A Unified TDMA-Based Scheduling Protocol for Vehicle-to-Infrastructure Communications

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***Abstract*—In this paper, we propose a unified TDMA-based scheduling protocol for Vehicle-to-Infrastructure (V2I) communications. In the proposed TDMA-based scheduling protocol, the roadside infrastructure collects the information from the vehicles within its communication coverage through a control channel at the beginning of each transmission frame and then decides how to allocate the time slots to the vehicles for their data transmission requests based on a new designed weight-factor-based scheduler. The provided weight factor jointly takes into consideration the channel quality of communication links, the speed based fairness among vehicles, and different access categories. Simulation results verify the efficiency of the proposed scheduling protocol in terms of the network throughput performance, the fairness among the vehicles, and different accessing priorities of different access categories.**

I. Introduction

Recently, vehicular networks have attracted great attention from both industry and academia due to their significance in various applications ranging from providing safety warnings to allowing on-road Internet data access [1]. The main objectives of vehicular networks are to provide efficient Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications, based on which many applications in safety, entertainment, and vehicle traffic optimization can be supported.

Various MAC protocols have been proposed for vehicular networks [2], based either on IEEE 802.11 CSMA/CA DCF [3], [4] or on channelization such as Time Division Multiple Access (TDMA) [5], [6]. Different from the widely implemented IEEE 802.11 contention-free MAC protocols, in [5], the ADHOC MAC protocol based on TDMA was proposed for inter-vehicle communication networks. The ADHOC MAC protocol operates in a time slotted structure, where time slots are grouped into virtual frames. By letting each vehicle report the status of all the time slots in the previous virtual frame, the ADHOC MAC can support a reliable broadcast service without the hidden terminal problem. In [6], a novel multichannel TDMA protocol developed based on the ADHOC MAC, named as VeMAC, was proposed specifically for Vehicular Ad hoc NETworks (VANETs). The VeMAC assigns disjoint sets of time slots to vehicles moving in opposite directions and roadside infrastructure, and hence can decrease the rate of transmission collision on the control channel caused by node mobility. However, as far as the authors' knowledge, few existing TDMA-based MAC protocols for vehicular networks takes the specific channel quality of different communication links (i.e., V2I and V2V communication links) into consideration when scheduling the communication resources, which can cause significant effect on the network throughput performance of vehicular networks. Besides, there exists a fairness problem with respect to the Quality-of-Service (QoS) guarantee for the vehicles with different velocities, since they have different limited time for acquiring demanded service within a certain zone. This fairness problem may come out sharply in some vehicular environments where the variance of vehicle velocities is high. And thus this needs to be solved effectively and efficiently when designing the MAC protocols for vehicular networks.

In this paper, we focus on V2I communications in vehicular networks and propose a unified TDMA-based scheduling protocol which can be easily employed into practical vehicular applications. In the proposed TDMA-based scheduling protocol, each vehicle that demands to access the roadside infrastructure for data transmission sends its transmission request and individual information to the roadside infrastructure periodically. The roadside infrastructure collects the information from the vehicles within its communication coverage through a control channel at the beginning of each transmission frame, and then decides how to allocate the time slots among the vehicles for their data transmission requests based on a new designed weight-factor-based scheduler. The designed weight factor consists of three parts, i.e., channel-quality-based weight factor, speed weight factor, and Access Category (AC) weight factor. Specifically, the channel-quality-based weight factor is designed taking the specific channel quality of V2I communication links into consideration in order to optimize the network throughput. The speed weight factor is provided to achieve the potential serving time fairness among the vehicles within the communication range of a certain roadside infrastructure. The AC weight factor is set to distinguish different accessing priorities of different ACs. Simulation results verify the efficiency of the proposed scheduling protocol in terms of the network throughput performance, the fairness among the vehicles, and different accessing priorities of different ACs.

