Distributed Connection Admission Control Integrated with Pricing for QoS Provisioning and Revenue Maximization in Wireless Random Access Networks

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***Abstract*—This paper studies the impact of connection admission control (CAC) on the congestion management practices and the revenue of a monopoly access point (AP). The AP provides congestion-indication signals that suggest users to choose their access probabilities in response to network loading conditions. A Stackelberg leader-follower game is then formulated to analyze the interaction between the AP and the users. In particular, the AP first estimates the probable utility degradation of existing users consequent upon the admission of an incoming user. Second, the AP decides whether the connection of the incoming user should be admitted or not. The proposed CAC policy is completely distributed and can be implemented by individual APs using only local information. Simulation results show that the proposed algorithm achieves higher saturation throughput as well as greater revenue gain when compared with an existing algorithm.**

I. Introduction

In an wireless network, an incoming user means a potential gain to the network revenue due to the improved resource utilization. On the other hand, the incoming user may cause congestion and degradation in Quality of Service (QoS) provided for the existing users. In case that the utility decreases below the price charged, an existing user may reject the price and leave, which in turn results in a loss to the network revenue.

The purpose of CAC is to limit the amount of traffic admitted into a particular service class so that the QoS of the existing users will not be degraded, while the radio resources (e.g., bandwidth) can be efficiently utilized. Therefore, CAC policy can play an important role in both QoS provisioning and revenue maximization.

In [1], authors investigated the economic behaviour of wireless users under an assumption that the network has limited capacity. The authors proposed an algorithm that limits the AP to admit at most m users at a time, and devised the optimal pricing strategy for optimizing the network revenue. However, it is argued that the limitation is a little bit strong. For instance, if the admission of the "$m+1$"-th user would increase the overall revenue, there is no reason to think that the AP will reject the new connection.

In [2], [3], [4], the maximum number of users to be admitted in a wireless network is derived by solving the revenue optimization problem using linear programming. Then a threshold-based CAC policy uses the maximum number of users to admit or reject incoming users. However, in the above-mentioned models, the diversity in user information, such as type of request was not sufficiently considered.

In [5], [6], authors tried to obtain user information from surveys on historical data, and proposed CAC policies for maximizing the network revenue as well as the users' payoffs. However, these policies require that the AP has a global knowledge of each user's utility and are hence not practical.

In this paper, a Stackelberg leader-follower game is structured to analyze the interaction between the AP and each incoming user. An incoming user chooses an access probability so as to optimize her payoff (i.e., best response). Given the best response, the AP can derive the private utility information of the incoming user through backward induction, and estimate whether the revenue growth from the incoming user can compensate for the revenue loss incurred by the quitting of existing users. Then the AP decides whether the connection of the incoming user should be admitted or not. The proposed CAC policy is completely distributed and can be implemented by individual APs using only local information.

The remainder of this paper is organized as follows. Section II introduces the system model. Section III describes the users' behaviour when no price is charged and proves that the network can be easily overtaken without a proper pricing scheme. Section IV presents the access-probability-based pricing scheme. Section V describes the Stackelberg game structure and finds the Nash equilibrium solution to this game. Section VI shows the simulation results. Section VII concludes this paper.

II. System model

As depicted in Fig.1, the model we are envisioning assumes that each user communicates with a single AP directly. The users always have a packet available for transmission. Namely,

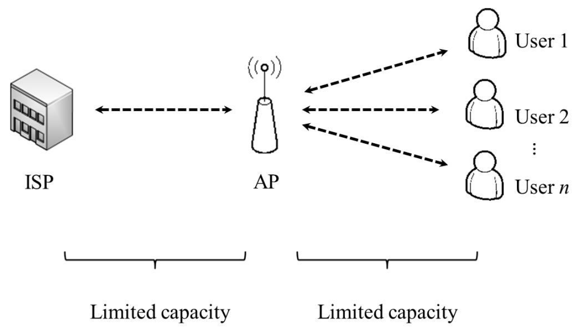


Fig. 1. System model.

the network is operated in saturation conditions. Each user contends for channel access according to some user-chosen access probability. A transmission is successful if and only if there is a single transmission attempt at that time. Hence, QoS differentiation is achieved when users with high access probabilities transmit more often than those with low access probabilities [7].

Let x be the access probability chosen by the incoming user. Moreover, there are n number of existing users, and the access probabilities chosen by the existing users are denoted by $x_i, i \in \{1, ..., n\}$. The saturation throughput 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* [8], and the utility of the incoming user is given by U as follows.

