2015 IEEE 14th International Symposium on Network Computing and Applications

Secondary Market Mobile Users for Internet Access

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Abstract — There is a fast growing number of public spaces offering Wi-Fi access to meet the rising demands for the Internet. It is common for such service to be offered to users at no charge or for a flat fee. Both situations provide very little incentive for Wi-Fi providers to offer better service to the users. Similarly, Wi-Fi providers pay a monthly flat-rate to ISP for Internet access, which does not incentivize ISP to offer better service to Wi-Fi users. As a result, Wi-Fi users may experience poor Internet connection when network becomes congested during peak hours. In this paper, we propose a dynamic pricing mechanism for both ISP and Wi-Fi providers in order to give mobile Wi-Fi users better service, while providing economic incentive for both ISP and Wi-Fi provider.

***Index Terms* - Dynamic Pricing, Network Economics, Wireless Network, Wi-Fi.**

I. Introduction

In the recent decade, wireless local area network technology (e.g. Wi-Fi) has become essential to our everyday activities including communication, commerce, entertainment, education, etc. To cater to the rising demand for Internet access, there is a growing number of public spaces offering Internet access, such as malls, airports, coffee shops, libraries, parks, etc. The Internet access providers in those spaces are referred to as Wi-Fi providers (WFP). As this paper is written, WFPs commonly offer Internet access service free-of-charge or for a flat price. For example, a hotel charges their guests $5 per day for Internet access. Both free-of-charge or flat-fee arrangements offer little economic incentives for WFPs to offer additional bandwidth to their users when they need more bandwidth. This is because WFPs do not gain additional reward for providing better service to their users and this may result in users being stuck with the default service offered by WFP.

WFPs rely on Internet Service Providers (ISP) for the Internet access and pay ISPs a monthly flat-rate for the service. This means that ISPs are also responsible for the traffic generated by Wi-Fi users through WFP. Similarly, due to the arrangement of monthly flat rate, there is also very little incentives for ISPs to provide additional bandwidth to Internet users of WFPs. The study in [1] reports that Starbucks' customers experience poor connection whenever there is a large amount of customers in a coffee shop using the Internet at the same time. While the customers enjoy their drinks, they may be dissatisfied with the Internet access service quality.

In this paper, we argue that dynamic pricing provides economic incentives to both ISP and WFP (unlike flat rate and free service) to offer additional bandwidth to their users. Following this argument, we design a dynamic pricing model that incentivizes both ISP and WFP to provide additional bandwidth. Our pricing model is built upon two considerations. The first consideration is that dynamic pricing may fluctuate according to the level of bandwidth demand. Thus, ISP decides the minimum sale price by considering the total traffic load generated by the WFP as well as those generated by ISP's other subscribers (not through WFP). Similarly, a WFP computes the price to its users according to service demand level, i.e. price increases as the level of demand increases. The second consideration is that the final price charged to WFP's users must be equal or higher than the minimum price set by ISP. This is because the final price should cover at least ISP's minimum price. For instance, when the minimum price set by ISP is higher than the price set by WFP, WFP charges their users with the price set by ISP. Importantly, our study shows that this pricing model provides incentive for both ISP and WFP to offer additional bandwidth to their users. The pricing model follows the economic principle on demand and supply, that is, WFP generates higher revenue when demand for access increases. We formulate those model and frameworks into a Network Utility Maximization (NUM) problem [2,3,4], which can be solved through a subgradient based algorithm. In other words, the ISP's and WFP's prices are obtained from the solutions to the NUM.

The rest of this paper is organized as follows. We begin by formulating the problem in section II where we discuss the related works, the impact on ISP, and different types of pricing. Following that, we present the dynamic pricing mechanism for both WFP and ISP in section IV. The simulation results are presented in section V, followed by concluding remarks.

