Flow Admission Control Method with Bounded Rationality Using Stochastic Evolutionary Game Theory

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***Abstract*—We propose a flow admission control method to maximize the satisfaction of all users when accommodating communications with different bandwidths in the same network, and we demonstrate its effectiveness using theoretical equations. Conventional flow admission control assumes the rationality of all users requesting the correct bandwidth. However, in a real network, some users may mistakenly select the incorrect bandwidth. Thus, we need to analyze user behavior to calculate an optimal control parameter for flow admission control. We model our flow admission control with user behavior by using stochastic evolutionary game theory and queueing theory. In addition, we analyze the characteristics of our flow admission control while accounting for user behavior. As a result, we find the total user satisfaction is maximized when the selection error probability is 20% under the conditions of our study.**

I. INTRODUCTION

The number of users using mobile devices such as smartphones and tablets is increasing. As a result, the amount of communication traffic is expected to reach 333 exabytes in 2022 worldwide. [1]. The number of users accessing video and music streaming services such as YouTube has been increasing as well. Streaming communication "flow" is a method in which packets are constantly flowing from a server, and the client downloads and plays the received packets in real time. In contrast to e-mail and file transfer, flow requests communication in real-time. Moreover, each flow application, such as music and video, requires a different bandwidth. When these flows are allocated in the network, they occupy many network bandwidth resources. To maintain the quality of service (QoS), a call admission control (CAC) method is used, which controls whether the arriving flow is accommodated.

In general, streaming communication (flow) is different from conventional best-effort communication because streaming communication needs to maintain QoS. Moreover, there are many types of streaming communication (heterogeneous traffic), such as music and video. In this environment, CAC is required depending on the characteristics of each flow to ensure QoS. In order to ensure QoS, A CAC in LET networks that has been used in recent years was proposed [2]. In this study, the bandwidth available for call acceptance is ensured by setting appropriate thresholds for adaptive based on the type of traffic.

A previously proposed CAC method [3] focused on the user's quality of experience (QoE) in two different flow environments. In this method, if the flow is accepted, the same level of satisfaction is obtained in both environments. The purpose was to maximize the overall satisfaction of all users (total user satisfaction). However, it did not account for when each user's satisfaction differs between two types of flows.

Furthermore, A CAC method was proposed which assumed that each user's satisfaction was different and maximized total user satisfaction by using replicator dynamics [4]. The method assumed that the user knew the selected bandwidth and the connection status of the surrounding area. The method also assumed the user's behavior, in other words, that the user cloud choose freely between two types of bandwidths, broadband and narrowband "user behavior". When the user behavior changed, the proportion of the number of requested narrowband flows to the number of all flows also changed, and the traffic intensity of each flow also changed. The CAC could assume that the intensity changed in the system.

In reality, users may make selection errors "Bounded rationality" [5]. For example, there is a possibility of users selecting the incorrect required bandwidth in CAC environment. However, the aforementioned method did not assume bounded rationality and instead assumed that all users behave rationally when selecting the bandwidth. If there are users who make selection errors, the amount of traffic in each band is assumed to change. As a result, the optimal values of the control parameters in our CAC are also expected to change.

In this study, we propose an admission control for streaming flow (flow admission control) which accounts for user behavior with bounded rationality. The user behavior with bounded rationality is modeled by stochastic evolutionary game theory. Thus, we can assume that each user behavior changes. By using the user behavior model, we can determine the flow admission control to derive the optimal control parameter.

The organization of this paper is as follows. Related work is presented in Section II. Section III introduces the proposed method. The numerical results and discussion are presented in Section IV, and Section V concludes the paper and discusses future directions.

II. Related Work

Streaming flow is a communication method over a network in which packets are downloaded in real time. The demand for CAC increases to ensure the quality of communication in the network. We need to assume the existence of user behavior to apply CAC to real network. In this section, we describe the previously developed CAC using the user satisfaction inferred from the call loss probability [4] and discuss its problems.

A. An Admission Control Method Using User Satisfaction Estimated from Call Loss Probability

The CAC method assumes the case of user satisfaction for two types of flows, broadband and narrowband flows [4]. In a real environment, the satisfaction obtained by communication may be different [6]. This method assumed that users will choose either broadband and narrowband and then change their selection. The user's change of selection was modeled using the replicator dynamics of evolutionary game. Shibayama et al. used the results of the model to propose a CAC that maximizes the satisfaction of broadband flows and narrowband flows when each user has different satisfaction.