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

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 (WTP).

III. Users' Behaviour without Pricing

When there is no price to be charged, the payoff for the incoming user is given by $F(x)$ as follows.

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

Consider the following optimization problem
P:

$$\text{maximize} \quad F(x) \tag{4}$$

$$\text{subject to} \quad 0 \leq x \leq \beta \tag{5}$$

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

$$L(x, \lambda) = \theta \ln \left[1 + x \prod_{i=1}^{n} (1 - x_i) \right] + \lambda(\beta - x) \tag{6}$$

where λ ($\lambda > 0$) is a Lagrange multiplier. Take the partial derivative with respect to x

$$\frac{\partial L(x, \lambda)}{\partial x} = \frac{\theta \prod_{i=1}^{n} (1 - x_i)}{1 + x \prod_{i=1}^{n} (1 - x_i)} - \lambda \tag{7}$$

After applying stationarity conditions, it can be concluded that, at a maximum of L over $x \geq 0$, the following conditions hold:

$$\begin{cases} \frac{\theta \prod_{i=1}^{n}(1-x_i)}{1+x \prod_{i=1}^{n}(1-x_i)} = \lambda & \text{if } x > 0 \\ \frac{\theta \prod_{i=1}^{n}(1-x_i)}{1+x \prod_{i=1}^{n}(1-x_i)} \leq \lambda & \text{if } x = 0 \end{cases} \tag{8}$$

The first row of conditions (8) could be used to construct the dual of **P**. The objective function of the dual problem is thus

$$\begin{aligned} & H(\lambda) \\ & = \theta \ln \frac{\theta \prod_{i=1}^{n} (1 - x_i)}{\lambda} + \lambda \left[\beta + \frac{1}{\prod_{i=1}^{n} (1 - x_i)} \right] - \theta \end{aligned} \tag{9}$$

and the dual problem is
D:

$$\text{minimize} \quad H(\lambda) \tag{10}$$

$$\text{over} \quad \lambda > 0 \tag{11}$$

Let $\frac{\partial H(\lambda)}{\partial \lambda} = 0$ then

$$-\frac{\theta}{\lambda} + \beta + \frac{1}{\prod_{i=1}^{n} (1 - x_i)} = 0 \tag{12}$$

Since $F(x)$ is concave and the constraint (5) is linear, there is no duality gap between the primal and the dual problem. It can therefore be concluded that, at a maximum of $F(x)$ over $0 \leq x \leq \beta$, the following condition holds.

$$x = \beta \tag{13}$$

From Eq. (13), it could be concluded that each incoming user tries to occupy the channel as much as possible. As a consequence, the network can be easily overtaken by the incoming users, leading to the *tragedy of the commons* [9].

IV. Access-Probability-Based Pricing

To address the above-mentioned tragedy of the commons problem, a novel *access-probability-based* pricing scheme is employed. Each user pays a price proportional to the amount of the access probability. To be specific, the price is set to be px for the incoming user, and px_i for the existing users $i \in \{1, 2, ..., n\}$. Here p is a constant.

The AP cannot suspend the service as long as the user can keep paying; while the user can disconnect voluntarily. The service session ends at the first time the user rejects the AP's price proposal, including three cases:

- The user finds the price is too high to accept.
- The user's utility decreases below the price charged due to congestion.
- The user does not intend to connect any more.

Therefore, the price stays unchanged for each user, and is merely dependent on the user-chosen access probability. The overall payment charged grows proportionally with the time each user connects.

V. STACKELBERG GAME AND REVENUE MAXIMIZATION

In Economics, the Stackelberg game is used to analyze competition in an oligopoly market (i.e., a market dominated by a small number of suppliers). In such a market, a leader firm commits a strategy first and then other follower firms move sequentially. The equilibrium of this formulation can be obtained by backward induction. For the case of oligopoly competition in quantity, given the best response of each follower, the leader can choose the optimal supply quantity to gain the highest revenue [10].

This Stackelberg game structure is applied to obtain the equilibrium of bandwidth resource sharing between the AP and each incoming user. It is assumed that the AP and the user are rational in the sense that they are aware of their alternatives, have clear preferences, and take action deliberately after some process to maximize their payoffs. The Stackelberg game, Γ(**Player, Strategy, Payoff**), is described as follows:

- **Player**: The AP and the incoming user are the players of this game.
- **Strategy**: For the incoming user, the strategy is the selection of access probability; and for the AP, the strategy is the decision on whether to admit the connection or not.
- **Payoff**: For both the AP and the incoming user, the payoffs are the corresponding revenue and profit.

