Short Paper

A Novel Centralized TDMA-Based Scheduling Protocol for Vehicular Networks

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***Abstract*—In this paper, we propose a novel centralized time-division multiple access (TDMA)-based scheduling protocol for practical vehicular networks based on a new weight-factor-based scheduler. A roadside unit (RSU), as a centralized controller, collects the channel state information and the individual information of the communication links within its communication coverage, and it calculates their respective scheduling weight factors, based on which scheduling decisions are made by the RSU. Our proposed scheduling weight factor mainly consists of three parts, i.e., the channel quality factor, the speed factor, and the access category factor. In addition, a resource-reusing mode among multiple vehicle-to-vehicle (V2V) links is permitted if the distances between every two central vehicles of these V2V links are larger than a predefined interference interval. Compared with the existing medium-access-control protocols in vehicular networks, the proposed centralized TDMA-based scheduling protocol can significantly improve the network throughput and can be easily incorporated into practical vehicular networks.**

***Index Terms*—Resource reusing, scheduling protocol, time-division multiple access (TDMA), vehicle-to-infrastructure (V2I), vehicle-to-vehicle (V2V).**

I. Introduction

Recently, vehicular networks have attracted great attention from both industry and academia due to their critical role in various applications, ranging from providing safety warnings to allowing on-road Internet data access [1]–[3]. 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 related to safety, entertainment, and vehicle traffic optimization can be supported.

Various medium-access control (MAC) protocols have been proposed for vehicular networks, which are based on either the IEEE 802.11 carrier sense multiple access with collision avoidance (CSMA/CA) distributed coordination function (DCF) [4], [5] or channelization such as time-division multiple access (TDMA) [6], [7]. Different from the widely implemented IEEE 802.11 contention-free MAC protocols, in [6], the ADHOC MAC protocol operates in a time-slotted structure, in which 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 [7], a novel multichannel TDMA protocol developed based on the ADHOC MAC, called VeMAC, was specifically proposed for Vehicular Ad hoc NETworks (VANETs). The VeMAC assigns the disjoint sets of time slots to vehicles moving in opposite directions and roadside infrastructure; hence, it can reduce the transmission collision on the control channel caused by node mobility. However, to the best of the authors' knowledge, very few existing TDMA-based MAC protocols for vehicular networks take 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 impact on the network throughput performance of vehicular networks. In addition, there also exists a fairness problem with respect to the QoS guarantee for the vehicles with different velocities since they have different limited times for acquiring the demanded service within a certain zone. This fairness problem may sharply come out in some vehicular environments in which the variance of vehicle velocities is high. Thus, this needs to be effectively and efficiently solved when designing the MAC protocols for vehicular networks.

In this paper, we propose a novel centralized TDMA-based scheduling protocol based on a new designed weight-factor-based scheduler. The roadside unit (RSU), as a centralized controller, collects the reported information from the communication links within its communication coverage and calculates the scheduling weight factor of each communication link, based on which scheduling decisions will be made more reasonably and intelligently. The designed scheduling weight factor mainly consists of three parts, i.e., the channel quality factor, the speed factor, and the access category (AC) factor. The channel quality factor is designed in order to optimize the network throughput by taking into consideration the channel state information of different communication links. The speed factor is provided to achieve the potential serving time fairness among the vehicles. The AC factor is set to prioritize different ACs. In addition, a novel resource-reusing mode for different V2V links is permitted if the distances

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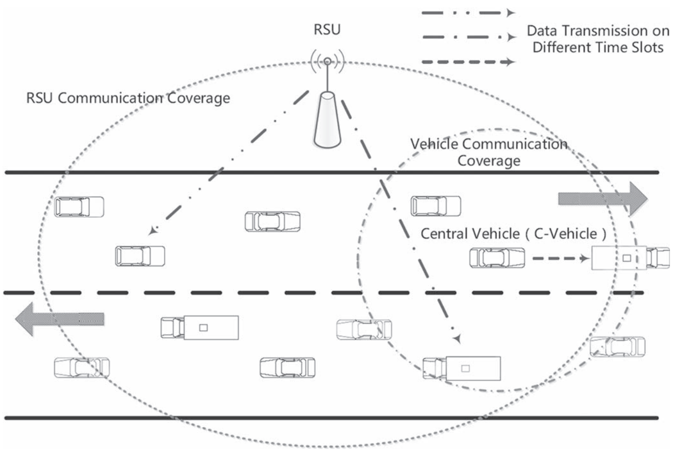

