Cognitive Radio Access Optimization Using Multi-parameter Match Ability Estimation

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Cognitive Radio Access Optimization Using Multi-parameter Match Ability Estimation

Kunqi Guo[1,3] , Lixin Sun[1], Xiaoqun Zhao[2], and Shilou Jia[3]

[1] School of Computer Science and Telecommunication Engineering,
Jiangsu University, Jiangsu, China
[2] School of Communication Engineering,
Tongji University, Shanghai, China
[3] Communication Research Center, Harbin Institute of Technology,
Harbin, China

Abstract. In this paper, we formulate the optimal channel access of secondary user system in cognitive radio networks as the total reward maximization by Partially Observable Markov Decision Processes (POMDPs). *Match Ability* is proposed that takes allowable channel transmission rate and *bit-error-rate* (BER) required by receiving end into account. A heuristic greedy algorithm for channel access is proposed that is based on the *local maximum match ability*. By combining the utility function of queuing delay with *local match ability*, we improve the global average delay fairness. It is demonstrated by simulation results that as the average arrival rate increases, the large stable region of low delay can be maintained by adjusting utility function of the average waiting time under the condition that all the control information time overhead is not considered in the centralized global fairness control.

Keywords: Cognitive radio; match ability; utility function; average waiting time.

1   Introduction

A novel solution to radio spectrum underutilization problems is to adopt cognitive spectrum access. It can be realized by first sensing frequency bands that are not used by the primary users and then accessing current idle frequency band. To achieve this goal in an autonomous manner, multiple user cognitive radio networks need to be adaptive to dynamic wireless network characteristics to use radio spectrum most efficiently. In general, the secondary user that is driven by service requirement starts to sense each channel of primary users at any given time, with probable sensing results of channels including (1) a idle (active) channel accurately sensed to be idle (active) and (2) a idle (active)Wrongly sensed to be active (idle). In case (2), the channel usage efficiency can be decreased because the same channel may be simultaneously used by more than two users, or not be utilized by secondary users. In secondary user system, the access decision is determined only according to the result of channel sensing. It can be completed by detecting the signal in frequency

bandwidth of primary users at physical layer. A great deal of effort has been made by considering spectrum detecting method, accessing strategy and traffic tail characteristics estimation in time domain respectively. In [1] and [2], a hierarchical cognitive network is considered for cognitive user transmission opportunities in multiple channel communication system. The queue tail distribution of cognitive users is estimated for the detection of channels of primary users in [3], with closed-form expressions under two primary users.

While there has been much investigation in channel usage in cognitive radio networks including opportunistic access [4, 5, 6, 7], spectrum sharing [8, 9] and stable and efficient access method [10, 11], there is a lack of the efficient effort in spectrum access efficiency of secondary users system that both the efficiency and fairness of the available spectrum utilization are considered. It is a complex multiple variants optimization problem we will face in this paper. Using Partially Observable Markov Decision Processes (POMDPs), we investigate the optimization objective that is formulated as the total reward maximization. The optimization implementation based on POMDP is to obtain the expected total reward by taking a sequence of decision actions. In our objective optimization for channel access, each access decision is made based on the multi-parameter match estimation considering the channel condition, the queuing delay, and the average arrival rate. To address this, we propose a novel channel access scheme using multidimensional parameters *match ability maximization*. In this scheme, for each secondary user, the statistical relationship between context parameters and the quality of service is derived according to queue theory. For wireless packet scheduling, much of efforts is made to achieve efficient wireless packet scheduling in [12], [13] and [14]. Proportionally fair (*PF*) scheduling is investigated in [15], [16] in order to maximize the long-term throughput in terms of user average channel conditions. In cognitive radio network, the interference to primary users may be increased due to the transmission power enhanced by a secondary user using a worse idle channel. In addition, a secondary user will reduce the utilization efficiency of channels being in better condition because its current service queue length is shorter. Thus, the trade-off between channel efficiency and queue length should jointly be considered for optimizing spectrum utilization. It becomes more important for secondary user system in cognitive radio networks using the constrained opportunistic spectrum access for service data transmission. In this paper, we focus on this problem. To our knowledge, as yet, it is not investigated. Considering cognitive access characteristics, we propose a novel metric *Match Ability* for channel access in secondary user system. *Match Ability* is constructed according to the required bit-error-ratio (BER) and the achievable transmission rate while considering the interference caused to its neighboring primary users. For single secondary user, *Match Ability* (*MA*) performs mapping between channel selection and the achieved quality of service (QoS). By this mechanism, secondary user accesses each channel based on *greedy Match Ability maximization (GMAM)*. However, when more than two secondary users have the requirement of using the same channel, we need to consider the fairness problem of the channel utilization. This motivates us to implement it by combining centralized management control with *GMAM* based local access. To adapt well to the trade-off between queue delay and channel efficiency, we use extended *Match Ability* called *EMA* that is based on the principle of the utility maximization. In this scheme, we combine queue delay with *MA* of each secondary

