., [28]). If a maximum usage is predetermined according to a flat price, and a user is not allowed to exceed the limit, that is called "Flat up to a Cap." "Cap then Metered" means that a user pays a flat price up to a predetermined volume of traffic beyond which the user is charged in proportion to the usage (e.g., [13], [25]). We further consider two types of payment options: prepaid vs postpaid, which is determined based on the time instance of service purchasing, and distinguish differentiated pricing vs. non-differentiated one, where "differentiated" means charging based on time of the day or congestion condition. This leads to altogether 16 possible combinations. Many of these are practiced by ISPs, but except few notable exceptions, like "nondifferentiated metered pricing with postpaid option" (e.g, [16], [20], [29]), their impact on ISP revenue, user utility, and surplus distribution among the entities have not been rigorously characterized.

Furthermore, users do not spread their traffic intensity evenly over 24 hours a day and 7 days a week. ISPs are inevitably torn between peak hour congestion and quiet hour overprovisioning. As a special case of traffic regulation functions, pricing incentives can help a more even spreading of the aggregate traffic via users self-interest. Congestion-based price has been originally used in transportation management to spread the traffic demand over the time: [7], [31] provided theoretic analysis for this traffic demand spreading problem and proved the existence of the equilibrium state, [6], [11] presented experimental results and public's responses for the congestion-based price. The concept of congestion pricing also appeared in electricity market [8], which coordinates the mismatch between the electricity demand and provisioning level. Open problems are as follows:

Q3: How to choose among different pricing models (or combination of pricing models) for provisioning broadband access to under-served broadband customers by considering different demographics? Should ISP carry out a location-differentiated pricing?

Q4: From ISPs' perspective, how to choose among different pricing models (or combination of pricing models) for provisioning different service packages? For example, ISP can use flat model to charge the general broadband access but without any premium services like online-game and HDTV recorder.

C. How Much to Charge?

As traffic demand grows rapidly, especially in the access network, usage-price has become more attractive to ISPs; it not only serves as a charging scheme but also is an efficient scheme for traffic management [2]. Regulators also recognize the importance of usage-price for traffic management [3]. However, in realizing usage-price, practical billing system and transaction cost restrict the frequent update of price strategy, which implies that ISP's practical pricing strategy is actually "time-constrained". This results in a mismatch between ISP's "time-constrained" pricing strategy and end user's "time-varying" traffic demand. Our recent work [13] identified two extreme cases under the time-constrained pricing strategy. One is that ISP can aggressively set a low usage-price and then drop end users' excessive traffic demands. Then, ISP can obtain the maximum revenue that is same as in the case without time-constrained pricing. The downside is that ISP has to drop packets of end users' traffic demands, which in turn may cause QoS deterioration [18], [34]. The other case is that ISP can conservatively set a high usage-price so that end users' aggregate traffic demands are less than the access link's capacity. The downside is that ISP may suffer revenue loss due to the inefficient use of its access link capacity.

A tradeoff exists between these two extreme cases [14]. How does the ISP optimally determine its usage and flat price for each end user in order to maximize the revenue? Let σ_f^t be the utility level at time t for flow f, and h and g be flat and usage prices, respectively. A general rate dropping constraint is as follows:

$$\sum_{t\in\mathcal{T}_q} \max\left(D_f(\sigma_f^t, h_f, g_f) - x_f^t, 0\right) \le \Gamma_f^q, \forall f\in\mathcal{F}, q\in\mathcal{Q} \quad (3)$$

i.e., during each specified time period $\mathcal{T}_q$, the gap between flow f's traffic demand $D_f(\sigma_f^t, h_f, g_f)$ and rate allocation x_f^t cannot exceed the specified threshold Γ_f^q. With this insight, questions of interests can be:

Q6: What is the optimal pricing strategy (including both the usage-price and flat-price) for ISP's revenue maximization under the general rate dropping constraint? What is the trade-off between ISP's revenue maximization and end-user's QoS deterioration, and what is the impact of user's price elasticity on this revenue-QoS deterioration tradeoff?

Q7: Data collection help model customers' traffic demand pattern (e.g., the pattern of the time-varying utility level σ_f^t) as well as ISP service tiers (e.g., price in each tier and capacity allocation across the tiers), which can be used as parameter inputs into our problem formulations. But what is the impact of the imperfect estimation of end-user's utility level, and what is the tradeoff between optimal-revenue and robust QoS protection?

Q8: What are the practical implementation methods of the rate dropping strategy (different time scales and the optimal rate dropping amount) under different user price elasticities?

III. Multi-Platform Two-Sided Pricing

In addition to being creative in charging the consumers, it is also important to study opportunities of ISP charging the providers of content and applications, which is the focus of this section.

A. Two-sided Pricing

Data exchange over a network is between entities hosting content and applications (content providers) and entities consuming the content and applications (end-users) as shown in Figure 2. The prevalent approach is to price end-user and content provider connectivity to the Internet separately, with no explicit consideration given to the value added from the end-to-end connectivity between the end-user and the content provider. This view point is increasingly being reconsidered to

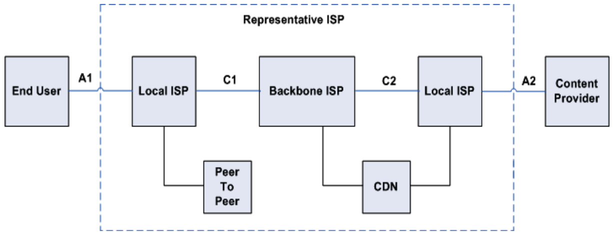


Fig. 2. ISP, End-User, Content Provider Interaction

explicitly value the connectivity between the content provider and the end-user, with pricing for connectivity appropriately split based on derived value. ISPs may also provide and charge for "hooks", such as network condition awareness, for content providers to provide better end user experiences. The content and connectivity industry each generate more than a trillion dollars in annual revenue and two-sided pricing can have a significant impact on the two industries.