Fig. 1. Scenario for vehicular networks with V2I and V2V communication links.

between every two central vehicles (c-vehicles) of these V2V links exceed a predefined interference interval. Compared with the well-known IEEE 802.11p CSMA/CA-based enhanced distributed channel access (EDCA) scheme, the proposed TDMA-based scheduling protocol can significantly improve the network throughput performance and meanwhile guarantee the QoS fairness among the communication links in vehicular networks. The proposed scheduling protocol can be also easily employed into practical vehicular networks due to its low implementation complexity.

The rest of this paper is organized as follows. Section II describes the investigated vehicular network including V2I and V2V communication links. In Section III, a novel centralized TDMA-based scheduling protocol for vehicular networks is proposed. Simulation results and discussions are given in Section IV, and the conclusion is drawn in Section V.

II. System Description

As illustrated in Fig. 1, we investigate a vehicular network consisting of one RSU and a set of vehicles moving in opposite directions on a two-way vehicle traffic road. In our investigated network, the TDMA protocol is employed to support multiple V2I and V2V communication links. The RSU, as a centralized controller, collects the channel state information and the individual information of the communication links within its communication coverage and then makes scheduling decisions about the time slots in each transmission frame. Each vehicle in the vehicular network is equipped with a GPS receiver, which can provide two important types of information. First, each vehicle can acquire its real-time geographical position and, thus, its velocity from the GPS receiver. In addition, the GPS receivers can provide fairly accurate time synchronization among the vehicles and the RSU based on the time adjusting information, which is a necessary guarantee for a TDMA-based MAC protocol [8]. We define the current transmitter of a certain V2V communication link as a c-vehicle, which can obtain the channel state information of the V2V communication link and feed it back along with other individual information to the RSU. Moreover, similar to IEEE 802.11p, there are also four different ACs with different priorities managed in the vehicular network, which are denoted by AC_j, $j = 1, 2, 3, 4$.

We assume that there exist K communication links, which are denoted by $U_k, k = 1, 2, \ldots, K$, in the investigated vehicular network that have communication demands, including M V2I communication links and N V2V communication links, with $M + N = K$. Note that K is a time-varying variable since some vehicles will leave and other vehicles will enter the current investigated 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. Suppose the RSU transmits with power p_r and each vehicle transmits with power p_v. Denote the set of indices $\{1, 2, \ldots, K\}$, the cluster of the V2I communication links, and the cluster of the V2V communication links by $\mathcal{K}$, $\mathcal{M}$, and $\mathcal{N}$, respectively. The channel gain of communication link 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., $g_k = \mathrm{PL}_k h_k$, 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 remains the same in both the time and frequency domains in one time slot and varies from one time slot to another. The thermal noise at the vehicles satisfies an independent Gaussian distribution with zero mean and variance σ^2. The total available channel bandwidth is W.

III. Centralized TDMA-Based Scheduling Protocol

In this section, we propose a novel centralized TDMA-based scheduling protocol for practical vehicular networks based on a new designed weight-factor-based scheduler. The RSU, as a centralized controller, collects the channel state information and the individual information of the demanding communication links within its communication coverage and calculates the scheduling weight factor of each communication link, based on which the scheduling decisions will be made.

In our designed centralized TDMA-based scheduling protocol, all demanding communication links need to periodically report their channel state information and individual information back to the RSU. Specifically, in a V2I communication link, the information feedback is performed by the moving vehicle, which includes the current channel state information of the V2I communication link, the speed of the moving vehicle, and the AC for transmission; in a V2V communication link, the information feedback is performed by the c-vehicle, which includes the current channel state information of the V2V communication link, the relative speed of the two vehicles, the location of the c-vehicle, and the AC for transmission. The RSU collects the feedback information from all communication links within its communication coverage at the beginning of each transmission frame and then calculates the corresponding scheduling weight factors based on this collected information.