B. Related Research Problems

The proposed CAC [4] assumes that all user behavior for the bandwidth selection is rational; in other words, they request the correct bandwidth flow. However, in a real network, some users may select an incorrect bandwidth. For example, users may mistakenly request narrowband flow when they intended to select broadband. Therefore, in this study, we consider bounded rationality in which some users mistake the bandwidth selection. We describe our proposed CAC in the next section.

III. Proposed Method

A. Procedure of Proposed Method

In this study, we propose CAC which maximizes total user satisfaction when the users' behaviors affect each other with bounded rationality. Let p be the transmission probability of user behavior. To achieve our purpose, a threshold value is used to control the call loss probability depending on the traffic. In this study, we use stochastic evolutionary game theory to model user behavior with bounded rationality. Let ε be the ratio of users with bounded rationality "user's selection error probability." Then, we calculate an optimal threshold to maximize the total user satisfaction.

An overview procedure of the proposed method is shown below.

(i) Each user $i \in \mathcal{N} = \{0, 1, \cdots, N\}$ selects either a broadband flow or a narrowband flow. We calculate the average gain f_i^H, f_i^L for broadband and narrowband flows.

(ii) Using a gain matrix A, we calculate the state transition probability p incorporating the user's selection error probability ε. Then, we calculate the steady state distribution $\boldsymbol{\pi_H}$ and $\boldsymbol{\pi_L}$ as the convergent value of the behavior for the number of users requesting broadband.

(iii) Assuming a call loss network, we calculate broadband and narrowband call loss probabilities $\boldsymbol{B_H}$,$\boldsymbol{B_L}$ by using arrival rates $\boldsymbol{\lambda_H}$,$\boldsymbol{\lambda_L}$ and traffic intensities $\boldsymbol{\rho_H}$,$\boldsymbol{\rho_L}$ according to $\boldsymbol{\pi_H}$,$\boldsymbol{\pi_L}$ obtained in (ii).

(iv) We calculate the total satisfaction U using the call loss probabilities $\boldsymbol{B_H}$,$\boldsymbol{B_L}$ obtained in (iii).

(v) We calculate the optimal threshold $\boldsymbol{k^*}$ to maximize the total satisfaction U by searching all thresholds from (i) to (iv).

We model our CAC method incorporating bandwidth selection error as bound rationality to derive an optimal threshold. In addition, we analyze how a selection error affects total user satisfaction. In this study, we compare total user satisfaction when user's selection error probability varies.

B. Model using Stochastic Evolutionary Game Theory

In stochastic evolutionary game theory, we assume users mutate stochastically and continuously similar to selection errors [7]. We can use this theory to analyze the dynamic behavior of the strategy distribution, i.e., the distribution of ratio of the number of user behaviors after convergence. In this study, we model the behavior of N users using stochastic evolutionary game theory in which the users choose either strategy H or strategy L. Strategy H is requesting broadband flow, and strategy L is requesting narrowband flow. Furthermore, let $i \in \mathcal{N} = \{0, 1, \cdots, N\}$ be the number of users selecting strategy H. Lastly, let ε be the probability of making a selection error (Selection error probability).

In our model, we assume a state space $\mathcal{N}$ for the number of players who choose strategy H. Thus, we can define the state i as the number of users who choose strategy H. In state i, each user's gain is compared with all other users. Then, we derive the highest average gain strategy by selecting optimal reaction dynamics. To model the optimal reaction dynamics, we introduce a gain matrix A to describe the gain of each user for each strategy,

$$A = \begin{array}{cc} & \begin{array}{cc} H & \;\;L \end{array} \\ \begin{array}{c} H \\ L \end{array} & \begin{pmatrix} \alpha_H & \alpha_{H,\varepsilon} \\ \alpha_{L,\varepsilon} & \alpha_L \end{pmatrix} \end{array}. \tag{1}$$

The rows in Eq. (1) refer to the bandwidth requested by the user, and the columns refer to the actual bandwidth allocated for the user. Note that each user always chooses either strategy H or L. Thus, the elements in 1-by-1 α_H and 2-by-2 α_L are the gains when the user actually obtains the flow he or she requests, and the elements in 1-by-2 $\alpha_{H,\varepsilon}$ and 2-by-1 $\alpha_{L,\varepsilon}$ are the gains when the user obtains the flow he or she does not request by selection error.