The rest of this paper is organized as follows. Section II describes the V2I communication network. In Section III, a unified TDMA-based scheduling protocol is proposed. Simulation results and analysis are given in Section IV, and the

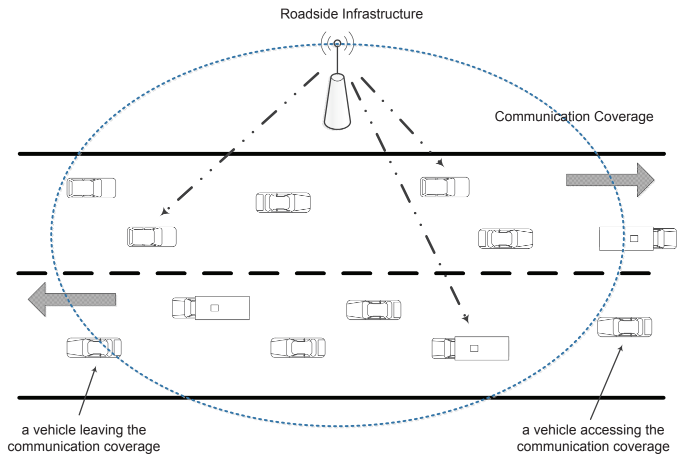

Fig. 1. Scenario for vehicle-to-infrastructure communications.

conclusions are drawn in Section V.

II. System Description

As illustrated in Fig. 1, we investigate a vehicular network consisting of one roadside infrastructure and a set of vehicles moving in opposite directions on a two-way vehicle traffic road. The roadside infrastructure, which can be also regarded as a central base station, delivers data to the vehicles in order to meet each vehicle's demand within its communication coverage. We assume that there exists K vehicles, denoted by U_k, $k = 1, 2, \ldots, K$, in the communication coverage of the roadside infrastructure that can access the roadside infrastructure for various data they need. Note that the number of vehicles, i.e., K, is a time-varying variable for that some vehicles will leave and other vehicles will enter the current communication coverage area from time to time. However, in a very short period of time, e.g., a transmission data frame, K can be assumed to be a constant. In this paper, we focus on data transmission scheduling for V2I communications in the investigated vehicular network. Following the assumptions in [13], at the MAC layer, a centralized TDMA protocol is employed to support multiple access of different V2I communication links, where the roadside infrastructure as a central base station collects the individual information from the vehicles under coverage and decides how to allocate the time slots in each frame to the vehicles in data transmission demands. Each vehicle in the vehicular network is equipped with a Global Positioning System (GPS) receiver, which provides two important types of information for the MAC protocol design. First, each vehicle can acquire its real-time geographical position and thus its speed from the GPS receiver. Besides, the GPS receivers can provide a fairly accurate time synchronization among the vehicles as well as the roadside infrastructure based on the time adjusting information, which is a necessary guarantee for a TDMA-based MAC protocol [7]. Similar to the MAC layer of IEEE 802.11p, in our assumption, there are also four different ACs with different priorities managed in the vehicular network, denoted by AC$_j$, $j = 1, 2, 3, 4$.

Suppose the roadside infrastructure transmit with power p_r. Denote the set of indices $\{1, 2, \ldots, K\}$ by $\mathcal{K}$. The channel gain of the V2I communication link from the roadside infrastructure to vehicle U_k is g_k, $k \in \mathcal{K}$. In this paper, the channel gains contain the distance-dependent path loss and the normalized small-scale fading, i.e., $g_k = PL_k h_k$, where PL_k and h_k represent the distance-dependent path loss and the normalized small-scale channel fading, respectively. Note that quasi-static and flat small-scale fading is assumed, i.e., the small-scale fading stays the same in both time and frequency domain in one time slot and varies accordingly from one time slot to another. The velocity of vehicle U_k is v_k, which is a non-negative value having no concern with the direction that the vehicle moves in. The thermal noise at the vehicles satisfies the independent Gaussian distribution with zero mean and the same variance denoted by σ^2. The total channel bandwidth is W.