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

$$S(x) = \theta \ln \left[1 + x \prod_{i=1}^{n}(1-x_i)\right] - px \tag{14}$$

$$\text{subject to} \quad 0 \leq x \leq \beta \tag{15}$$

Take the first derivative of $S(x)$ with respect to x

$$S^{'}(x) = \frac{\theta \prod_{i=1}^{n}(1-x_i)}{1 + x\prod_{i=1}^{n}(1-x_i)} - p \tag{16}$$

As shown in Fig. 2, let $S^{'}(x)$ equal to 0.

$$x^* = \frac{\theta}{p} - 1 \tag{17}$$

If taking the second derivative of $S(x)$ with respect to x

$$S^{''}(x) = -\frac{\theta \left[\prod_{i=1}^{n}(1-x_i)\right]^2}{\left[1 + x\prod_{i=1}^{n}(1-x_i)\right]^2} < 0 \tag{18}$$

, which suggests that the function is concave down at x^*. Therefore, at a maximum of $S(x)$ over $0 \leq x \leq 1$, the following condition holds.

$$x = \begin{cases} 0 & \text{if } \theta \leq p, \\ \min(\beta, x^*) & \text{if } \theta > p. \end{cases} \tag{19}$$

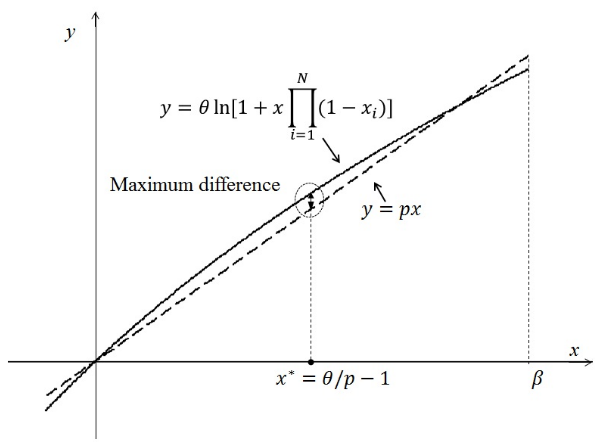


Fig. 2. Optimal access probability.

Now looking at the AP's side, without the exact knowledge about the incoming user's preference (i.e., θ), the AP has to make a decision based on the history of incoming user's choice (i.e., x). Specifically, the AP can obtain the θ through backward induction.

$$\theta \begin{cases} = (1+x)p & \text{if } x \in (0, \beta), \\ \geq (1+x)p & \text{if } x = \beta. \end{cases} \tag{20}$$

Similarly, the priority of existing user i's WTP can be obtained by

$$\theta_i \begin{cases} = (1+x_i)p & \text{if } x_i \in (0, \beta), \\ \geq (1+x_i)p & \text{if } x_i = \beta. \end{cases} \tag{21}$$

The system is dynamic in terms of the fact that users join and leave dynamically. The utility of each existing user decreases with the admission of an incoming user. For example, when the incoming user with access probability x is admitted, the utility of existing user i drops from $\theta_i \ln\left[1 + x_i \prod_{j=1,j\neq i}^{n}(1-x_j)\right]$ to $\theta_i \ln\left[1 + x_i(1-x) \prod_{j=1,j\neq i}^{n}(1-x_j)\right]$. In case that the utility decreases below the price charged (i.e., px_i), the existing user i may reject the price and leave. This imposes the AP a capacity constraint on her revenue maximization problem.

Let t, $\widetilde{t}$, and $\Delta t = \widetilde{t} - t$ be the arrival time, the intended departure time, and the intended stay duration of the incoming user. The revenue received from the incoming user is therefore denoted by

$$R^{\text{growth}} = px\Delta t \tag{22}$$

When each existing user adopts a *myopic strategy* [11], i.e., the existing user remains connected if the price charged is less than her utility, otherwise the user rejects the price and leaves, the revenue loss incurred by the quitting of existing users is denoted by R^{loss} as follows.

$$R^{\text{loss}} = \sum_{\theta_i \ln\left[1+x_i(1-x)\prod_{j=1,j\neq i}^{n}(1-x_j)\right]<px_i} px_i(\widetilde{t}_i - t) \tag{23}$$

where $\widetilde{t}_i$ is the intended departure time of the existing user i.