We assume this game is played with $N-1$ users other than oneself. An average gain of strategy H and strategy L when the number of users in strategy H is i can be expressed by the following equations [7],

$$f_i^H = \frac{\alpha_H(i-1) + \alpha_{H,\varepsilon}(N-i)}{N-1}$$

$$f_i^L = \frac{\alpha_{L,\varepsilon} i + \alpha_L(N-i-1)}{N-1}.$$

This transition in user strategy selection can be considered by the Moran process with frequency dependent gain in population genetics [8]. Then the probability of one user choosing a strategy every time is proportional to the average gain [9], that is, the probability of choosing strategy H is given by $if_i^H/[if_i^H+(N-1)f_i^L]$.

The transition process of the number of users choosing a strategy H is a Markov process with state space $i \in \mathcal{N} = \{0,1,\cdots,N\}$ and state transition probabilities p. Here, when there are i users selecting strategy H, the state transition probability when one more user selects the strategy is $p_{i,i+1}$, and when one less user selects the strategy is $p_{i,i-1}$. These state transmission probabilities can be expressed as follows:

$$p_{i,j}=0\ (|i-j|>1),\ p_{0,1}=p_{N,N-1}=\varepsilon,$$

and for $i=1,\cdots,N-1$,

$$p_{i,i+1}=\frac{if_i^H(1-\varepsilon)+(N-i)f_i^L\varepsilon}{if_i^H+(N-i)f_i^L}\frac{N-i}{N}$$
$$p_{i,i-1}=\frac{if_i^H\varepsilon+(N-i)f_i^L(1-\varepsilon)}{if_i^H+(N-i)f_i^L}\frac{i}{N}$$
$$p_{i,i}=1-p_{i,i-1}-p_{i,i+1}.$$

Note that $p_{i,j}=0$ when $|i-j|>1$. Since the Moran process is a birth-death process, the stationary distribution can be clearly shown. We show a vector of stationary probability distribution $\boldsymbol{\pi_H}=(\pi_0^H,\pi_1^H,\cdots,\pi_N^H)$ of the user behavior in selecting a strategy H [7],

$$\left.\begin{aligned}\pi_i^H&=\frac{\Lambda_i}{\Lambda_0+\cdots,\Lambda_i}\\ \Lambda_i&=\prod_{k=0}^{i-1}\frac{p_{k,k+1}}{p_{k+1,k}}\end{aligned}\right.\quad \text{for } i=0,1,\cdots,N.$$

Since there are two strategies in this study, the stationary distribution $\boldsymbol{\pi_L}$ of the user behavior for choosing strategy L is equal to $\boldsymbol{\pi_H}$.

C. Total User Satisfaction

In the previous section, we used stochastic evolutionary game theory to select two types of strategies. Next we derive a stationary distribution $\boldsymbol{\pi_H}$ for the number of users choosing strategy H. We assume that a vector of average arrival rate of users requesting broadband flows is $\boldsymbol{\lambda_H}=(\lambda_0^H,\lambda_1^H,\cdots,\lambda_N^H)=(0,1,\cdots,N)$ in the CAC system. In the CAC system, users choose a strategy based on stochastic evolutionary game theory. In this situation, the steady state probability vector $p_H^{\lambda}=(p_0^{H,\lambda},p_1^{H,\lambda},\cdots,p_N^{H,\lambda})$ for average arrival rate is considered equal to $\boldsymbol{\pi_H}$. Similarly, let $\boldsymbol{\lambda_L}=(\lambda_0^L,\lambda_1^L,\cdots,\lambda_N^L)$ be the average arrival rate of narrowband flows. Then we can consider the vector of steady state probability vector $\boldsymbol{p_L^{\lambda}}=(p_0^{L,\lambda},p_1^{L,\lambda},\cdots,p_N^{L,\lambda})$ of $\boldsymbol{\lambda_L}$ to be equal to $\boldsymbol{\pi_L}$ (i.e. $\boldsymbol{\pi_H}$).

Let $1/\mu_H$ and $1/\mu_L$ be the average service times for broadband and narrowband flows, respectively. Then a vector of traffic intensities of broadband and narrowband flows can be expressed as $\boldsymbol{\rho_H}=(\rho_0^H,\rho_1^H,\cdots,\rho_N^H)=(\lambda_0^H/\mu_0^H,\lambda_1^H/\mu_1^H,\cdots,\lambda_N^H/\mu_N^H)$, $\boldsymbol{\rho_L}=(\rho_0^L,\rho_1^L,\cdots,\rho_N^L)=(\lambda_0^L/\mu_0^L,\lambda_1^L/\mu_1^L,\cdots,\lambda_N^L/\mu_N^L)$. A vector of their steady state probabilities $\boldsymbol{p_H^{\rho}}=(p_0^{H,\rho},p_1^{H,\rho},\cdots,p_N^{H,\rho})$ and $\boldsymbol{p_L^{\rho}}=(p_0^{L,\rho},p_1^{L,\rho},\cdots,p_N^{L,\rho})$ can also be expressed as $\boldsymbol{\pi_H}$ and $\boldsymbol{\pi_L}$.