II. Background

A. Free Service, Flat-rate, and Dynamic Pricing

In order to decide which pricing mechanism is appropriate to provide additional bandwidth, we first explore the tradeoffs between free service, flat-rate, and dynamic pricing. Free Internet access is commonly employed by WFPs to entice

978-1-5090-1849-9/15 $31.00 © 2015 IEEE
DOI 10.1109/NCA.2015.13

customers to boost their business sales. For example, a coffee shop offers free Wi-Fi to attract more customers to come and linger, with the objective of achieving higher sales per customer. However, a WFP has very little incentive to provide additional bandwidth to its customers because it does not gain additional benefit from users enjoying good service, especially when good service has little direct impact on increasing the sale of their primary product/service. Similarly, flat-rate pricing strategy for Internet access also provides little incentive for a WFP to offer additional bandwidth. For example, a hotel guest may pay a daily flat-rate ($10 per day) during his/her stay, thus, providing better service does not increase the hotel's revenue because the guest still pays the same rate regardless of the quality of the connection. By the same token, there is little incentive for an ISP to offer additional bandwidth if a WFP pays a flat-rate to the ISP. As a result, without the ISP's support for providing additional bandwidth, the WFP may not be able to offer additional bandwidth even if it desires to.

Dynamic pricing is a usage-based pricing strategy where users pay according to how much bandwidth they use. This pricing model may provide more incentive to a WFP to offer additional bandwidth because users can and must pay more for a better connection quality, which leads to higher earning for WFP. This pricing strategy can also be used to avoid congestion when there is more demand than available bandwidth. In such a situation, a WFP increases the price to reduce traffic load. Therefore, dynamic pricing not only offers more opportunity for higher revenue, it also gives a WFP better control over traffic. Similar arguments apply to an ISP on the employment of dynamic pricing to support providing additional bandwidth to WFPs and their end users.

B. Related Work

In [1], the authors propose a pricing strategy based on *online mechanism design* to provide Wi-Fi service to Starbucks' customers. Their pricing strategy is designed on the basis of users dynamically arriving at and leaving a coffee shop in a period of time, and considers that users make certain decisions based on certain outcomes as time progresses. For instance, a customer may decide to leave the shop after he/she has finished his/her drink, or to stay longer for more drinks. In addition, their pricing strategy also requires users to reveal their true valuation on the Internet access and their arrival time at the coffee shop. Our proposal, on the other hand, does not require users to reveal their valuation of the service to a WFP, and Wi-Fi price is determined according to network traffic and is available after users start transmitting data. Our approach provides more flexibility, and the price in our scheme can be updated dynamically in real time. Furthermore, the role of an ISP is not incorporated in the design in [1]. Our model, on the other hand, allows an ISP to influence WFP's pricing, especially when ISP is experiencing high traffic demand.

IV. PRICING MODEL

In this section, we introduce an ISP's pricing to a WFP and the WFP's pricing to user. The WFP computes its *WFP's price* λ_s, and determines the *final sale price* λ_s^f, formulated as

$$\lambda_s^f = max(\lambda_s, g_s + \rho),$$

where ρ denotes a constant minimum profit decided by the WFP, for $\rho \geq 0$. Then, the WFP presents price λ_s^f to user s and user s pays the WFP at price λ_s^f. Furthermore the ISP decides the minimum sale price g_s to support user s and at the same time the WFP also decides the its own price λ_s to user s. Then, user s pays the service at price λ_s^f. The pricing mechanism also considers multiple users at any point of time. We begin by first addressing WFP's price to user.

A. Wi-Fi Provider's Price

Let S_w denotes a set of user s using the Internet, for $s \in S_w$. The objective of user s is to solve

$$max\, U(x_s, \lambda_s^f), \quad \text{for } x_s, \lambda_s^f \geq 0, \tag{1}$$

where x_s denotes the amount of data usage by user s and λ_s^t denotes the price to be paid by user s for Internet access at time t. The price is dynamically determined according to the level of demand for network service. The utility function of the user is defined as follows.

$$U(x_s, \lambda_s^f) = U_{bw}(x_s) + U_{cost}(x_s, \lambda_s^f),$$

where $U_{bw}(x_s)$ and $U_{cost}(x_s, \lambda_s^f)$ denote user s utilities relating to bandwidth consumption x_s and service cost, respectively. Considering that the WFP operates at frequency band B_s, the utility of bandwidth usage is defined as follows

$$U_{bw}(x_s) = W_s \log\left(x_s\left(1 + \frac{P_s\,|c_s|^2}{\partial_s^2\, B_s}\right)\right),$$

where P_s is the transmission power of user s mobile device, c_s is the channel gain from WFP w to user s, and ∂_s^2 is the Gaussian noise variance for the channel between w and s [14]. In other words, $U_{bw}(x_s)$ is influenced by the channel quality and the amount of bandwidth. Additionally, $U_{bw}(x_s)$ follows the law of diminishing return, as more bandwidth does not always mean higher satisfaction and SNR measurement for wireless is concave [14].