A. *Scheduling Weight Factor Design*

The key issue of the proposed centralized scheduling protocol lies in the design of the scheduling weight factor. Each AC of each communication link requesting for data transmission has a corresponding weight factor, which is denoted by $Q_{k,j}$, $k \in \mathcal{K}$, $j = 1, 2, 3, 4$, which is calculated according to its reported channel state information and individual information. Based on the obtained scheduling weight factors, a scheduling order is decided by the RSU, where the AC_j of communication link U_k with a larger scheduling weight factor will be scheduled first to fulfill its transmission demand.

The designed scheduling weight factor mainly consists of three parts, i.e., the channel quality factor, the speed factor, and the AC factor. The channel quality factor is designed by considering the channel quality of different communication links to optimize the network throughput. The speed factor is provided to achieve the potential serving time fairness among the moving vehicles within various velocities. Finally, the AC factor is set to distinguish the 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 communication links scheduled in one transmission frame.

The scheduling weight factor $Q_{k,j}$, $k \in \mathcal{K}$, $j = 1, 2, 3, 4$, in the proposed centralized scheduling protocol is designed as

$$Q_{k,j} = (\mathrm{CQF}_k(t))^{\alpha} (\mathrm{SF}_k)^{\beta} (\mathrm{ACF}_j)^{\gamma} \tag{1}$$

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

1) Channel Quality Factor: In order to improve the network throughput of the vehicular networks compared with the IEEE 802.11 DCF scheme [4], we incorporate the channel quality of different communication links into the design of the scheduling weight factor. When maximizing the network throughput, the communication link with the highest channel quality currently is always preferred to be served first. However, in order to guarantee the QoS of the communication links suffering from relative long time and bad channel conditions, the fairness among communication links should be also considered. Therefore, similar to the scheduler designed in [14], the channel quality factor of communication link U_k, $k \in \mathcal{K}$, can be designed as

$$\mathrm{CQF}_k(t) = \frac{C_k(t)}{\mathcal{R}_k(t-1)} \tag{2}$$

where $C_k(t) = W \log_2(1 + (p_{\mathrm{tr}} g_k(t)/\sigma^2))$ represents the potential transmission rate requested by communication link U_k based on its reported channel state information $g_k(t)$ at the beginning of transmission frame t, p_{tr} denotes the transmit power of the RSU or the c-vehicle depending on whether U_k is a V2I or V2V link (i.e., $p_{\mathrm{tr}} = p_r$ if $U_k \in \mathcal{M}$ and $p_{\mathrm{tr}} = p_v$ if $U_k \in \mathcal{N}$), and $\mathcal{R}_k(t)$ is the average transmission rate calculated by an iteration process as

$$\mathcal{R}_k(t) = \left(1 - \frac{1}{t_c}\right) \mathcal{R}_k(t-1) + \frac{1}{t_c} R_k(t) \tag{3}$$

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 communication link U_k at transmission frame t. The value of parameter t_c defined here is related to the maximum amount of time for which an individual communication link can be starved (i.e., not receive service for a certain long time). If communication link U_k does not obtain any transmission service from the RSU at transmission frame t, then $R_k(t) = 0$. Note that the average transmission rate is updated by the RSU at the start of each transmission frame for each communication link, including the communication links receiving no transmission service during the previous transmission frame.

2) Speed Factor: Due to the mobility pattern in vehicular networks, vehicles with various velocities have a quite different residence time within the communication coverage of the RSU/c-vehicles, and this leads to a potential serving time fairness problem among the vehicles in vehicular networks. To achieve this potential serving time fairness that the vehicles with different velocities can obtain with almost the same possibilities of the transmission service from the RSU/c-vehicles, we design the speed factor based on the accessing probabilities of different vehicles when considering the speed effect only. Therefore, the speed factor of communication link U_k can be designed as

$$\mathrm{SF}_k = \left(\left[\frac{L}{\tilde{v}_k T_f} \right]_{\mathrm{int}} \right)^{-1} \tag{4}$$

where L is the communication diameter of the RSU or a c-vehicle depending on whether U_k is a V2I or V2V link, T_f is the transmission frame duration, $\tilde{v}_k$ is the absolute value of the relative speed between the receiver and the transmitter of communication link U_k, and $[x]_{\mathrm{int}}$ denotes the largest integer that does not exceed x.