III. TDMA-Based Scheduling Protocol

In this section, we propose a unified TDMA-based scheduling protocol for V2I communications in a vehicular network. In the proposed TDMA-based scheduling protocol, each vehicle that demands to access the roadside infrastructure for data transmission sends its transmission request and individual information to the roadside infrastructure periodically. The roadside infrastructure collects the information from the vehicles within its communication coverage through a control channel at the beginning of each transmission frame, and then decides how to allocate the time slots among the vehicles for their data transmission requests based on the proposed scheduler. Each transmission frame consists of two major segments, i.e., the information segment including the scheduling decisions broadcasted to the vehicles and the data segment. We assume that there are N time slots in the data segment of each transmission frame, indexed by $\{1, 2, \ldots, N\}$, where the time slot period is T_s and the transmission frame period is T_f.

The key issue of a scheduling protocol lies in the design of the corresponding scheduler. In the proposed TDMA-based scheduling protocol, we design a weight-factor-based scheduler, in which for each AC of each vehicle requesting for data transmission access, a weight factor denoted by $Q_{k,j}$, $k \in \mathcal{K}$, $j = 1, 2, 3, 4$, is calculated according to the individual information each vehicle reports, and then based on the weight factors a scheduling order is decided by the roadside infrastructure, where AC$_j$ of vehicle U_k with a higher weight factor will be scheduled first to satisfy its transmission demand. The designed weight factor consists of three parts, i.e., channel-quality-based weight factor, speed weight factor, and AC weight factor. The channel-quality-based weight factor is designed by considering the channel quality of V2I communication links to optimize the network throughput. The speed weight factor is provided to achieve the potential serving time fairness among the vehicles within the communication range of a certain roadside infrastructure. And the AC weight factor is set to distinguish different accessing priorities of different ACs. Here, by applying the Shannon capacity formula, we define the *network throughput* as the average of the sum transmission rate of all the V2I communication links scheduled in one transmission data frame.

A. Channel-Quality-Based Weight Factor

In order to improve the network throughput of the vehicular network compared with the traditional IEEE 802.11 CSMA/CA DCF scheme [3], we employ the channel quality of different V2I communication links into the design of the scheduling weight factor. When maximizing the network throughput, the vehicle with the highest channel quality currently is always preferred to be served first. However, in order to guarantee the Quality-of-Service (QoS) of the vehicles suffering relative long time bad channel conditions, the accessing fairness concept among the vehicles should be also considered. Thus, similar to the scheduler designed in [18], the channel-quality-based weight factor of vehicle U_k, $k \in \mathcal{K}$, in our proposed scheduling protocol can be designed as

$$CQF_k(t) = \frac{C_k(t)}{\mathcal{R}_k(t-1)} \tag{1}$$

where $C_k(t) = W \log_2\left(1 + \frac{p_r g_k(t)}{\sigma^2}\right)$ represents the potential transmission rate requested by vehicle U_k based on its reported channel state information $g_k(t)$ at the start of transmission frame t, and $\mathcal{R}_k(t)$ is the update average transmission rate calculated by an iteration process as

$$\mathcal{R}_k(t) = \left(1 - \frac{1}{t_c}\right)\mathcal{R}_k(t-1) + \frac{1}{t_c} R_k(t) \tag{2}$$

where t_c is a predefined number of transmission frames denoting the length of the averaging window, and $R_k(t)$ is the total transmission rate acquired by vehicle U_k at transmission frame t. The value of the parameter t_c defined here is related to the maximum amount of time for which an individual vehicle can be starved (i.e., not receive service for a certain long time). If vehicle U_k doesn't obtain any transmission service from the roadside infrastructure at transmission frame t, then $R_k(t) = 0$. Note that the update average transmission rate is updated by the roadside infrastructure at the start of each transmission frame for each vehicle including the vehicles receiving no transmission service at the previous transmission frame.