user by the utility function of queue delay. In addition, one of advantages of our methods is that it allows us to use conventional Proportionally fair scheduling (*PF*) as centralized management control by only replacing the single parameters with the integrated parameter *MA*, which can adapt well to the channel efficiency maximization requirement.

2 System Description and Optimization Formulation

In this section, we give the system description for the shared channel usage and analyze the optimization objective by partially observable Markov decision processes (POMDPs).

2.1 System Description

We consider a multiple channels cognitive radio networks with *M* primary users and *N* secondary users (cognitive users). In primary user system, each primary user has a channel (frequency band) to exclusively and randomly use. In secondary user system, each secondary user (cognitive user) uses idles channel of primary user to transmit its data queue in dynamic opportunistic way. The same spectrum channel can be shared at the same time between secondary user and primary user. Under this the setting, when we concentrate on idle channel usage, one of key problems we must face is the co-channel interference caused by secondary users to primary users. It mainly is due to two reasons. The first is that secondary users wrongly detect busy channels of primary users as being idle. The second is from how to utilize channels rightly sensed by secondary users as being idle. We focus on the latter one in this paper. Thus, our objective is equivalent to optimizing the utilization of channels shared between primary users and secondary users. The co-channel interference can be avoided when the same channel is used only by a primary user in the prescribed time, however, the spectrum utilization efficiency will be lowered when the space distance between a primary user and a secondary user is long enough to simultaneously use the same frequency band. With the interference protection of primary users, the optimization objective becomes a constrained optimization problem.

Two schemes are considered in our optimization objective implementation. The first one is the distributed spectrum access that the channel access in secondary user system is based on *GMAM*. With the *GMAM* based distributed way, each secondary user can take shorter time from sensing to accessing channel. However, the channel utilization optimization is subject to both the allowable transmission rate and service queue condition that jointly leads to the constrained optimization problem. The total optimization depends on the *optimum match* between the allowable channel transmission ability and the queue condition. This needs a centralized based trade-off control to allocate the same channels that are requested by two or more secondary users. By combining *GMAM* for channel sensing with the queue delay state, we propose the secondary scheme called *GMAMC* that considers trade-off between channel transmission efficiency and queue delay. By maximizing the *utility function* of the average waiting time, *GMAMC* has the global balance ability by controlling

greedy maximization degree used in *GMAM*, The framework for channel access in secondary user system is shown in Fig. 1.
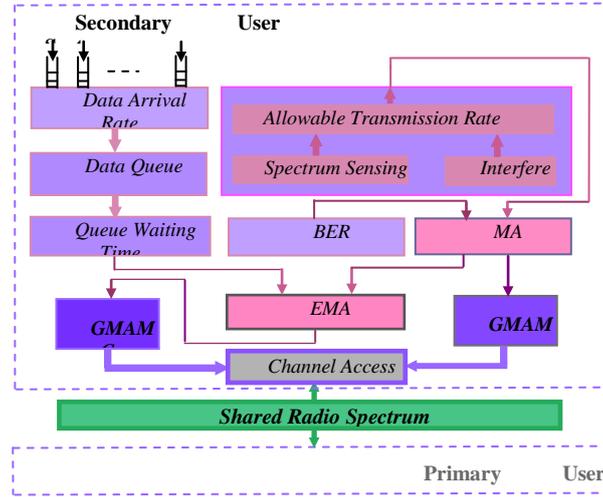

