# Priority-Based Multi-carrier Access Schemes for Safety Message Transmission in Vehicular Networks

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**Abstract.** With the explosive growth of vehicles, current vehicular networks, based on CSMA/CA, are unable to guarantee the low latency and high reliability for safety message transmission under heavy traffic condition. In this paper, we propose a Priority-based Multi-carrier Random Access with Carrier Switching (PMRA/CS) scheme, which is designed for OFDMA-based vehicular networks to support massive concurrent access of large number of vehicles. Compared to CSMA/CA, PMRA/CS utilizes a special short detecting frame to resolve the alarm message collision with less cost. Moreover, the scheme provides more opportunities for vehicles to access the channel in one period by allowing the loser of one sub-carrier to switch to another idle one and continue to access contention. Use of vehicle priority assignment makes the proposed strategy more applicable to realistic scenarios. Furthermore, we provide some theoretical analysis of the proposed scheme combined with derived formula derivation. Simulation results are provided to demonstrate the improvements of message sending success rate and average delay reduction of our proposed scheme.

**Keywords:** PMRA/CS · Concurrent access · Conflict resolution
Vehicle priority

## 1 Introduction

As a promising approach to bring real-time traffic condition and vehicle driving information in a large area to the users, vehicular networks attract considerable interest recently. By providing efficient communication between vehicles and road side infrastructure, vehicular networks are helpful in decreasing traffic and improving the driving experience. Furthermore, with the aid of accurate and reliable information in vehicular networks to prevent accident, road safety can be further enhanced. However, the strict latency requirement in traffic warning message dissemination and the high mobility of vehicles make the design of efficient transmission schemes in vehicular networks a challenge [1].

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To reduce data transmission delay and boost the reliability of safety-critical messages sent by vehicles, it is essential to design an efficient way to allocate channel resource. In [2], IEEE 802.11p/WAVE (Wireless Access in the Vehicular Environment), supporting high-speed mobile communication, is used to provide vehicle services. However, WAVE cannot support the absolute priorities of different types of messages to access the resource. Besides, the hidden terminal and high latency problem in high-density traffic flow remain unsolved [3–5]. In the last few years, a variety of researches suggest that the advanced communication systems, such as long-term evolution (LTE) 4G or 5G technology using orthogonal frequency division multiple access (OFDMA) could replace WAVE networks [6]. Hidden terminal problem was avoided through the allocation of resources. The authors in [7] show that LTE-V is feasible in vehicular scenarios. In [8], a multiple access mechanism of OFDMA was compared with the CSMA/CA in IEEE 802.11p and the results showed a higher delivery rate and lower delivery delay of OFDMA in high-load conditions. Use of OFDMA for alert message was discussed in [9]. It improved reliability and resource use efficiency, while this solution had a drawback of an increase in delivery delay. In summary, previous works mainly focused on delay-insensitive scenarios leaving the message transmission with strict delay constraints scarcely considered. Additionally, message loss problem caused by conflicts in heavy density traffic is totally ignored.

In this paper, we mainly focus on dynamic resource allocation and sub-carrier competition mechanism for safety-related messages in vehicular networks. An OFDMA-based access method with vehicle priorities is proposed. We achieved in our scheme a high sending success rate and low average delay in high-density networks. Specifically, the main contents and contributions of this paper are as follows.

Firstly, we propose the concept of vehicle priority. Vehicles access the channel in different ways according to their priorities. Therefore, special public vehicles with high-priority, such as police vans, ambulances, fire engines and engineering rescue vehicles could access first using the assigned resource. Other ordinary vehicles access sub-carriers in competition.

Secondly, an efficient channel utilization access scheme, named PMRA/CS is proposed. PMRA/CS uses a short detecting frame to resolve collisions of emergency warning messages. Reduction of alarm message loss improves traffic safety and reliability level.

Thirdly, in the course of channel sense, vehicles can not only confirm success of access, but also recognize the idle sub-carriers to further reuse. Specifically, if a vehicle fails to access on one sub-carrier, it would switch to another idle one and continues to contend for channel access. Since the PMRA/CS scheme provides more opportunities for vehicles to access the channel in one period, the efficiency of special reuse will be improved, especially for the massive vehicles scenario.

The remainder of this paper is structured as follows: Sect. 2 describes the system model. Next, Sect. 3 presents the channel allocation scheme and details of the PMRA/CS competitive strategy. Thereafter, we compare simulation results with CSMA/CA mechanism in Sect. 4. Finally, conclusions are summarized in Sect. 5.