TABLE I
PARAMETERS FOR THE FOUR ACs IN THE IEEE 802.11p EDCA SCHEME

AC	AC_1	AC_2	AC_3	AC_4
CW_{min}	3	3	7	15
CW_{max}	7	15	1023	1023

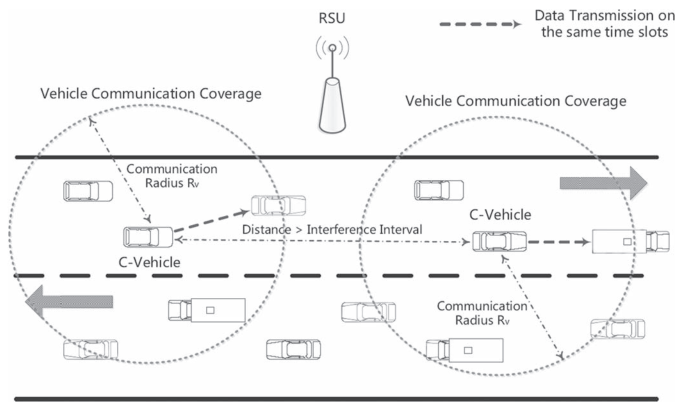

Fig. 2. Illustration of the designed resource-reusing mode for different V2V communication links.

3) AC Factor: As aforementioned in Section II, there are four different ACs, i.e., AC_j, $j = 1, 2, 3, 4$, in the investigated vehicular network, and each has a corresponding priority to indicate its accessing probability. In the IEEE 802.11p EDCA 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 IEEE 802.11p EDCA scheme, we design the AC factor based on the approximate accessing probabilities of different ACs calculated in the IEEE 802.11p EDCA scheme.

From the work in [12], we know that the accessing probability of a certain AC is approximately inversely proportional to its corresponding minimum CW, which means that

$$\mathrm{Pr}_{\mathrm{AC}}(j) \approx \frac{1}{\mathrm{CW}_{\min}(\mathrm{AC}_j)} \tag{5}$$

where $\mathrm{Pr}_{\mathrm{AC}}(j)$ denotes the accessing probability of AC_j, $j = 1, 2, 3, 4$. Note that the minimum CWs of AC_1 and AC_2 defined in the IEEE 802.11p EDCA scheme have the same value 3; therefore, in order to distinguish the accessing probability of these two ACs, we employ the maximum CW factor into the design of the AC factor. Then, the AC factor of AC_j in our proposed scheduling protocol indicating the different accessing probabilities of different ACs can be designed as

$$\mathrm{ACF}_j = \frac{1}{\mathrm{CW}_{\min}(\mathrm{AC}_j)} + \frac{1}{\mathrm{CW}_{\max}(\mathrm{AC}_j)} \tag{6}$$

where $\mathrm{CW}_{\min}(\mathrm{AC}_j)$ and $\mathrm{CW}_{\max}(\mathrm{AC}_j)$ are given in Table I.

B. Resource-Reusing Mode for V2V Communication Links

As illustrated in Fig. 2, in the proposed centralized scheduling protocol, we also employ a novel resource-reusing mode for different V2V communication links. Different V2V communication links are permitted to share the same time slots for their individual data transmissions if and only if the distances between every two c-vehicles of these V2V communication links exceed a predefined interference