Utility function $U_{cost}(x_s, \lambda_s^f)$ represents user satisfaction for monetary surplus when the cost paid for Internet access is less than the budget, which is defined as follows.

$$U_{cost}(x_s, \lambda_s^f) = 1 - \frac{x_s\,\lambda_s^f}{m_s},$$

where m_s denotes the budget that user s is willing to spend for bandwidth x_s. Note that $x_s\,\lambda_s^t$ can be interpreted as the price that user s must pay for the service. Ideally, a user's budget matches the price that he/she must pay for the service, such that $\frac{x_s \lambda_s^f}{m_s} = 1$ and hence $U_{cost}(x_s, \lambda_s^f) = 0$. Therefore, given final price λ_s^f, user s utilizes m_s to influence the amount of bandwidth x_s allocated to him/her.

The objective of WFP w is to maximize its own revenue without exceeding its monthly bandwidth capacity. The maximization problem is expressed as follows.

$$max \sum_{s \in w} x_s \lambda_s^f, \tag{2}$$

$$s.t. \sum_{s \in w} x_s \leq C_w,$$

$$over\ x_s \geq 0, \ \forall s \in w,$$

where $s \in w$ denotes that user s receives from w, and capacity C_w is the WFP's bandwidth capacity. Considering the objectives of the user and the WFP at the system level, we derive the following network utility maximization (NUM), following a similar approach in [2].

$$max \sum_{s \in w} U(x_s, \lambda_s^f) \tag{3}$$

$$s.t. \sum_{s \in w} x_s \leq C_w,$$

$$\text{over } x_s \geq 0, \ \forall s \in w.$$

In this formulation, the solution to problem (3) also solves problem (1) and (2). The Lagrangian optimization problem is formulated as

$$L(\bar{x}_s, \bar{\lambda}_s) = \sum_{s \in w} U(x_s, \lambda_s^f) - \sum_{s \in w} x_s \lambda_s + \sum_{s \in w} \lambda_s C_w,$$

where $L(.)$ is the Lagrangian form and λ_s is known as the Lagrangian multiplier, which is often interpreted as link price, and $\bar{x}_s$ is a vector of x_s, for $\forall s \in w$, and $\bar{\lambda}_s$ is a vector of λ_s. The common solution to a NUM problem is the subgradient based method [3]. Typically, the dual problem D to the primal problem is constructed as follows $\min D(\bar{\lambda}_s)$, $s.t\ \bar{\lambda}_s \geq 0$, where the dual function

$$D(\bar{\lambda}_s) = \max_{0 \leq \bar{x}_s \leq x^{max}} L(\bar{x}_s, \bar{\lambda}_s).$$

To solve $D(\bar{\lambda}_s)$, user s maximizes over x_s given λ_s. That is

$$x_s = \arg\max_{0 \leq x_s \leq x_s^{max}} \left(U(x_s, \lambda_s^f)\right)$$

Next, $L(\bar{x}_s, \bar{\lambda}_s)$ is minimized with subgradient projection method in an iterative solution given by

$$\lambda_s = \left[\lambda_s - \sigma^t \left(C_s - \sum_{s \in w} x_s\right)\right]^+, \tag{4}$$

where $C_s - \sum_{s \in S} x_s$ is a subgradient of $D(\lambda_s)$ and σ^t denote the step size to control the tradeoff between convergence guarantee and convergence speed, such that

$$\sigma^t \rightarrow 0, as\ t \rightarrow \infty\ and \sum_{t=1}^{\infty} \sigma^t = \infty. \tag{5}$$

Next, after solving λ_s, then we solve for λ_s^f according to $\lambda_s^f = max(\lambda_s, g_s + \rho)$. Notice that, $g_s + \rho$ serves the minimum price charged to user s, such that $\lambda_s^f \geq g_s + \rho$. The subgradient based solution relies on feedback loop mechanism. That is, the user determines the transmission rate according to the price set by WFP by solving (3) and the price is adjusted according to the traffic load by solving (4). It is repeated until it converges to an optimal solution. Price λ_s is also an indication of the demand for service. However, before determining the final sale price, the WFP must consider the minimum price charged by the ISP according to $\lambda_s^f = max(\lambda_s, g_s + \rho)$. This is because WFP depends on ISP's infrastructure to provide the service to users.