We define the following equations as user satisfaction for ith users of broadband and narrowband flows, F_i^H and F_i^L which are users select a requested flow and $F_i^{H,\varepsilon}$ and $F_i^{L,\varepsilon}$ which are users selected a no requested flow by a selection error, obtained for each call loss probability B_i^H and B_i^L,

$$F_i^H=(1-B_i^H)\alpha_H+B_i^H\beta_H$$
$$F_i^L=(1-B_i^L)\alpha_L+B_i^L\beta_L$$
$$F_i^{H,\varepsilon}=(1-B_i^H)\alpha_{H,\varepsilon}+B_i^H\beta_{H,\varepsilon}$$
$$F_i^{L,\varepsilon}=(1-B_i^L)\alpha_{L,\varepsilon}+B_i^L\beta_{L,\varepsilon}.$$

We can rephrase each element of the gain matrix α_H, α_L, $\alpha_{H,\varepsilon}$ and $\alpha_{L,\varepsilon}$ in stochastic evolutionary game theory as the user satisfaction when the flow is accommodated by admission control. β_H, β_L, $\beta_{H,\varepsilon}$ and $\beta_{L,\varepsilon}$ denote user dissatisfaction when a flow is not accommodated. Let $\boldsymbol{B_H}=(B_0^H,B_1^H,\cdots,B_N^H)$ and $\boldsymbol{B_L}=(B_0^L,B_1^L,\cdots,B_N^L)$ be the call loss probability vector for broadband and narrowband flows. Let $\boldsymbol{F_H}=(F_0^H,F_1^H,\cdots,F_N^H)$ and $\boldsymbol{F_L}=(F_0^L,F_1^L,\cdots,F_N^L)$ be a user satisfaction vector for each strategy which are users select a requested flow, and $\boldsymbol{F_{H,\varepsilon}}=(F_0^{H,\varepsilon},F_1^{H,\varepsilon},\cdots,F_N^{H,\varepsilon})$ and $\boldsymbol{F_{L,\varepsilon}}=(F_0^{L,\varepsilon},F_1^{L,\varepsilon},\cdots,F_N^{L,\varepsilon})$ be a user satisfaction vector for each strategy which are users select a no requested flow by selection error. Then a vector of steady state probabilities of call loss probability and satisfaction in the broadband flow $\boldsymbol{p_{B_H}}=(p_0^{B_H},p_1^{B_H},\cdots,p_N^{B_H})$, $\boldsymbol{p_{F_H}}=(p_0^{F_H},p_1^{F_H},\cdots,p_N^{F_H})$ and $\boldsymbol{p_{F_{H,\varepsilon}}}=(p_0^{F_{H,\varepsilon}},p_1^{F_{H,\varepsilon}},\cdots,p_N^{F_{H,\varepsilon}})$ can be expressed as $\boldsymbol{\pi_H}$. Similarly, a vector of steady state probabilities of call loss probability and satisfaction for narrowband flows $\boldsymbol{p_{B_L}}=(p_0^{B_L},p_1^{B_L},\cdots,p_N^{B_L})$, $\boldsymbol{p_{F_L}}=(p_0^{F_L},p_1^{F_L},\cdots,p_N^{F_L})$ and $\boldsymbol{p_{F_{L,\varepsilon}}}=(p_0^{F_{L,\varepsilon}},p_1^{F_{L,\varepsilon}},\cdots,p_N^{F_{L,\varepsilon}})$ can also be expressed as $\boldsymbol{\pi_L}$.