B. Speed Weight Factor

Due to the mobility pattern in vehicular networks, the vehicles with various velocities have different residence time within the communication range of the roadside infrastructure and thus significantly different chances to access the roadside infrastructure for their individual data transmission services. Then, there exists a potential serving time fairness problem among the vehicles in vehicular networks [14]. To achieve this potential serving time fairness that the vehicles with different velocities can obtain almost the same transmission service from the roadside infrastructure, we design the speed weight factor based on the accessing probabilities of different vehicles when considering the velocity factor only.

Suppose the accessing probability of vehicle U_k with a velocity v_k is $Pr_v(v_k)$. Then, the accessing probability $Pr_v(v_k)$ satisfies

$$\left[\frac{L_k}{v_k T_f}\right]_{\text{int}} \cdot N \cdot \frac{Pr_v(v_k)}{\sum\limits_{l \in \mathcal{K}} Pr_v(v_l)} = a \tag{3}$$

where a is a constant that should be the same for all the vehicles when achieving the fairness, L_k is the distance that the vehicle moves in the communication range of the roadside infrastructure, and $[x]_{\text{int}}$ denotes the largest integer that is no larger than x. Since all the vehicles move in the same road and the road width is much smaller than the communication radius of the roadside infrastructure, L_k can be degraded as L which is the same for all the vehicles. If the accessing probability $Pr_v(v_k)$ is a normalized one, leading to that $\sum\limits_{l \in \mathcal{K}} Pr_v(v_l) = 1$, then

$$Pr_v(v_k) = \frac{a}{N\left[\frac{L}{v_k T_f}\right]_{\text{int}}}. \tag{4}$$

Removing the parameters a and N that yield the same effect on the accessing probability for all the vehicles in (4), the speed weight factor of vehicle U_k, $k \in \mathcal{K}$, in our proposed scheduling protocol to achieve the potential serving time fairness can be designed as

$$SF_k = \left(\left[\frac{L}{v_k T_f}\right]_{\text{int}}\right)^{-1}. \tag{5}$$

Note that in practical scenarios, let d and r denote the vertical distance from the roadside infrastructure to the road and the radius of the roadside infrastructure's communication range, respectively, and then L in (5) can be calculated as

$$L = 2\sqrt{r^2 - d^2}. \tag{6}$$

C. AC Weight Factor

As mentioned in Section II, there are four different ACs, i.e., AC_j, $j = 1, 2, 3, 4$, in the vehicular network and each has a corresponding priority to indicate its accessing probability. In the traditional IEEE 802.11 CSMA/CA DCF scheme, the priorities of different ACs are distinguished by the predefined minimum and maximum Contention Window (CW) values for each AC, which is shown in Table I. In order to guarantee the accessing probabilities of different ACs to stay almost the same with that in the traditional IEEE 802.11 CSMA/CA DCF scheme, we design the AC weight factor based on the approximate accessing probabilities of different ACs calculated in the traditional IEEE 802.11 CSMA/CA DCF scheme.

From [14], we have that the accessing probability of a certain AC is approximately inversely proportional to its corresponding minimum CW, which means

$$Pr_{AC}(j) \approx \frac{1}{CW_{min}(\text{AC}_j)} \tag{7}$$

TABLE I
PARAMETERS FOR THE FOUR ACS IN THE TRADITIONAL IEEE 802.11 CSMA/CA DCF SCHEME

AC	AC_1	AC_2	AC_3	AC_4
Arrival Interval	20 ms	32 ms	12.5 ms	6.25 ms
Packet Size	160 bytes	256 bytes	200 bytes	200 bytes
CW_{min}	3	3	7	15
CW_{max}	7	15	1023	1023