B. Minimum Price by ISP

Here, we address how an ISP determines the minimum price for bandwidth. Consider a network managed by an ISP with a set of links L, and a set of link capacities C over the links in L. Given a utility function $U_s(x_s, \lambda_s^f)$ of user s, the user's maximization problem can be formulated as follows.

$$max \sum_{s \in S} U(x_s, \lambda_s^f) \tag{6}$$

$$s.t. \sum_{s \in S} x_s \leq C_l,$$

$$\text{over } x_s \geq 0.$$

Here, users in set S include all users who get Internet service from those WFPs that supported by the ISP. To solve problem (6), the ISP determines the minimum price to sell on each link l by solving

$$g_l = \left[g_l - \sigma^t \left(\left(C_l - \sum_{s \in S} x_s\right) - \sum_{s \in l} \sum_{s \in w} x_s\right)\right]^+. \tag{7}$$

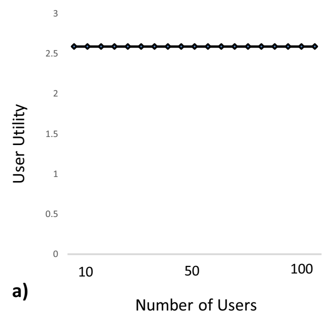
Here, $s \in l$ denotes user s who transmits data through link l. The total *minimum price* to charge user s is

$$g_s = \sum_{s \in l} g_l, \forall s, s \in w.$$

Since the speed of the convergence is determined by step size σ, the running time required to obtain convergence also depends on the value of σ. Higher value of σ increases the speed of convergence but the risk is that the algorithm may not converging. Similarly, lower value of σ decreases the convergence speed but increases the convergence guarantee.

V. Simulation and Discussion

Our simulation setup includes a WFP providing 1000MB/sec to users with initial minimum price charged by an ISP of 10 units currency, the minimum profit desired by a WFP is 5 units currency, users' minimum willingness to pay is 100 units currency, and user utility is measured using the utility function described before.



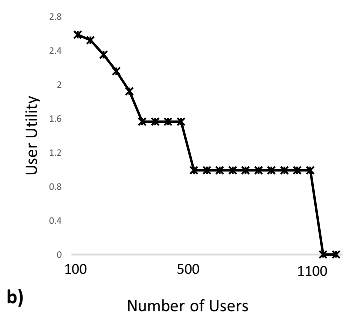


Figure 1. (a) Average user utility when the demand for bandwidth is *low*. (b) Average user utility when the demand for bandwidth is *high*.

In the simulation, we consider two case studies: (1) When a WFP experiences *lower* and (2) *higher* demand for bandwidth. **Case 1.** There are 10 to 100 users acquiring service from the WFP. Figure 1(a) demonstrate that users' average utility is stable when there is sufficient bandwidth for users. That is when the total bandwidth usage of 100 users is only 700 MB/sec < 1000 MB/sec. **Case 2**: There are 100 to 1100 users subscribing from the WFP. The steep incline depicted in Figure 1(b) shows that user utility decreases as the price increases, when user demands for bandwidth exceed capacity limit. This results in users obtaining less bandwidth for higher price. In summary, a WFP must strike the balance between attaining a higher revenue and being able to meet users' demand for Internet service.

VI. Conclusion

In this paper, we introduce a dynamic pricing strategy to provide incentives for ISP and WFP to offer additional bandwidth to their users. We demonstrate that a WFP must strike the balance between attaining a higher revenue and being able to meet users' demand for Internet service. Otherwise users may be dissatisfied with the service. In our future work, we will investigate whether the economic interplay and negotiation between ISP, WFPs, and users can reach an equilibrium; and if it does, we will investigate the impacts of revenue sharing mechanisms.

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