In this study, the CAC sets an appropriate threshold $\boldsymbol{k}=(k_H,k_L)$ for determining the acceptability of each flow so that the total satisfaction of each flow is maximized. Let U be the total user satisfaction which is the sum of each user's satisfaction as follows,

$$\begin{aligned}U=\sum_{i=0}^{N}\pi_i^H[\lambda_i^H\{(1-\varepsilon)F_i^H+\varepsilon F_i^{H,\varepsilon}\}\\ +\lambda_i^L\{(1-\varepsilon)F_i^L+\varepsilon F_i^{L,\varepsilon}\}].\end{aligned}$$

Let K be a set of threshold parameters affecting $\boldsymbol{B_H}$ and $\boldsymbol{B_L}$. We find the optimal threshold $\boldsymbol{k^*}\in K$ maximizing the total satisfaction U when enough time has passed and the steady state probability of the system is $\boldsymbol{\pi_H}$,

$$\begin{aligned}\boldsymbol{k^*}&=\arg\max_{\boldsymbol{k}\in K}U\\ &=\arg\max_{\boldsymbol{k}\in K}\sum_{i=0}^{N}\pi_i^H[\lambda_i^H\{(1-\varepsilon)F_i^H+\varepsilon F_i^{H,\varepsilon}\}\\ &\qquad+\lambda_i^L\{(1-\varepsilon)F_i^L+\varepsilon F_i^{L,\varepsilon}\}].\end{aligned}$$

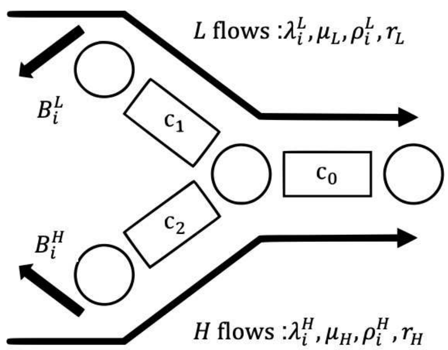

Fig. 1. Call loss network [4]

To obtain $\boldsymbol{k}^*$, we need to calculate the call loss probability for all states i in $\boldsymbol{\rho_H}$ and $\boldsymbol{\rho_L}$. In this study, we calculate the call loss probability $\boldsymbol{B_H}$ and $\boldsymbol{B_L}$ by modeling using queueing theory.

D. Admission Control Method and Control Parameters

In this paper, we consider a virtual call loss network [10] consisting of three links $j = 0, 1$ and 2, as shown in Figure 1. In this way, we calculate the call loss probability for CAC. As shown in Figure 1, we define the capacity of link j as c_j and classify types of requested bandwidth into broadband and narrowband flows on the basis of the selection strategy determined by stochastic evolutionary game theory in Section III.C. When a flow is accepted, narrowband flows go through links $j = 1, 0$, and broadband flows go through links $j = 2, 0$. In other words, c_0 is the bandwidth of a bottleneck link to allow both broadband and narrowband flows to communicate, c_1 is the bandwidth of the virtual link to allow only narrowband flows to communicate, and c_2 is the bandwidth of the virtual link to allow only broadband flows to communicate. The probability vector of the average arrival rate of the flows in each bandwidth is determined by stochastic evolutionary game theory. We assume that each flow in class i arrives following a Poisson process with rate λ_i^H,λ_i^L,$i \in \mathcal{N} = \{0, 1, \cdots, N\}$. We also assume the service time follows an exponential distribution with means $1/\mu_H$ and $1/\mu_L$. In addition, the bandwidth requirements of each band flow are r_H and r_L. The traffic intensity at each steady state is given by ρ_i^H and ρ_i^L. In other words, we assume $N + 1$ types of steady states and calculate the call loss probability for every steady state.

We consider two-dimensional state Ω with $\boldsymbol{n} = (n_H, n_L)$, where n_H is the number of networks occupied by a broadband flow of type H and n_L is the number of networks occupied by a narrowband flow of type L. As we mentioned, Ω is limited by the bandwidth that each flow goes through. Thus, we also consider limited two-dimensional states $\Omega(c_1)$ by using c_1 and $\Omega(c_2)$ by using c_2. Given the traffic intensities ρ_i^H and ρ_i^L, if only $c_1 - r_L$ of c_1 and $c_2 - r_H$ of c_2 are free, each bandwidth flow is accommodated. Then we can calculate the call loss probabilities B_i^H and B_i^L for broadband and narrowband flows as follows [10],

$$B_i^H = 1 - \frac{\sum_{\boldsymbol{n} \in \Omega(c_2 - r_H)} \frac{(\rho_i^H)^{n_H}}{n_H!}}{\sum_{\boldsymbol{n} \in \Omega(c_2)} \frac{(\rho_i^H)^{n_H}}{n_H!}} \quad (2)$$

$$B_i^L = 1 - \frac{\sum_{\boldsymbol{n} \in \Omega(c_1 - r_L)} \frac{(\rho_i^L)^{n_L}}{n_L!}}{\sum_{\boldsymbol{n} \in \Omega(c_1)} \frac{(\rho_i^L)^{n_L}}{n_L!}}. \quad (3)$$

