Regulating Network Traffic by Exploiting the Price Elasticity of Demand in Wireless Random Access Networks

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***Abstract*—In this paper, pricing is adopted as incentive mechanism to encourage users to choose their access probabilities considering the real-time network congestion level in a contention-based wireless random access network. A Stackelberg leader-follower game is formulated to analyze the competitive interaction between the service provider and the users. In particular, each user chooses the access probability to optimize its payoff, while the self-interested service provider decides whether to admit or reject the user's connection request in order to optimize its revenue. The stability of the Stackelberg leader-follower game in terms of convergence to the Nash equilibrium is established. The proposed CAC scheme is completely distributed and can be implemented by individual access points using only local information. Compared with the existing schemes, the proposed scheme limits the amount of traffic admitted into the network and achieves higher QoS performance without decreasing the total revenue of the service provider.**

***Keywords*—CAC, Stackelberg game, backward induction, pricing, wireless random access network**

I. INTRODUCTION

We consider a wireless random access network that adopts a slotted-Aloha like MAC protocol. When multiple users transmit packets simultaneously, their packets collide and have to be dropped. The dropped packets must be retransmitted later. The users contends for channel access according to their user-chosen access probabilities. QoS differentiation is achieved in such a way that users with high access probabilities transmit more often than those with low access probabilities [1].

The number of existing users is denoted by n, and the access probabilities chosen by the existing users are denoted by $x_i, i \in \{1, ..., n\}$. Moreover, let x be the access probability chosen by the incoming user. Since a transmission is successful if and only if there is a single transmission attempt at that time, the saturation throughput (rate of success) of the incoming user is given by τ as follows.

$$\tau = x \prod_{i=1}^{n} (1 - x_i) \tag{1}$$

User demand is assumed to be *elastic* [2], and the utility of the incoming user is given by U as shown in Eq.(2).

$$U = \theta \ln(1 + \tau) \tag{2}$$

where θ is a user-dependent scale factor and can be thought of as a parameter representing the priority of the incoming user's willingness to pay.

In such contention-based wireless networks, users always act selfishly without considering the overall resource utilization and performance. As studied in [3], if each user tries to occupy the channel as much as possible, the overall saturation throughput decreases dramatically. Incentive mechanisms are hence essential for users to voluntarily cooperate with each other to improve the overall resource utilization and performance.

A simple pricing scheme is therefore adopted to dynamically regulate the network traffic by exploiting the elasticity of demand with respect to price [4]. In particular, we assume that each user pays a price per unit time that is proportional to the value of the access probability. Namely, the price per unit time is set to be px for the incoming user, and px_i for the existing users $i \in \{1, 2, ..., n\}$, where the rate of charge p is a constant.

Applying the access-probability-based pricing, the payoff for the incoming user is given by

$$S(x) = \theta \ln \left[1 + x \prod_{i=1}^{n} (1 - x_i) \right] - px \tag{3}$$

$$\text{subject to} \quad 0 \leq x \leq \beta \tag{4}$$

where $\beta \in (0, 1)$ is the maximum value of access probability that a user can choose.

II. STACKELBERG LEADER-FOLLOWER GAME AND NASH EQUILIBRIUM SOLUTION

A Stackelberg leader-follower game is formulated to analyze the competitive interaction between the service provider and the users. We assume that the service provider and the users are rational in the sense that they are fully aware of their alternatives, have clear preferences, and take action in order to maximize their payoffs [5]. The Stackelberg leader-follower game, Γ(**Player, Strategy, Payoff**), is described as follows:

- **Player**: The service provider and each incoming user are the players of this game. Specifically, the service provider is the leader and the incoming user is the follower.
- **Strategy**: For the incoming user, the strategy is the selection of access probability; and for the service provider, the strategy is the decision on whether to admit or reject the connection request.
- **Payoff**: For the service provider, the payoff is the corresponding revenue; for the incoming user, the payoff is the net utility as shown in Eq.(14).

Steps involved in QoS negotiation and CAC [6] are summarized as shown as follows.