Fig. 1. Framework for Channel Access in Secondary User System

2.2 Optimization Formulation

A POMDP denotes an observation (estimation) and decision process taking a sequence of actions to maximize the reward value under uncertain estimated factors. Let S, A, and O, be a set of states, a set of actions and a set of observations (estimated parameters). If the system is currently in a state $s \in S$, after an action (decision) is taken, the system is driven into a new state s' from s and as a result, a reward value $R(s,a)$ is obtained. Due to uncertain predicted parameters, the end state s' can be modeled as a conditional probability function $T(s,a,s') = p(s'|s,a)$. The optimization objective is to maximize the total reward: $\max \sum_{s \in S, a \in A} R(s,a)$. Let

$S_j[k]=1$ and $S_j[k]=0$ denote the idle and busy condition of the channel of primary user j in time slot k respectively. Taking channel usage efficiency as the system optimization goal, we represent the system state S by the vector $[S_i, S_2, ...S_M]$. I_{ij} is the interference caused by secondary user i using channel j to primary user j. We by $I_{threshold}$ denote the maximum interference threshold that primary user can tolerate. For each secondary user, we consider two channel access schemes including the distributed access action and the centralized control. The set of access actions is expressed by A. Let $a_{ij}=1$ and $a_{ij}=0$ denote the distributed access and the centralized control scheme respectively for access channel j adopted by secondary

user i. Each secondary user can access one channel by one of two ways indicated by $a_{ij} \in \mathbf{A} = \{0,1\}$. Let $r_{ij}(a_{ij})$ be the required reliable transmission rate of secondary user i over channel j by accessing mode a_{ij}. By choosing the appropriate access scheme, our objective is to maximize the total system reward in terms of transmission rate

$$\max \sum_{i=1}^{N} \sum_{j=1}^{M} r_{ij}(a_{ij}) \tag{1}$$

$$\text{s.t.} \quad 1) \sum_{i} I_{ij} < I_{threshold} ; \quad 2) \; a_{ij} \in \mathbf{A} = \{0,1\}$$

where $\sum_{i} I_{ij} < I_{threshold}$ guarantees that the total interference caused by secondary user to each primary user is under the specified condition. However, the channel utilization efficiency can be reduced because the channel access is determined only according to two states, the busy and idle condition. Dynamic network environment makes it feasible to allocate the same channel at the same time to a secondary user and a primary user due to time-varying user location diversity. We consider secondary user system that time is divided into slots of fixed length T_s and define

$$S_{ij}[k] = \begin{cases} 1, \text{ if } I_{ij}[k] + \sum_{n \neq i} I_{nj}[k] < I_{threshold} \\ 0, \text{ if } I_{ij}[k] + \sum_{n \neq i} I_{nj}[k] \geq I_{threshold} \end{cases} \tag{2}$$

where $i, n \in \{1,2,...,N\}, j \in \{1,2,...,M\}$. In (2), $S_{ij}[k] = 1$ and $S_{ij}[k] = 0$ represent idle and busy condition of channel i in time slot k respectively. It means that a secondary user access a channel of primary user system by considering the interference already suffered by secondary user i and the interference to be caused by secondary user i due to using this channel.

2.3   Multidimensional Parameters

By the effective bandwidth theory [17], [18], we can obtain the probability that the packet delay violates the delay requirements using

$$\Pr\{W_i > D_{\max}\} \approx e^{-\theta \delta D_{\max}} \tag{3}$$

where $D_{\max}$ is the delay requirement and θ is a positive constant referred to *QoS* exponent, δ is a constant jointly determined by the arrival process and service process. It means that a large θ implies that a stringent delay requirement can be guaranteed by the system while a small θ implies that a loose delay requirement can be guaranteed by the system. We express by $q_i[k]$ and λ_i the amount of bits of secondary user i waiting for service at time kT_s and the average arrival bit rate

respectively. According to Little's principle, we obtain the average waiting time for secondary user i, W_i by $W_i = q_i/\lambda_i$ where $q_i = \lim_{N \to \infty} \sum_{k=0}^{N-1} q_i[k] \Big/ N$. By the time low-pass window with length T_w, we obtain the average queue length of secondary user i over the time window, $\overline{q}_i[k]$