A call loss network connects an arrival flow only if the requested bandwidth for the flow exists in the link when the flow is accommodated. In our proposed flow admission control method, a threshold vector $\boldsymbol{k} = (k_H, k_L)$ limits the number of accommodated flows for each strategy. Thus, in the model shown in Figure 1, the call loss network with threshold $\boldsymbol{k}$ consists of k_H corresponding to c_2 and k_L corresponding to c_1. As mentioned earlier, c_0 represents the actual capacity to be accommodated and c_1 and c_2 are free to be modified for the CAC. When $\boldsymbol{k} = (k_H, k_L)$ is the maximum available number of broadband and narrowband flows, we can consider the bandwidths c_1 and c_2 in the virtual model in terms of threshold and requested bandwidths. Thus, c_1 can be expressed as follows,

$$c_1 = k_L r_L, 0 \leq k_L \leq \lfloor \frac{c_0}{r_L} \rfloor.$$

Similarly for c_2, it can be expressed by the threshold k_H as follows,

$$c_2 = k_H r_H, 0 \leq k_H \leq \lfloor \frac{c_0}{r_H} \rfloor.$$

In this study, we calculate the call loss probability of Eqs. (2) and (3) for all traffic densities $\boldsymbol{\rho_H}$ and $\boldsymbol{\rho_L}$ to obtain the total user satisfaction U. Then we derive the optimal threshold $\boldsymbol{k}^* = (k_H^*, k_L^*)$, maximizing total user satisfaction by searching all thresholds.

IV. Numerical Results

A. Parameter Settings

In our numerical analysis, the requested bandwidth for the narrowband flow is $r_L = 1\ Mbps$, the requested bandwidth for the broadband flow is $r_H = 2\ Mbps$, and the total bandwidth is $c_0 = 50\ Mbps$. The processing rate is $\mu_H = \mu_L = 1\ flows/s$. In addition, the number of users in stochastic evolutionary game theory in this study is $N = 40\ people$. That is, we assume $N + 1$ types of average arrival rates for broadband and narrowband flows with $\boldsymbol{\lambda_H} = (0, 1, \cdots, 40)$ and $\boldsymbol{\lambda_L} = (40, 39, \cdots, 0)$ in the queueing model used to calculate call loss probability. As mentioned in the previous section, the steady state probabilities for each average arrival rates follows $\boldsymbol{\pi_H}$ and $\boldsymbol{\pi_L}$, and the traffic intensities for broadband and narrowband flows are $\boldsymbol{\rho_H} = (0, 0.02, 0.04, \cdots, 0.78, 0.8)$ and $\boldsymbol{\rho_L} = (1.6, 1.56, 1.52, \cdots, 0.04, 0)$.

In this section, we calculate total user satisfaction by using the call loss probabilities of the $N + 1$ types of steady state traffic. Then, we analyze the total satisfaction changes with the given threshold. In the previous section, we considered the threshold k_L for narrowband flows to be in the range $k_L \leq \lfloor c_0/r_L \rfloor$, the threshold k_H for broadband flows to be in

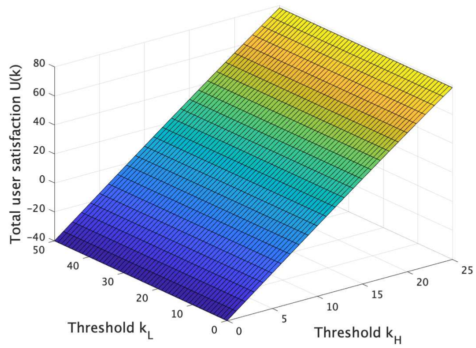

Fig. 2. Satisfaction and Threshold when $\varepsilon = 0$ as in existing research.

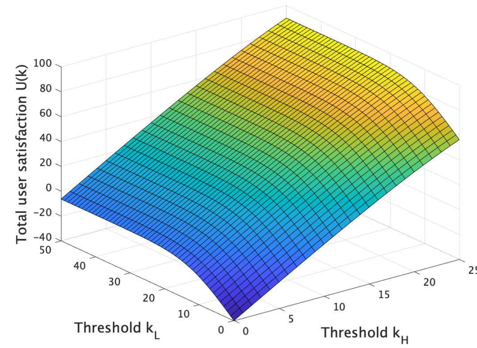

Fig. 4. Satisfaction and Threshold when $\varepsilon = 0.2$.