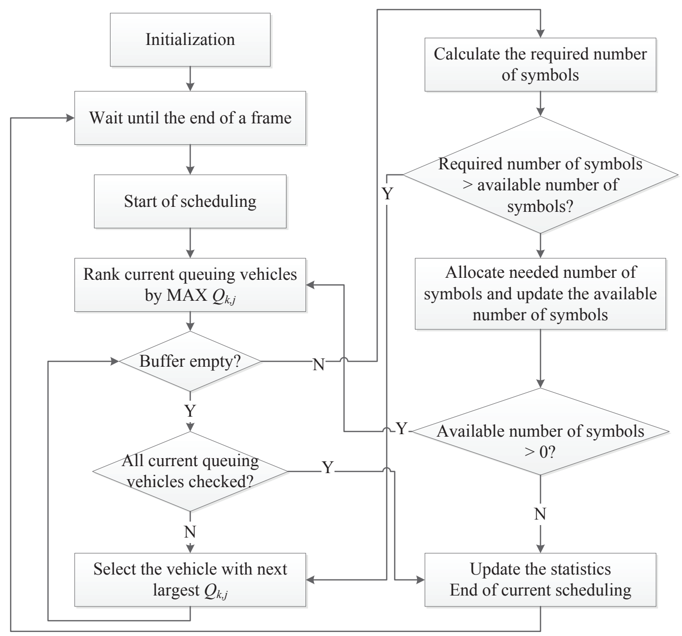

Fig. 2. Flow diagram of the proposed weight-factor-based scheduling algorithm.

where $Pr_{AC}(j)$ denotes the accessing probability of AC_j, $j = 1, 2, 3, 4$. Note that the minimum CW of AC_1 and AC_2 defined in the traditional IEEE 802.11 CSMA/CA DCF scheme have the same value 3, thus in order to distinguish the accessing probability of these two ACs, we meanwhile employ the maximum CW factor into the design of the AC weight factor. Then, the AC weight factor of AC_j in our proposed scheduling protocol indicating different accessing probabilities of different ACs can be designed as

$$ACF_j = \frac{1}{CW_{min}(\text{AC}_j)} + \frac{1}{CW_{max}(\text{AC}_j)} \tag{8}$$

where $CW_{min}(\text{AC}_j)$ and $CW_{max}(\text{AC}_j)$ are given in Table I.

D. Weight-Factor-Based Scheduling Algorithm

According to the analysis in the previous subsections, the weight factor $Q_{k,j}$, $k \in \mathcal{K}$, $j = 1, 2, 3, 4$, in the proposed TDMA-based scheduling protocol can be given as

$$Q_{k,j} = \left(CQF_k(t)\right)^{\alpha} \left(SF_k\right)^{\beta} \left(ACF_j\right)^{\gamma} \tag{9}$$

where t denotes the time index of the current transmission frame, and α, β, and γ are the balancing factors. Note that

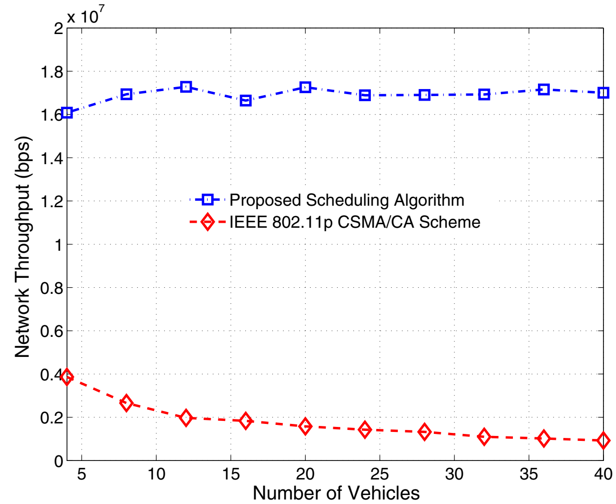

Fig. 3. Network throughput performance in the proposed weight-factor-based scheduling algorithm and the traditional IEEE 802.11 CSMA/CA DCF scheme.