## 2 System Model

Figure 1(a) shows the OFDMA-based vehicular networks communication system. In the system, a base station locates on the side of a bidirectional two-lane highway, providing communication services to vehicles and controlling resource allocation. Base stations allocate bandwidth to traffic safety service separately, avoiding interference with the normal messages [10]. A number of vehicles moving in different directions access vehicular wireless networks. Considering the practical situation, we divide vehicles into two groups according to their traffic modes. One group is the vehicles that involve public safety such as ambulances. The system should guarantee these special vehicles with high-priority to access the vehicular networks even when the channel resource is in shortage. The other group is ordinary vehicles with lower priority. Different groups will adopt certain access methods under the control of the base station.

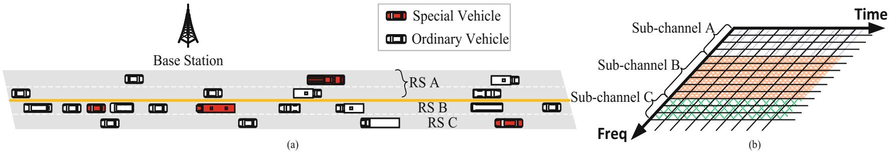


**Fig. 1.** (a) The scenario shows four road sections in two directions and different traffic flows. (b) Sub-channel resource allocation based on road sections.

We assign separated resource to vehicles in opposite directions to reduce collisions. Also, traffic flows can be different for each road section (RS). Dynamic resource allocation according to traffic flows can make channel resource to be utilized more efficiently [11]. In OFDMA-based system, sub-channels are assigned to each section in accordance with direction and vehicle flows. Then, vehicles use the sub-channel belonging to their section to send safety-critical messages.

In this paper, vehicles receive the signal of all bands, which means that they can collect all occupied sub-carriers and free sub-carriers. Assume $N$ sub-carriers are to support $K_o$ ordinary vehicles and $K_s$ special vehicles. Vehicles of the same type have a fixed probability to generate critical safety message. Let $p_o$ and $p_s$ represent the alarm probability of ordinary and special vehicles, respectively.

## 3 Sub-channel Resource Allocation and Sub-carrier Contention Strategy

This section describes a distributed-centralized combination structure that contains a roadside system controlling resource allocation and vehicles using PMRA/CS strategy to access sub-carriers.

### 3.1 Resource Allocation Arrangement

In vehicular environment, in order to guarantee high reliability and low latency for the safety messages delivery, the roadside system as the control center should fulfill two requirements as follows.

Firstly, roadside system dynamically allocates sub-channel resource based on the driving direction and vehicle density. The roadside system receives traffic information from sensors or vehicle beacon messages. According to the traffic information, the roadside system adjusts the number of sub-carrier to different road sections to achieve resource dynamical equilibrium. In addition, the dynamic partition of resource also decreases channel interference and suppresses the hidden terminal problem.

Secondly, the roadside system only assists vehicles to contend for sub-carriers rather than allocating sub-carriers to the vehicles. The reason is that the procedure of allocation will introduce high latency, which will increase safety risks. Thus, vehicles need to access sub-carrier in a competitive way.

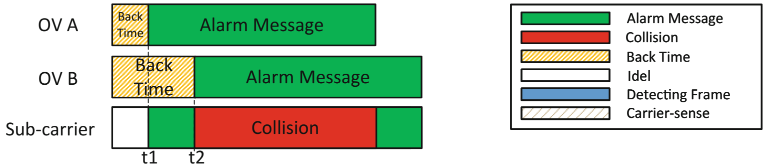
The carrier access scheme is related to vehicle priority. When a vehicle enters the coverage of a new cell, it will send a message regarding its priority to the roadside system. The roadside system chalks up the priority level and provides the appropriate access strategies. There are two ways for vehicles to use sub-carrier resource: fixed allocation and competition. Special vehicles have right to access the channel first without competition. In general, the number of high priority vehicles is less than the number of sub-carriers. Thus, the roadside system would allocate a certain sub-carrier named exclusive sub-carrier directly to each special vehicle. When special vehicles need to alarm, they send safety-critical messages using their private exclusive sub-carriers rapidly. On the other hand, ordinary vehicles have a large number. Channel resource may not be enough when lots of vehicles need to send messages simultaneously. The roadside system informs the ordinary vehicles information about the directly available sub-carriers, exclusive sub-carriers and the competitive approach. In CSMA/CA, an ordinary vehicle can just choose directly available sub-carriers. The exclusive sub-carriers are likely to be wasted. Therefore, it is important to design an efficient access scheme to reuse the wasted resources.