- An incoming user arrives at the network, and detects the existence of APs via periodically broadcasted beacons, which contains: rate of charge p and the access probability of each existing user (i.e., the congestion-indication signal).
- The incoming user tries to begin a session by initially sending a Service Level Specification (SLS) packet, which contains: the access probability (i.e., x). Note that the incoming user can specify the expected saturation throughput instead, since there is a direct correspondence between the access probability and the expected saturation throughput.
- The rational service provider admits the connection of an incoming user as long as the revenue growth from the incoming user is enough to compensate for the revenue loss incurred by the quit of existing users.

Assumption 1. *Each existing user adopts a myopic strategy [7], i.e., the user remains connected if the price charged is less than its utility, otherwise the user rejects the price and leaves;*

Assumption 2. *The stay duration of each user follows an exponential distribution;*

Assumption 3. *The service provider is a risk-averse decision maker, namely, without the complete information about user i's preference (i.e., θ_i), the service provider uses the lower bound value $\left[\frac{1}{\prod_{j=1}^{n_i}(1-x_j)}+\beta\right]p$ to estimate θ_i.*

Lemma 1. *The following strategy profile is a Nash Equilibrium.*

1) The incoming user chooses the access probability

$$x=\begin{cases}0, & \text{if } \theta\ln\left[1+x\prod_{i=1}^{n}(1-x_i)\right]<px\\[2ex] \max\left[0,\min\left(\beta,\frac{\theta}{p}-\frac{1}{\prod_{i=1}^{n}(1-x_i)}\right)\right], & \text{otherwise}\end{cases}$$

2) On the other hand, the service provider admits the connection of the incoming user if and only if

$$x>\sum_{\left[\frac{1}{\prod_{j=1}^{n_i}(1-x_j)}+x_i\right]\ln\left[1+x_i(1-x)\prod_{j=1,j\neq i}^{n}(1-x_j)\right]<x_i} x_i$$

TABLE I. A SUMMARY OF THE SIMULATION SETTINGS.

Arrival rate	10 per hour
Average stay duration	1 hour
Raw bit rate	11 Mbps
Priority of willingness to pay (θ)	[0, 1000]
Access probability (x)	[0, β]
Rate of charge (p)	100

Proof: The proof is omitted due to space limitations. ■

III. SIMULATION RESULTS

Without loss of generality, we assume that users arrive according to a Poisson process and stay for a period, which is exponentially distributed. The priority of users' willingness to pay is uniformly distributed between 100 and α. Access probability is uniformly distributed between 0 and β. Each simulation lasts 10 hours, and is repeated for 10,000 times. Reasonably accurate results are obtained by taking average of all these repetitions. Detailed simulation settings are summarized as shown in TABLE I.

In order to explore the performance of the proposed scheme on QoS provisioning and the total revenue of service provider, we employ two existing schemes, i.e., *fixed* scheme and *threshold* scheme, for comparison. The distinctions are described as follows:

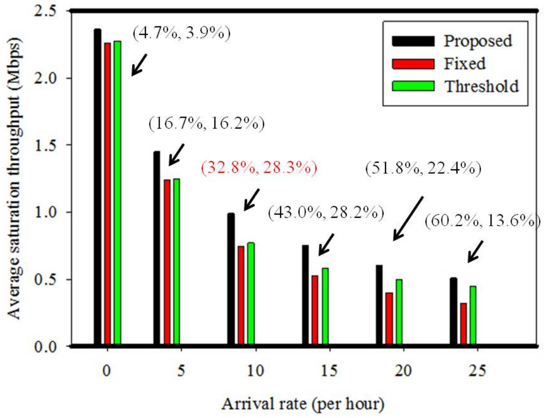
- In the fixed scheme, service provider admits all users straightforwardly.
- In the threshold scheme [8], service provider uses a threshold value m to admit or reject connection requests, where m is decided beforehand based on the average load of users' requests.
- In the proposed scheme, service provider examines the potential revenue loss dynamically before admitting an incoming user (Lemma 1. (2)).

In order to achieve a fair comparison, the same value of p, α, and β are selected for the three schemes. In particular, p, α, and β are set to 100, 150, and 0.5, respectively.