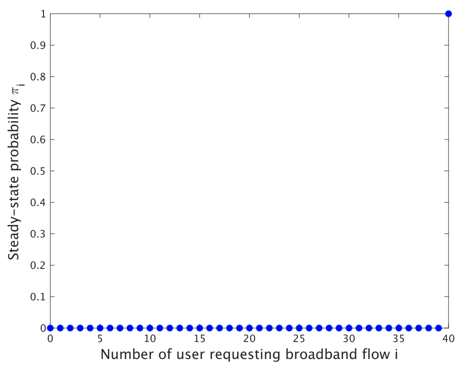

Fig. 3. Relationship between steady state probability and the number of broadband flow requesters when $\varepsilon = 0$ as in existing research.

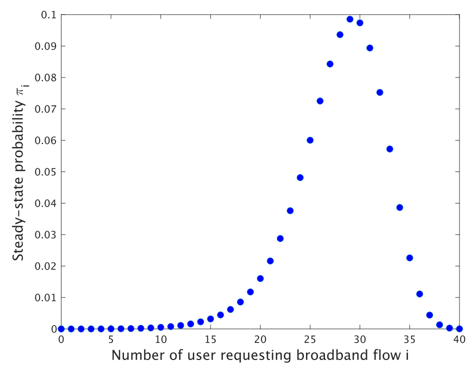

Fig. 5. Relationship between steady state probability and the number of broadband flow requesters when $\varepsilon = 0.2$.

the range $k_H \leq \lfloor c_0/r_H \rfloor$, and the range $r_L k_L + r_H k_H \leq \lfloor c_0 \rfloor$. However, for the analysis in this section, we consider all possible threshold combinations.

We set the gain and user satisfaction parameters to $A = \begin{pmatrix} 4 & 1 \\ 1 & 2 \end{pmatrix}$, $\beta_H = -1$, $\beta_L = -1$, $\beta_{H,\varepsilon} = -1$ and $\beta_{L,\varepsilon} = -1$. This gain matrix implies the users allocated the broadband are more satisfied when they allocate a desired bandwidth. It also means users will get a lower gain if the user does not allocate a desired bandwidth.

B. Total User Satisfaction When Thresholds Change

Figure 2 shows the relationship between threshold and total user satisfaction when $\varepsilon = 0$. The horizontal axis is the threshold k_H for broadband flows and the threshold k_L for narrowband flows, and the vertical axis represents the total user satisfaction U. When $\varepsilon = 0$, there is no user who makes a selection error as in existing research. From Fig. 2, we can see U takes the maximum value when $\boldsymbol{k^*} = (k_H^*, k_L^*) = (25, 0)$. Figure 3 shows the steady state probability $\boldsymbol{\pi_H}$ of the user behavior requesting a broadband flow at $\varepsilon = 0$. From this graph, we notice that $\pi_i^H = 1$ when $i = 40$ and $\pi_i^H = 0$ when $i \neq 40$. In other words, all users are requesting broadband flows. Because all users have requested broadband flows, no narrowband flows are accommodated in the network, and U does not change when k_L varies. Therefore, U also takes the maximum value when $\boldsymbol{k^*} = (k_H^*, k_L^*) = (25, 1), (25, 2), \cdots, (25, 50)$. In addition, because all users require broadband flows, the higher k_H becomes, the higher U becomes. In general, when the value of $\boldsymbol{k} = (k_H, k_L)$ is small, both narrowband and broadband flows are not accommodated in the network and call loss occurs. Therefore, each user's satisfaction with the flows are affected by the call loss, and the call loss probability is higher and U is smaller.