$$\overline{q}[k] = (1 - \rho_w)\overline{q}_i[k-1] + \rho_w q_i[k] \tag{4}$$

where $\rho_w = T_s/T_w$. Using this time window, the average waiting time for secondary user i at time kT_s, $W_i[k]$ is estimated by $W_i[k] = \overline{q}_i[k]\big/\lambda_i$. Let $A_i[k]$ be the amount of arrival bits of secondary user i during time k. We by $R_i[k-1]$ denote the supportable transmission rate of secondary user i for its service during time slot $k-1$, then, its queue length at time kT_s, $q_i[k]$ is

$$q_i[k] = q_i[k-1] + A_i[k-1] - R_i[k-1]T_s \tag{5}$$

Thus, the predicted average waiting time at end of time slot k $W_i[k]$ is the function of the service arrival rate, the average queue length, and the obtainable transmission rate

$$W_i[k] = \frac{(1 - \rho_w)\overline{q}_i[k-1] + \rho_w\left(q_i[k-1] - T_s R_i[k-1] + \lambda_i T_s\right)}{\lambda_i} \tag{6}$$

Since T_s and ρ_w are known at end of time slot k, $W_i[k]$ is the function in terms of λ_i, $R_i[k-1]$ and $q_i[k-1]$, reflecting the joint effect of multiple parameters on the average waiting time.

3 Channel Access

In this section, we propose two schemes for channel access in secondary user system, *MA-weight channel access* and *Combining queuing delay with MA-weight for channel access*.

3.1 MA-Weight Channel Access (*GMAM*)

During time slot k, secondary user i can decide whether to access channel j based on the maximization of *Match Ability* (*MA*) adopting distributed self-decision. Secondary user i using the channel j can get *Match Ability* MA_i^j

$$MA_i^j[k] = R_i^j[k]S_{ij}[k] \tag{7}$$

where $S_{ij}[k]$ is given by (2) and $R_i^j[k]$ is the achievable transmission rate of secondary user i using channel j that can satisfy the required *bit-error-rate* (BER_i) at receiving end. If QAM modulation is used, we can estimate $R_i^j[k]$ from

$$R_i^j[k] = \log_2 \left(1 - \frac{1.5\gamma_i^j[k]}{\ln(5BER_i)} \right) \qquad (8)$$

where $\gamma_i^j[k]$ is the *SINR* of the transmission link of the secondary user i using channel j during time slot k [19]. Let $h_{ij}[k]$ and $g_{ij}[k]$ represent the pathloss power gain and the normalized composite of shadowing and fading random variable with unit mean of the transmission link from secondary user i to primary user j respectively. Let where $P_i[k]$ be the transmitting power of secondary user i. If secondary user i complete one transmission during time slot t by $R_i^j[k]$, then we can obtain the power of interference received at primary user $I_{ij}[k]$ by $I_{ij}[k] = P_i[k]h_{ij}[k]g_{ij}[k]$. Due to the location dependence of wireless link, the maximization of the total *MA* results in the high computation complexity of maximizing the total $MA_i^j[k]$. To reduce complexity, we propose low complexity heuristic distributed algorithm based on *greedy match ability maximization* (*GMAM*) search that is formulated by

$$SU[k] = \arg\max\left\{ MA_i^j[k] \right\} \qquad (9)$$

where $i = 1,2,...,N; j \in D_i[k]$. By (9), each secondary user at end of current time slot k, selects the channel with the *local maximum match ability* out of channels that can be sensed. Two factors, the link supportable transmission rate and the maximum interference power to be tolerated by the primary user are considered in (9). The best short term performance achieved by (9) depends on the available *optimal match* between two factors during current time slot.

3.2 Combining Queue Delay with *MA* for Channel Access (*GMAMC*)

Trade off between resource efficiency and fairness can be realized by maximizing system utility function [20]. Due to the balance ability of maximizing utility, we use the utility function to determine the access priority for secondary users having the requirement of using the same channel. The delay performance is subject to both allowable channel transmission ability and queue condition. Consider both the transmission efficiency and delay fairness, we use the utility function of the average waiting time to control the trade-off between *maximum match ability based transmission efficiency* and *average queuing delay*. The utility function for this purpose is

$$U_i\left(W_i[k]\right) = W_i^b[k]; i = 1,2,...,N \qquad (10)$$

Let ρ_w be small enough. Since $\Delta U(W_i[k])$ corresponds to the utility addition that should be maximized during current time slot and $R_i[k-1]$ is known before the end of current time slot k, when the arrival process is given, using a first-order approximation of the Taylor's expansion, we can formulate the utility maximization based optimization objective as

$$\max \sum_{i=1}^{N} \frac{dU_i}{dW_i}\Big|_{W_i=W_i[k]} \left(\frac{R_i[k]}{\lambda_i}\right) \tag{11}$$