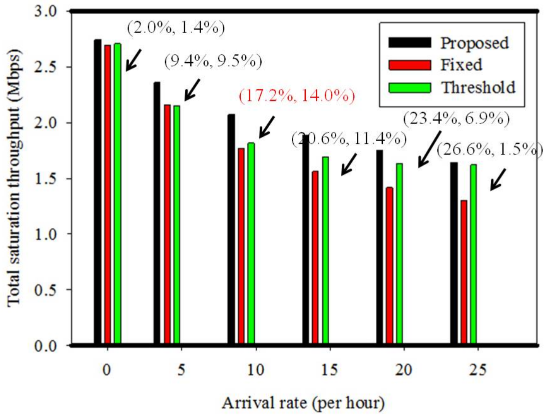
Figure 1 (a) and (b) show that the proposed scheme outperforms it counterparts in terms of QoS provisioning. For instance, when the arrival rate is set to 10 users per hour, the average saturation throughput per user is increased by 32.8% and 28.3%; meanwhile, the total saturation throughput is increased by 17.2% and 14.0%, respectively, compared with that of the fixed scheme and threshold scheme.

Figure 2 (a) shows that the proposed scheme generally outperforms its counterparts in terms of increasing the average revenue. Figure 2 (b) shows that the proposed scheme performs better in terms of increasing total revenue compared with the threshold scheme. However, the improvement is very limited. On the other hand, compared with the fixed scheme, the proposed scheme shows at most comparable performance in terms of increasing the total revenue.

The results shown in Fig.2 (b) are not surprising, because the total revenue depends on two factors: (i) the number of admitted users; and (ii) the average revenue. The proposed scheme tends to reject connection requests to provide the existing users with a higher level of QoS, and hence retrieve

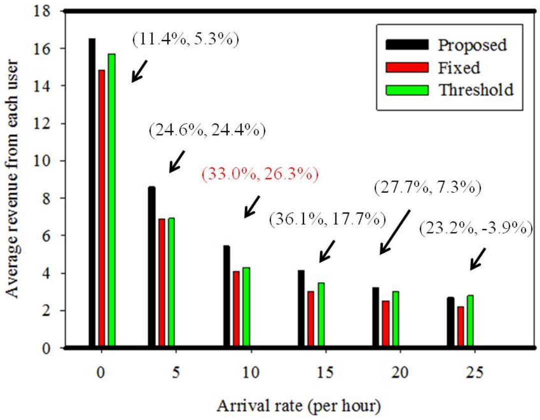


(a) Average saturation throughput vs. arrival rate

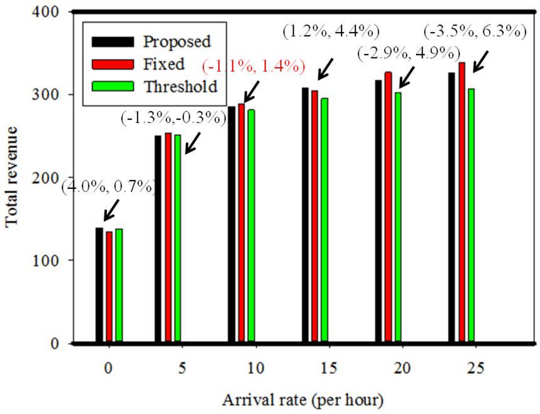


(b) Total saturation throughput vs. arrival rate

Fig. 1. Comparison between the proposed scheme and the existing schemes in terms of the saturation throughput.



(a) Average revenue vs. arrival rate



(b) Total revenue vs. arrival rate

Fig. 2. Comparison between the proposed scheme and the existing schemes in terms of the revenue.

a higher reward from each user. In other words, the proposed scheme benefits the existing users with higher network utility by rejecting the incoming users with lower network utility.

IV. CONCLUSIONS AND FUTURE WORK

In this paper, a Stackelberg leader-follower game structure is applied to obtain the equilibrium of network resource sharing between the service provider and the users. The game is composed of three steps: (i) the service provider predefines a pricing scheme and provides congestion-indication signals for users; (ii) an incoming user chooses the access probability to optimize the payoff, namely, the best response strategy; (iii) based upon the best response strategy, the service provider then decides whether to admit or reject the user's connection request. The simulation results show that the proposed scheme achieves higher total saturation throughput without decreasing the total revenue gain when compared with the best existing schemes.

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