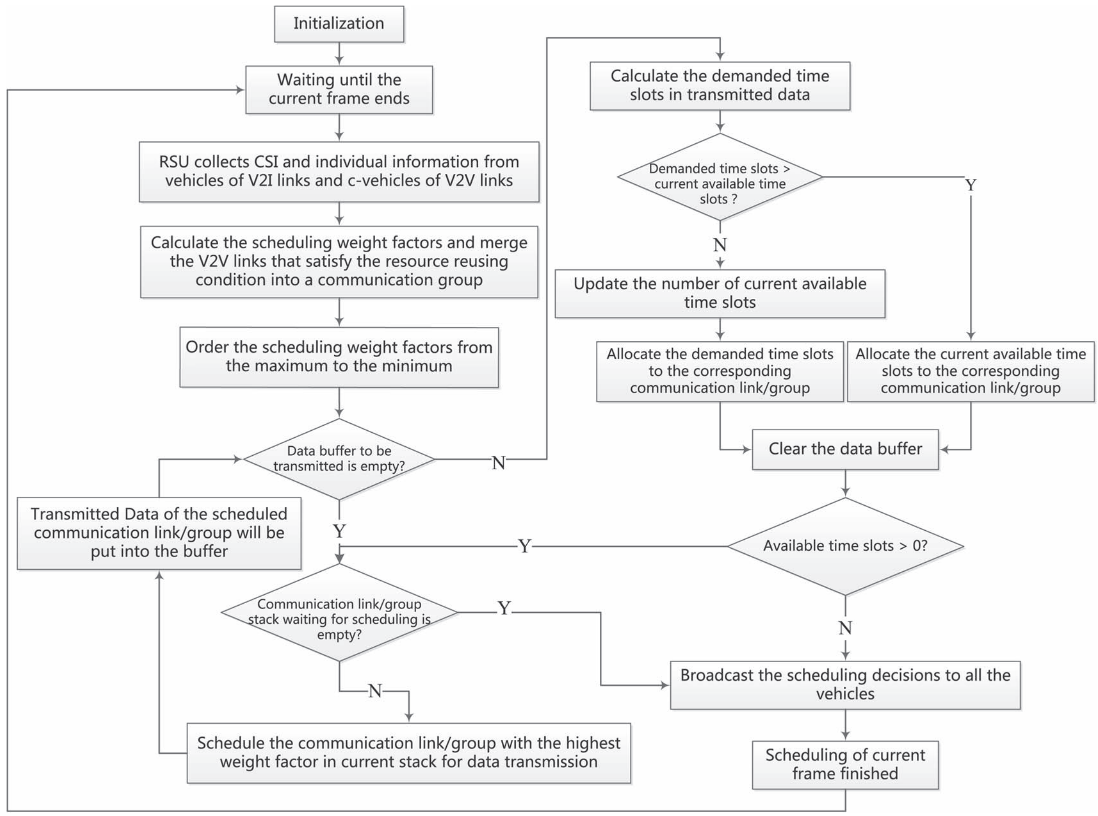

Fig. 3. Flow diagram of the proposed weight-factor-based scheduling algorithm.

interval D_{in} (here, we set $D_{\text{in}} = 2R_v$, where R_v is the communication radius of the vehicle). The V2V communication links that meet the condition of the resource-reusing mode will then merge into an enhanced communication group, the scheduling weight factor of which is the sum of the scheduling weight factors of all the communication links in it. Note that, in our designed protocol, V2I communication links are not permitted to share the resource with other communication links (either V2V communication links or V2I communication links). The RSU sorts the scheduling weight factors of all the communication links/groups in a decreasing order, and then, the communication link/group with a bigger scheduling weight factor will be prioritized in the data transmission scheduling.

C. Weight-Factor-Based Scheduling Algorithm

The procedure of the weight-factor-based scheduling algorithm is provided in Fig. 3. During the scheduling process, the RSU collects the reported information, including the current channel state information, the position and relative speed information, and the transmission AC information from the vehicles/c-vehicles within its communication coverage, and it updates the scheduling weight factors of the ACs of each communication link at the beginning of each transmission frame. Note that any V2V communication link meeting the condition of the resource-reusing mode will be merged into an enhanced communication group, and the scheduling weight factor of the communication group is the sum of the scheduling weight factors of all the V2V communication links in it. The scheduling weight factors of the communication links/groups are then sorted in the decreasing order. The AC of a communication link with a higher scheduling weight factor will be always prioritized in the current transmission frame until its transmission demand is met. This scheduling process continues until all transmission requests are satisfied or the time slots in the current transmission frame are completely scheduled; then, the RSU will broadcast the scheduling decisions to all vehicles, based on which the communication links acquiring resources can perform their individual data transmissions during the allocated time slots.