Let $EMA_i^j[k]$ be the extended *Match Ability* at time slot k of secondary user i denoted by $EMA_i^j[k] = W_i^{b-1}[k]MA_i^j[k]$. The total performance optimization is to achieve the optimal trade-off between queue delay and channel transmission efficiency that can be realized by maximizing the total extended *MA*

$$\max\left\{\frac{1}{\lambda_i} \sum_{i=1}^{N} EMA_i^j[k]\right\} \tag{12}$$

Let $M_i = MA_i^j[k]$ $(i = 1,2,...,N)$ and $T_i = W_i^{b-1}[k]/\lambda_i$ be the *match ability* and the factor of service condition of secondary user i in time slot k respectively.

First, we need find *the global optimal trade-off parameter* G_{opt}. It can be realized efficiently by *binary search* (1) Sort M_i $(i = 1,2,...,N)$ in increasing order. (2) Get the lowest T_l and the highest T_h in user service state space $\left\{W_i^b[k]/\lambda_i ; i = 1,2...N\right\}$. (3) If $T_h - T_l > 0$, then $T_{center} \leftarrow \lfloor (T_h + T_l)/2 \rfloor$ and $T \leftarrow T_{center}$. (4) If $T - (U_h'(W_h)/U_l'(W_l)) > 0$, then $T_l \leftarrow T_{center}$; Otherwise $T_h \leftarrow T_{center}$. (5) Let $G_{opt} \leftarrow T_l M_l$.

Second, allocate channel j to the secondary user i which can satisfy $\min\left\{\left|G_{opt} - (W_i^{b-1}[k]M_i[k]/\lambda_i)\right|; i = 1,2,..,N\right\}$. By this method, the channel j is likely allocated to a secondary user that has $W_i^b[k]M_i[k]/\lambda_i$ approximating to G_{opt}. The service arrival rate, the queue delay and the allowable transmission rate are jointly considered to determine the current G_{opt}. The complexity of the algorithm is low because of the computing overhead largely depending on in sorting-search for *the global trade-off parameter* G_{opt} [21].

4   Performance Evaluation

In our simulation, each channel used by secondary users is assumed to suffer slow fading. Let the *BER* required by the receiving end of each secondary user be 10^{-6}. It is assumed for *GMAM* that each secondary user can know the interference of its neighboring primary users through its *local spectrum sensing*. An ON-OFF model is

used to model the traffic streams of secondary user. The length of time slot is 2 *ms*. The ON period is modeled as Pareto distribution and an exponential distribution is used for OFF duration. The frequency bandwidth of each channel is 20 kHz. Four different rates $\Omega = (1, 2, 5.5, 11)Mbps$ are used for *MA maximization based adaptation* transmission in secondary user system (SUS). First, we consider a square area of size $500 \times 500m$ in which 10 secondary users and 10 primary users are fixedly and randomly deployed. Let $b = 1, 2, 3$ respectively for the utility function (10). Figure 2 shows the obvious differences between *GMAM* and *GMAMC* in terms of queuing delay under the average arrival rate $\lambda_i = 60kbps$ of SUS. The best result is achieved by *GMAMC* with $b = 3$. Let *SU* denote the number of secondary users. Figure 3 and 4 show the average delay under different average arrival rates in SUS. Let the exponent of utility function b be $1, 2, 3, 4$ and 5 respectively. The effect of the trade-off exponent b on the queuing delay is shown in Figure 5. It can be seen that the maximum lower delay stable region of about 7 ms is achieved by *GMAMC* when $b = 5$ that can allow the average arrival rate of 180 *kbps* in SUS. The better delay performances result from the adaptive trade-off between channel access efficiency and queue delay fairness that can be provided by maximizing the utility function of queue delay.
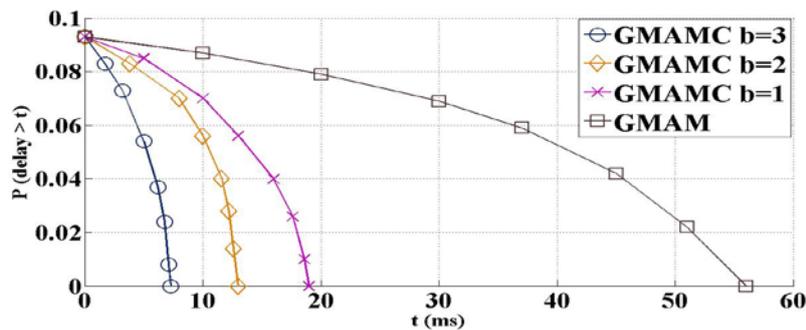