Figure 4 shows the relationship between the threshold and total user satisfaction when $\varepsilon = 0.2$. Here, U takes its maximum value when $\boldsymbol{k^*} = (k_H^*, k_L^*) = (25, 33)$. Figure 5 shows the steady state probabilities of the user behavior when requesting broadband flow at $\varepsilon = 0.2$. In this case, 20% of users have made a selection error. As shown in Fig. 5, the number of users selecting the broadband flow ranges from $i = 7$ to 40. In other words, the number of users requesting narrowband flows both unintentionally due to selection error and intentionally has increased from 0 to 33. Moreover, the number of users requesting broadband flows has changed from 7 to 40. In this situation, if $k_L = 33$, almost all the narrowband flows requested can be accommodated in the network. Meanwhile, because the maximum average arrival rate for broadband flows is 40, we can accommodate as many broadband flows as possible by taking the maximum threshold

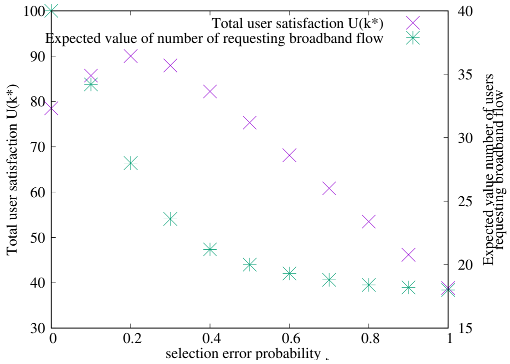

Fig. 6. Relationship between user satisfaction, the expected value of the number of broadband users and probability of selection errors.

$k_H = 25$. Therefore, the optimal threshold can be stated as $\boldsymbol{k^*} = (25, 33)$.

C. Relationship between Selection Error and Total User Satisfaction with Optimal Threshold

Total user satisfaction of Fig. 6 shows the relationship between selection error and the total user satisfaction with the optimal threshold $U(k^*)$ and expected value of number of users requesting broadband flow. Figure 6 shows that the total user satisfaction increases from 0 to 0.2 for ε, and decreases after 0.2. We also found that total user satisfaction is higher when few users make selection errors.

As shown in expected value of number of broadband users in Fig. 6, when the selection error probability increases, the number of users who request broadband flows decreases and the number of users who request narrowband flows increases due to selection errors. When ε is 0, expected value of number of users who request broadband flows is 40. This means that all users select the broadband flow. Since all users choose the broadband flow, the number of arriving broadband flows exceeds the number of broadband flows that can communicate $\lfloor c_0/r_H \rfloor = 25$. As a result, the call loss probability of broadband flows is high. In comparison, when ε is 0.2, the expected number of users who request broadband is 28.0. This value is close to the number of broadband flows that can communicate $\lfloor c_0/r_H \rfloor = 25$. This indicates that the call loss probability of the broadband flows is smaller than one when ε is 0.

In this study, the satisfaction $\alpha_{L,\varepsilon}$ is 1 when a narrowband flow is requested due to a selection error, and the dissatisfaction β_H is -1 when a broadband flow is requested but the call is dropped. In other words, users are more satisfied if narrowband flows are allowed to communicate due to selection errors than if broadband flows are dropped. Here, expected value of number of users requesting narrowband flows is obtained by subtracting expected value of number of users requesting broadband flows from all users. Thus, when the selection error is 0.2, expected value of number of users requesting narrowband flows is 12.0. Therefore, the total user satisfaction is higher when $\varepsilon = 0.2$ than when $\varepsilon = 0$, because the call loss probability of the broadband flow is lower and the satisfaction when the narrowband flow is accommodated is also added.

When the ε exceeded 0.2, expected value of number of users requesting broadband flows is less than the number of broadband flows that can be communicated $[c_0/r_H] = 25$. In this study, the satisfaction when a flow is obtained as requested is defined as $\alpha_H = 4$ and $\alpha_L = 2$. On the other hand, the satisfaction when the flow is not as requested due to a selection error is $\alpha_{H,\varepsilon} = 1$ and $\alpha_{L,\varepsilon} = 1$. In other words, it indicates that making a selection error will lower the satisfaction. Therefore, the total user satisfaction decreases when the ε exceeds 0.2.

V. Conclusion

We proposed an admission control method that accounts for when users make selection errors. We analyzed the user behavior by using stochastic evolutionary game theory and changing the probability of making a selection error. We also analyze total user satisfaction using queueing theory. We calculated the user behavior and call loss probability for each behavior, and determined the optimal threshold to maximize the total user satisfaction. By changing the probability of selection errors, we were able to confirm that when some users made a selection error, the total user satisfaction increased compared to when they did not make a selection error, and that the total user satisfaction was the greatest when the selection error probability is 0.2 under the conditions of this study.

In the future, we need to study and consider the relationship between selection error and total user satisfaction under various conditions, such as different gains for broadband and narrowband. We need also to confirm the effectiveness of our method compared to existing methods. Furthermore, we will also consider to increase the number of traffic types, since our study is limited to two types of traffic, which is different from the 5G networks currently being considered.

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