From Eq. (21), it could be concluded that: (i) when the existing user i sets the access probability as $x_i \in (0, \beta)$, the AP can obtain the θ_i by $(1+x_i)p$; and (ii) when the existing user i sets the access probability as x_i equals β, the AP cannot know the priority of existing user i's WTP exactly. In this paper, we assume that the AP is risk-averse, and uses the minimum value, namely, $(1 + x_i)\,p$ to estimate θ_i.

$$R^{\text{loss}} = \sum_{(1+x_i)p\ln\left[1+x_i(1-x)\prod_{j=1,j\neq i}^{n}(1-x_j)\right]<px_i} px_i(\widetilde{t}_i - t) \tag{24}$$

Therefore, in order to maximize her overall revenue, the AP has to decide the CAC policy based on not only the revenue growth from the admission of an incoming user, but also the potential revenue loss incurred by the quitting of existing users. To be specific, a rational AP admits the connection of the incoming user when the revenue growth from the incoming user can at least compensate for the revenue loss incurred by the quitting of existing users. Therefore, the connection of the incoming user is admitted when the following condition holds.

$$R^{\text{growth}} > R^{\text{loss}} \tag{25}$$

Combining Eq. (22), (24), and (25), it could be concluded that the AP admits the connection of the incoming user if and only if

$$x\Delta t > \sum_{(1+x_i)p\ln\left[1+x_i(1-x)\prod_{j=1,j\neq i}^{n}(1-x_j)\right]<px_i} x_i(\widetilde{t}_i - t) \tag{26}$$

On the other hand, the incoming user accepts the price px if and only if

$$\begin{aligned} S(x) &= (1+x)\,p\ln\left[1+x\prod_{i=1}^{n}(1-x_i)\right] - px \\ &\geq 0 \end{aligned} \tag{27}$$

The pricing and CAC processes are executed one user after another according to their arrival time. The steps involved in QoS negotiation and admission control [12] are shown in Fig. 3.

Step 1: An incoming user arrives at the network, and detects the existence of APs via periodically broadcasted beacons. The beacon packet contains: price index p and the access probability of each existing user, namely, the congestion-indication signal.

Step 2: The incoming user tries to begin a session by initially sending a Service Level Specification (SLS) packet.

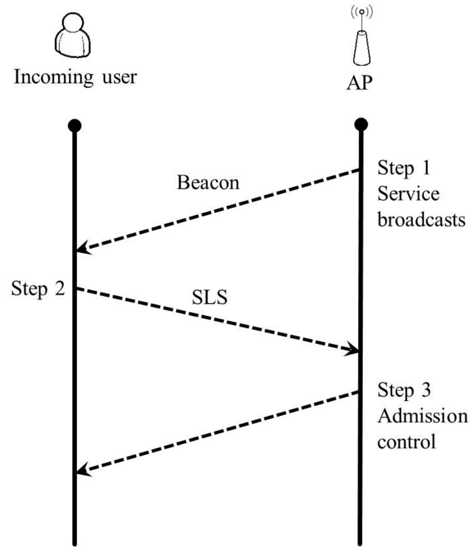


Fig. 3. Diagram showing the sequence of steps involved in pricing and connection admission control.

The SLS packet contains: the access probability (i.e., x) and the stay duration (i.e., Δt).

Step 3: The AP that receives the request, decides whether the connection of the incoming user should be admitted or not by comparing R^{growth} with R^{loss}.

VI. Simulation Results

As described in the previous section, we consider the uplink of random access MAC where each user contends for channel access according to some user-chosen access probability. A transmission is successful if and only if there is a single transmission attempt - there is no carrier sensing, and we do not model explicit back-off.

Each user arrives according to a Poisson process and stays for a time, which is exponentially distributed. Each simulation lasts 10 hours, and is repeated for one thousand times. Other detailed simulation settings are summarized as shown in TABLE I.

TABLE I
A summary of the simulation settings.

Arrival rate	[1, 20] per hour
Average stay duration	1 hour
Raw bit rate	11 Mbps
Constant β	0.5
Constant p	100
Users' Willingness to Pay (θ)	uniformly distributed in [100, 150]
Access probability	uniformly distributed in [0.0, 0.5]