TABLE II
SIMULATION PARAMETERS

Parameters	Value
Channel Bandwidth	10 MHz
Transmit Power of RSU	40 dBm
Transmit Power of Vehicle	20 dBm
Communication Radius of RSU	500 m
Communication Radius of Vehicle	100 m
Interference Interval D_{in}	200 m
Small Scale Fading	Rayleigh fading coefficient $\mathcal{CN}(0,1)$
Path Loss Model	$-12.88 + 35.22\log_{10}(d(\text{m}))$ dB
Velocity of Vehicles	30 - 60 km/h
Time Slot Duration	8 us

IV. SIMULATIONS AND DISCUSSIONS

In this section, we evaluate the efficiency of the proposed centralized TDMA-based scheduling protocol by conducting the following simulations. For simplicity, we only consider one RSU, and all the vehicles investigated are randomly located within the communication coverage of the RSU. Note that, when there are multiple RSUs in the network, each RSU can independently perform our proposed scheduling protocol to serve the communication links within its control area; thus, our proposed protocol can be effectively employed in a scenario with multiple RSUs. The simulation parameters are set in Table II.

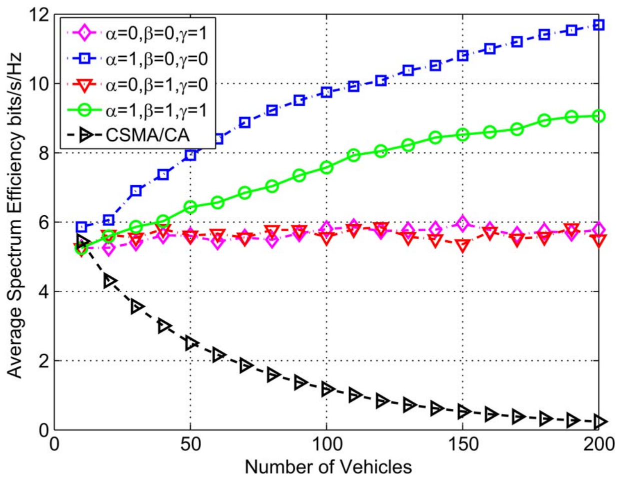

Fig. 4. Average spectrum efficiency performance in the proposed TDMA-based scheduling protocol and the IEEE 802.11p CSMA/CA-based EDCA scheme.

Fig. 4 shows the performance comparison in terms of the average spectrum efficiency (defined as the network throughput over the unit bandwidth) between the proposed TDMA-based scheduling protocol and the IEEE 802.11p CSMA/CA-based EDCA scheme in [4]. In Fig. 4, we can see that the spectrum efficiency achieved in our proposed TDMA-based scheduling protocol has a significant performance gain compared with that in the IEEE 802.11p CSMA/CA-based EDCA scheme, particularly when the number of vehicles in the investigated vehicular network is large. Note that, when the number of vehicles in the investigated vehicular network is large, although we do not incorporate the channel quality factor into the scheduling weight factor in our proposed scheduling protocol, i.e., setting $\alpha = 0$, the performance of our proposed scheduling protocol is still much better than that of the IEEE 802.11p CSMA/CA-based EDCA scheme. This is because when the number of vehicles is large, the collisions among different communication links accessing the same time slots are more likely, which leads to the significant failure of data transmission and, thus, noticeable degradation in the network performance. In addition, note that, with our proposed scheduling protocol, the performance under conditions $\alpha = 1$, $\beta = 0$, and $\gamma = 0$ is always better than that under conditions $\alpha = 1$, $\beta = 1$, and $\gamma = 1$; however, with the speed factor and the AC factor incorporated into our proposed scheduling protocol, it can achieve much better fairness.