α, β, and γ can be adjusted to practical demands in order to achieve an efficient tradeoff among the effects of the three parts of the designed weight factor. The corresponding weight-factor-based scheduling algorithm is provided in Fig. 2. During the scheduling process, the roadside infrastructure collects the reported information including the channel state information, the velocity, and the AC characteristic from the vehicles in its communication range, and updates the weight factors of the ACs of each vehicle at the start of each transmission frame. Then, the weight factors are sorted in a "Max-to-Min" order. The AC_j of vehicle U_k with the largest $Q_{k,j}$ will be served first in the current transmission frame by the roadside infrastructure for data transmission until its transmission demand is met, and then the AC of a vehicle with the next largest weight factor will be served. This serving process goes on until all the transmission requests are satisfied or the current transmission frame concludes, then another scheduling process for the next transmission frame will start.

IV. SIMULATION RESULTS AND ANALYSIS

In this section, we evaluate the efficiency of the proposed weight-factor-based scheduling protocol by conducting the following simulations. The simulation parameters are set in Table II.

Fig. 3 shows the performance comparison in terms of network throughput between the proposed weight-factor-based scheduling algorithm and the traditional IEEE 802.11 C-SMA/CA DCF scheme in [3]. From Fig. 3, we can see that the network throughput in our proposed weight-factor-based scheduling algorithm has a significant performance gain compared with that in the traditional IEEE 802.11 CSMA/CA DCF scheme, since we employ the channel quality factor into the design of the weight factor, whereas the traditional IEEE 802.11 CSMA/CA DCF scheme is a randomized-contention-based scheme where the channel quality of the communication

TABLE II
SIMULATION PARAMETERS

Parameters	Value
Channel Bandwidth	10 MHz
Transmitting Power of Roadside Infrastructure	20 dBm
Communication Range of Roadside Infrastructure	500 m
Small Scale Fading	Rayleigh fading coefficient with zero mean and unit variance
Slot Period T_s	10 us
Frame Period T_f	20 ms
v_{min}	30 km/h
v_{max}	100 km/h
Balancing Factors in (9)	$\alpha = 1$, $\beta = 1$, and $\gamma = 1$

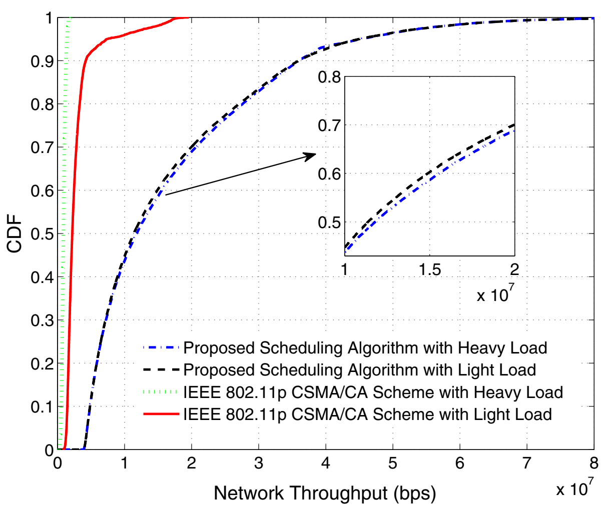

Fig. 4. CDF performance of network throughput in the proposed weight-factor-based scheduling algorithm and the traditional IEEE 802.11 CSMA/CA DCF scheme.

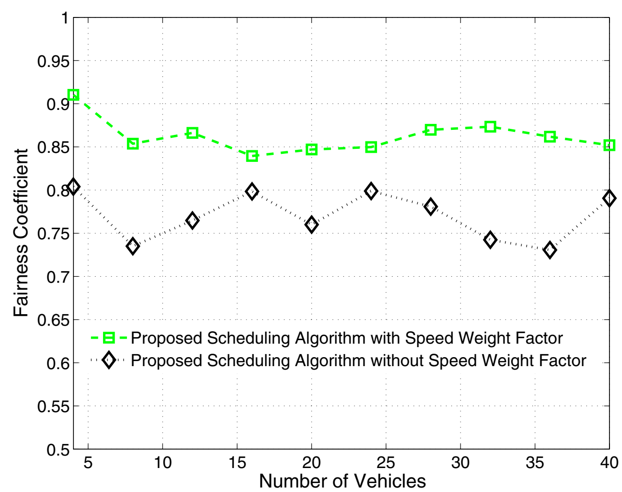

Fig. 5. Fairness coefficient with and without the speed weight factor in the proposed weight-factor-based scheduling algorithm.

links accessing the roadside infrastructure for data transmission is out of consideration.