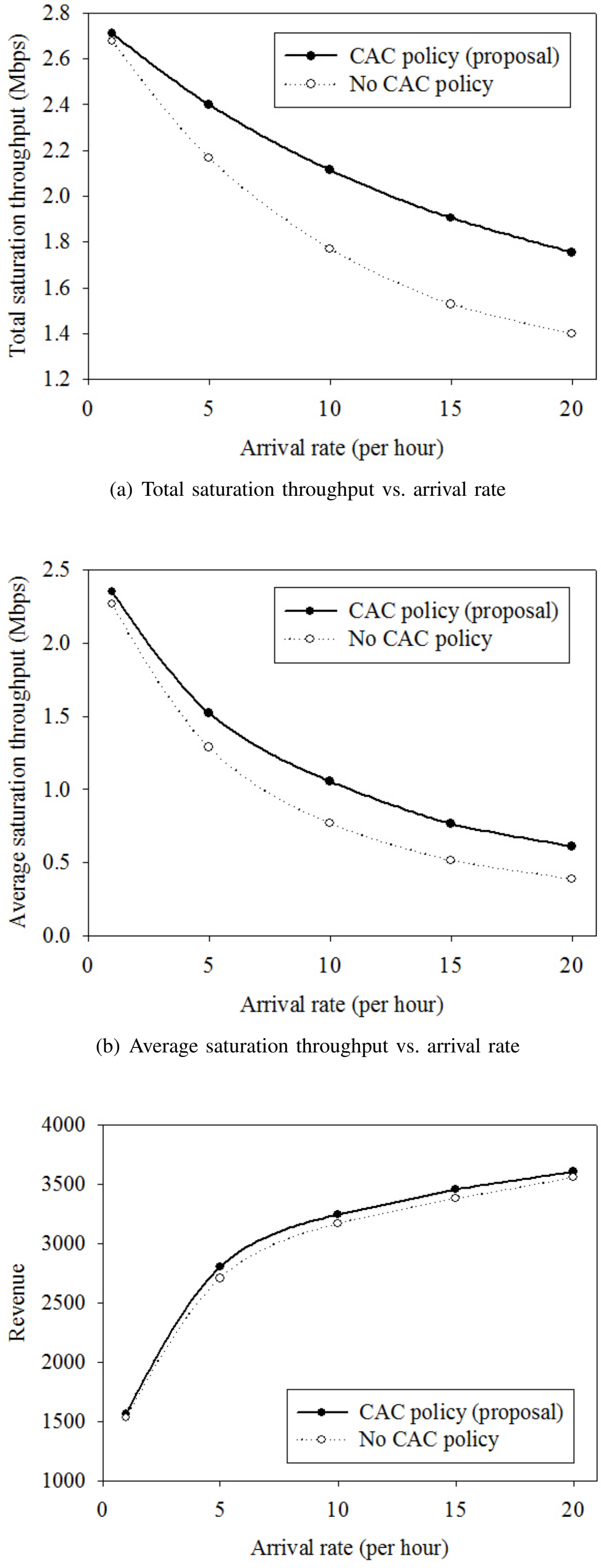
In order to explore the performance of the proposed algorithm on QoS provisioning and revenue, we use *no CAC policy* (NCP) for comparison. The distinction between NCP and our proposed algorithm is that: the proposed scheme examines the potential revenue loss before admitting an incoming user, while NCP admits all users straightforwardly.

Figure 4 (a), (b), and (c) show the total saturation throughput, the average saturation throughput, and the revenue as a function of the arrival rate, respectively. The curves plotted in Fig. 4 (a) and (b) show the effect of the proposed algorithm in terms of improving QoS. When the arrival rate is 20 users per hour, the total saturation throughput and the average saturation throughput are increased by 19.5% and 37.4%, respectively, compared with those of NCP. For the revenue, the curves plotted in Fig. 4 (c) show that the performance of the proposed algorithm is slightly better than that of NCP, but the difference between them is not significant.

VII. Conclusions and Future Work

In this paper, a Stackelberg game structure is applied to obtain the equilibrium of bandwidth resource sharing between the AP and each incoming user. The game is composed of three steps: (i) The AP predefines a pricing scheme and provides congestion-indication signals for users; (ii) An incoming user chooses the access probability to optimize her payoff, namely, the best response strategy; (iii) Based upon the best response stategy, the AP then decides whether the connection of the incoming user should be admitted or not. The simulation results show that the proposed algorithm achieves higher saturation throughput as well as greater revenue gain when compared with NCP.

Future work includes the extension of this algorithm to multi-AP scenarios, in which the rejected users could associate themselves to other APs through channel switching or network directed roaming.



(a) Total saturation throughput vs. arrival rate

(b) Average saturation throughput vs. arrival rate

(c) Revenue vs. arrival rate

Fig. 4. The effect of the proposed algorithm in terms of improving saturation throughput and revenue.

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