Pricing content provider and the end-user jointly for their end-to-end connectivity can be studied under the "two-sided model" [27], which has been extensively studied in the economics literature in recent years. The two-sided model considers the content provider and the end-user as two sides that interact in a market enabled by the platform (in this case, the network) provider, the ISP. The price level in a two-sided market is the total price charged by the platform to the two sides interacting on the platform and the price structure refers to the split in the price level between the two sides. The total volume of the market in a two-sided model is determined by the price structure rather than the price level alone.

A useful result from a two-sided model is the realization that the price structure should reflect the extent of mutual benefits from interaction on the platform. The mutual benefit is modeled through network externality effects in [27] where the utility for each side is a function of the number of members on the other side. Content provider pricing models in [10], [23], [27] use this basic framework developed in [27] and analyze the appropriate price split between the two sides under various conditions on the platform market.

Our recent work [12] is a two-sided analysis of content provider pricing that models the benefits from the mutual interaction between the content provider and the end-user as dependent on the data rate of the traffic flow between the two entities. The work derives the price structure in a competitive ISP market and a monopoly ISP market. The work showed that net benefits generally increase for the all the entities involved with two-sided pricing. In particular, the content provider derives increased net benefit if the end user price elasticity is high and the cost of the connectivity is low. Followings are open questions:

Q9: Does data collected on price elasticity and utility level (on end users and on content providers) justify a case for two-sided pricing? What is the global change in content-provider and total surplus under two-sided pricing? What is the trade-off in benefits in the two-sided pricing model under alternate pricing models that are less flexible?

Q10: What is the trade-off in benefits in the two-sided pricing model when the end-user buys connectivity, along with content, from the content provider instead of the ISP?

B. *Multi Platform Revenue Splitting*

An end-to-end connection between a consumer and a content provider often passes through *multiple* ISPs. Since most of ISPs only concern about their own profits, one of the challenging problems in networking economics is how a group of ISPs carry out an efficient inter-charging mechanism so that the total profit of the offered Internet services can be maximized. Clearly, if each ISP only carries out a non-cooperative charging mechanism, then the total price faced by end-user may be very large, and thus adversely impact the potential demands. Recently, [15] investigated the profit loss with non-cooperative inter-charging and proposed a fair profit allocation strategy that can encourage collaboration among ISPs, and [19] studied a similar problem with Shapley value in cooperative game theory. However, there is a loss of social optimality.

In contrast, revenue-sharing supply chain model can provide a way for both the social revenue maximization of all ISPs on the same chain and the revenue sharing scheme among them after achieving the social optimality. For example, [9] investigated the "revenue-sharing contract": a retailer pays a supplier a wholesale price for each unit purchased, plus a percentage of the revenue the retailer generates. Aided with the appropriately designed revenue-sharing contract, different entities in the supply chain can be coordinated to maximize the entire chain's profit.

IV. Concluding Remarks

In this short survey we explored various topics in network economics focusing on enabling universal broadband coverage. We addressed the issue of differential pricing as a network management, specifically about what to charge, how to charge, and how much to charge. We also outlined research towards multi-platform two-sided pricing focusing on ISP charging the providers of content and application. Open questions in the paper suggest future research on network economics.

Finally, as in any scientific study, hypotheses must be validated (or falsified), and simple models refined, through a large volume of empirical data. In the case of network economics, accessing and gathering such data is often the *bottleneck difficulty* for an academic research team. For example, studies based on ISP data are rare because ISPs do not reveal their data sets to universities, e.g., customers' usage pattern, take rate, application demand, network utilization, capacity cost, etc., although such information is essential for understanding network economics. As another example on user models, since the 1990s, utility functions have been widely used [35]. Yet, with few exceptions like MOS score for voice applications, shapes of these functions are not discovered out of user behavior data.

We are currently collaborating with *National Exchange Carrier Association (NECA)* which has many years of experience and strong capability in collecting and analyzing empirical data, through polling and surveying ISPs and other business entities like content providers. NECA was established by the

FCC in 1983 as a non-profit, member-funded association of more than 1200 rural local exchange carriers (RLECs), the vast majority of which have ISP subsidiaries, and it runs FCC's Access Charge Plan for local ISPs. NECA routinely conducts studies on their behalf to answer public policy questions from the FCC and Congress, such as how to define a minimum broadband speed, what geographic areas should be funded, what should be the effect of competition, should there be carriers of last resort with most-favored access to content, how should government support be linked to access reform, should landline or wireless networks receive more funding, should the government fund networks or individuals, and should government aid Americans without computer training to boost take rates.

Together with the modeling and analysis work, as well as implementation of network measurement and user interface in support of the design, our research team (at the Princeton EDGE Lab http://scenic.princeton.edu, at NECA, and other collaborators such as Junshan Zhang and Yung Yi) will go all the way from data collection through mathematical analysis to practical impact on FCC policy decisions and ISP business decisions, thus closing the loop in the study of network economics for universal broadband coverage.

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