Fig. 5 shows the cumulative distribution function (cdf) performance comparison of the network throughput between the proposed TDMA-based scheduling protocol and the IEEE 802.11p CSMA/CA-based EDCA scheme with a heavy traffic load ($K = 100$) and a light traffic load ($K = 20$), respectively. Here, in our proposed scheduling protocol, we set $\alpha = 1$, $\beta = 1$, and $\gamma = 1$. Note that K represents the total number of vehicles in the considered communication area, which can indicate the current traffic load in the investigated network. In Fig. 5, we can see that the proposed TDMA-based scheduling protocol always has a significant performance gain than the IEEE 802.11p CSMA/CA-based EDCA scheme whether the traffic load is light or heavy. With the IEEE 802.11p CSMA/CA-based EDCA scheme, the network performance significantly degrades from when the traffic load is turning from light to heavy, whereas with the proposed TDMA-based scheduling protocol, there even exists a network performance gain in the heavy-traffic-load case compared with the light-traffic-load case due to the multiuser diversity gain. This indicates that our proposed centralized TDMA-based scheduling protocol has much enhanced robustness against a heavy traffic load in vehicular networks in terms of the network performance.

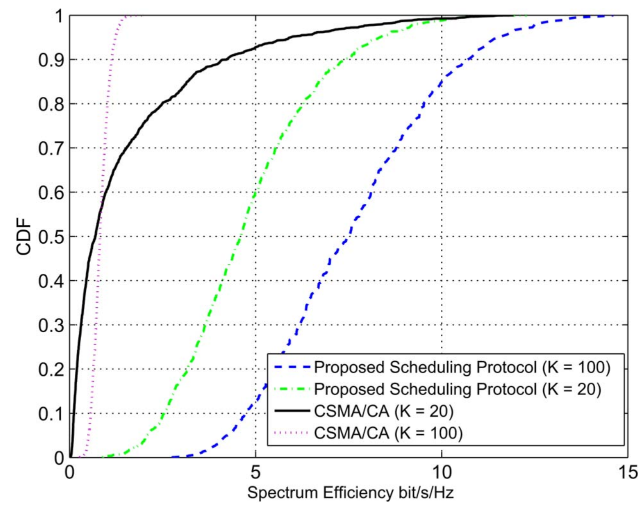

Fig. 5. CDF performance of the spectrum efficiency in the proposed TDMA-based scheduling protocol and the IEEE 802.11p CSMA/CA-based EDCA scheme.

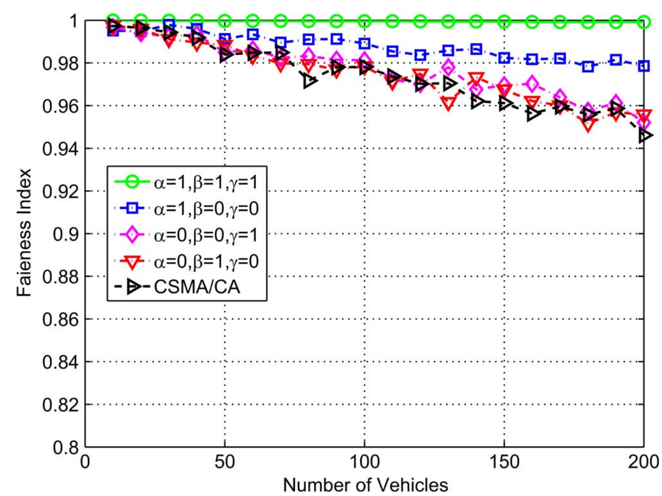

Fig. 6. Fairness coefficients in the proposed TDMA-based scheduling protocol and the IEEE 802.11p CSMA/CA-based EDCA scheme.

Fig. 6 shows the fairness coefficients in our proposed TDMA-based scheduling protocol and the IEEE 802.11p CSMA/CA-based EDCA scheme. Note that according to the definition of a fairness coefficient in [12], a value closer to 1 means a more fair situation, and 1 indicates absolute fairness among all communication links. In Fig. 6, we can see that the fairness coefficient with all the three weight factors (i.e., the channel quality factor, the speed factor, and the AC factor) in the proposed scheduling protocol, as well as that in the IEEE 802.11p CSMA/CA-based EDCA scheme, is closer to 1 than those without any of the weight factors, which verifies the efficiency of the designed weight factors in our proposed scheduling protocol in solving the fairness problem in vehicular networks.