Fig. 4 shows the CDF performance comparison of network throughput between the proposed weight-factor-based scheduling algorithm and the traditional IEEE 802.11 CSMA/CA DCF scheme with heavy traffic load and light traffic load, respectively. From Fig. 4, we can see that the proposed weight-factor-based scheduling algorithm always has a significant performance gain than the traditional IEEE 802.11 CSMA/CA DCF scheme no matter with heavy traffic load or light traffic load. Besides, we can also find that the proposed weight-factor-based scheduling algorithm has a similar performance with heavy traffic load compared with that with light traffic load, whereas in the traditional IEEE 802.11 CSMA/CA DCF scheme, the performance gap between the heavy traffic load case and the light traffic load case is quite large. This indicates that the performance in the traditional IEEE 802.11 CSMA/CA DCF scheme degrades significantly in a heavy traffic load scenario, whereas our proposed weight-factor-based scheduling algorithm has much stronger robustness to heavy traffic load in terms of the network throughput performance.

Fig. 5 shows the fairness coefficient with and without the speed weight factor in the proposed weight-factor-based scheduling algorithm. Note that according to the definition of fairness coefficient in [14], a value more approaching 1 means a more fair situation, where 1 indicates thoroughly fair among the vehicles. Then, from Fig. 5, we can see that the fairness coefficient with the speed weight factor in the proposed weight-factor-based scheduling algorithm is larger and more approaching 1 than that without the speed weight factor, which verifies the efficiency of the proposed speed weight factor in solving the serving time fairness problem due to various velocities of the vehicles in the vehicular network.

Fig. 6 shows the CDF of throughput of different ACs in the proposed weight-factor-based scheduling algorithm. From Fig. 6, we can see that the AC with a higher priority has a better performance in terms of throughput, which indicates that it has a larger accessing probability for data transmission. This verifies the efficiency of the AC weight factor in distinguishing different priorities of different ACs.

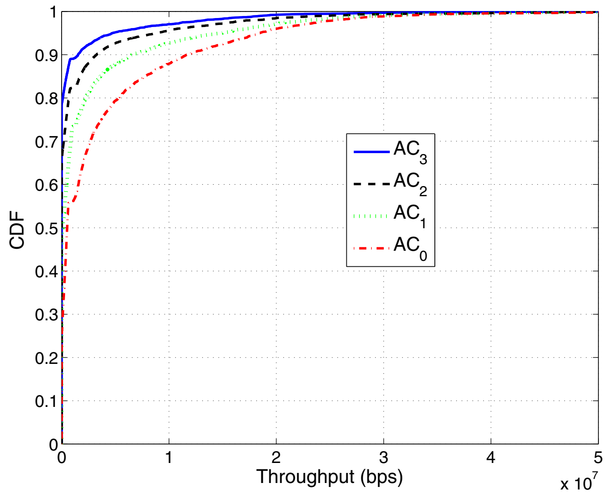

Fig. 6. CDF of throughput of different ACs in the proposed weight-factor-based scheduling algorithm.

V. Conclusions

In this paper, we have proposed a novel TDMA-based scheduling protocol for V2I communications. The proposed scheduling protocol is based on a new designed weight-factor-based scheduler that consists of channel-quality-based weight factor, speed weight factor, and AC weight factor. From simulation results, we can see the efficiency of the proposed scheduling protocol in terms of the network throughput performance, the fairness among the vehicles, and different accessing priorities of different ACs.

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