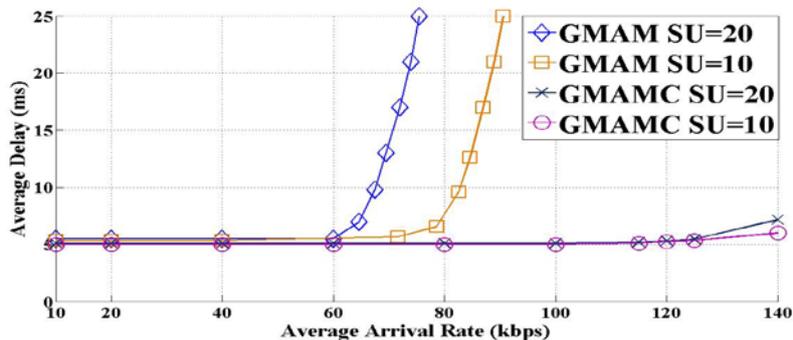**Fig. 2.** Delay violation probability difference between *GMAMC* and *GMAM*

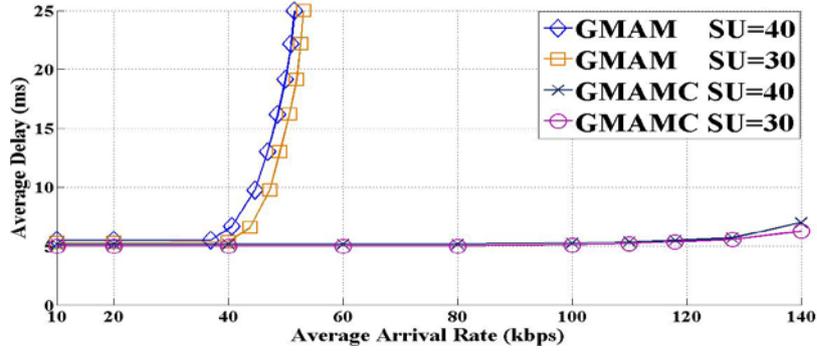**Fig. 3.** Delay performance under SU=10 and SU=20

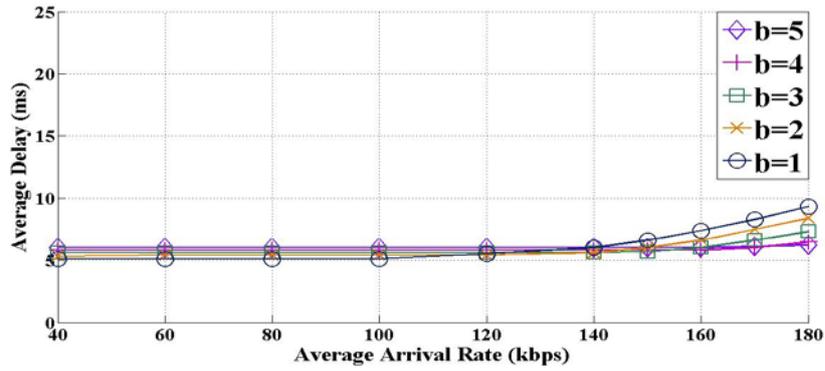**Fig. 4.** Delay performance under SU=30 and SU=40

Fig. 5. Delay stable region of *GMAMC* with different trade-off exponent *b*

5   Conclusion

Based on POMDP decision theory, we formulate the optimal channel access of secondary user system in cognitive networks as the total reward maximization. Two schemes for the optimization objective are proposed based on maximizing the short term spectrum efficiency and minimizing the long term delay fairness difference respectively. We demonstrate by simulation results that the large stable region of low the average delay can be maintained by the centralized global fairness control scheme. Combining the schemes proposed in this paper with efficient time window based traffic control is our future research.

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