Fig. 7 shows the cdf of the network throughput of different ACs in the proposed TDMA-based scheduling protocol. In Fig. 7, we can see that the AC with a higher priority has better performance in terms of the network throughput, which indicates that it has a higher probability for data transmission. This verifies the efficiency of the AC factor in distinguishing the different priorities of different ACs.

Fig. 8 shows a performance comparison in terms of the network transmission delay between the proposed TDMA-based scheduling

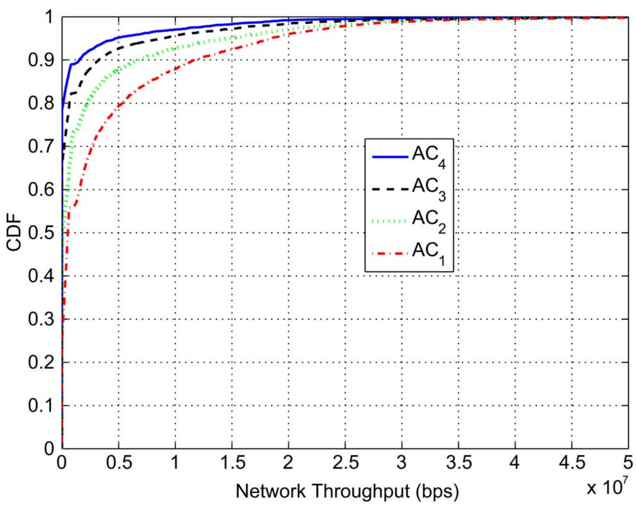

Fig. 7. CDF of the network throughput of different ACs in the proposed TDMA-based scheduling protocol.

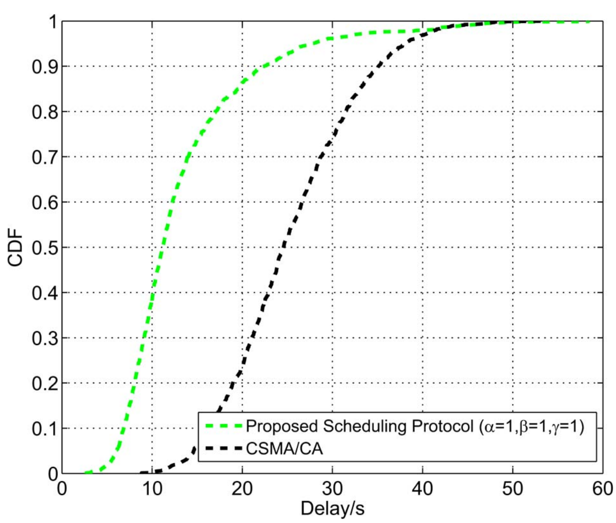

Fig. 8. CDF of the network transmission delay.

protocol and the CSMA/CA-based scheme. In this simulation, we consider 40 V2I links and 40 V2V links in a vehicular network with one RSU, where each link has a transmission demand for a 100-KB data file. Here, the network transmission delay is defined as the sum of the delay for the data file transmission of all the links in the investigated network. In Fig. 8, we can find that the network transmission delay of the proposed protocol is much smaller than that of the CSMA/CA-based scheme, which verifies the efficiency of the proposed protocol in decreasing the network transmission delay.

V. Conclusion

In this paper, we have proposed a novel centralized TDMA-based scheduling protocol for vehicular networks based on a new weight-factor-based scheduler. The designed scheduling weight factor mainly consists of three parts, i.e., the channel quality factor, the speed factor, and the AC factor. In addition, a novel resource-reusing mode for multiple V2V links was provided. Compared with the existing MAC protocols in vehicular networks, the proposed centralized TDMA-based scheduling protocol can significantly improve the network throughput performance and meanwhile guarantee the QoS fairness among the communication links in vehicular networks.

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