### 3.2 PMRA/CS in Wireless Vehicular Networks

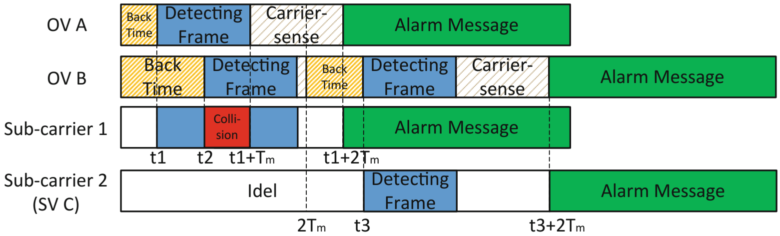
Except for wasted resources, message collision is another main factor to degrade the performance of vehicle networks. Under the emergency state, ACK messages and continuous retransmission are not allowed. Hence, message collision directly contributes to alarm message loss. Although CSMA/CA mechanism already satisfies the requirement of collision avoidance and enhances the channel access performance, it is still possible for safety messages to be collided because of message delay. Assume that the vehicle system is identical and stable, and message delay $T_m$ can be regarded as a fixed value. Obviously, $T_m$ is shorter than the entire transmission cycle $T$. However, it still will affect the message transmission success rate.

In this paper, a transmission cycle consists of contention period (CP) and data period (DP). Figure 2(a) and (b) illustrate the competitive process using CSMA/CA and PMRA/CS schemes. In Fig. 2(a) vehicle A has already generated a message at $t_1$, and other vehicles don't receive its message until $t_1 + T_m$. When the back-off time of vehicle B is over at $t_2$, it will also start to send a message. Such message conflicts cannot be avoided by CSMA/CA, while PMRA/CS scheme using detecting frame and carrier-sense solves the message conflict perfectly.

The contention period of PMRA/CS is distributed into random back-off, detecting frame and carrier-sense stages. In random back-off period, to reduce collisions, PMRA/CS uses a random back-off process. Unlike CSMA/CA mechanism, PMRA/CS has a collision avoidance control which prevents the collisions from message delay $T_m$. To simplify the model, the maximum back-off time is set as long as the message delay $T_m$. After random back-off period, the system goes into detecting frame period. Vehicles broadcast a detecting frame instead of an alarm message. When nodes send messages, they are unable to accept messages at the same time. It means that vehicles are unaware if detecting frame collisions occur. The duration of detecting frame is set as $T_m$ in accordance with the maximum difference between maximum and minimum back-off time. Otherwise, vehicles with longer back-off time may miss the detecting frame of the other vehicles in carrier-sense period. In carrier-sense period, carrier-sense is the key step in CP, because vehicles can confirm whether they can successfully access the sub-carriers and prepare for second competition in this period. At the beginning of this period, vehicles stop sending the detecting frame and listen for the frames from others. If the selected channel is idle, it means the vehicle is the only one in this sub-carrier or it has the shorter back-off time than all other competitors. Thus, the vehicle could send alarm message using the sub-carrier. Before sending messages, the successful vehicles still need to wait $T_m$ to avoid conflicts between their alarm messages and detecting frames of other vehicles. Failed competitors will receive detecting frame signal from others immediately. They will give up the chosen sub-carriers and the intercept signal of all bands to find free sub-carriers. At $2T_m$, failed access vehicles could reuse free sub-carriers by re-competition.



(a)Example of vehicles compete a sub-carrier adopting CSMA/CA



(b)Example of vehicles compete sub-carriers adopting PMRA/CS

**Fig. 2.** Collision scenarios in sub-carrier competition

As shown in Fig. 2(b) vehicle A and B choose sub-channel 1 first. Utilizing PMRA/CS, Vehicle A successfully accesses the sub-carrier 1 and sends an alarm message, while B gives up this sub-carrier and senses again for free sub-carriers. Then, B starts a new round of competition, and accesses the sub-carrier 2 which belongs to special vehicle C, but not used in this transmission cycle. Thus, it can be seen that PMRA/CS reduces message loss, and idle sub-carrier is fully utilized in a transmission cycle.

Contention period of PMRA/CS quickly and efficiently determines the only user in each sub-carrier. When the carrier-sense period is over, access vehicles start to send messages. If the remaining time of CP permits, PMRA/CS allows failed vehicles to compete for idle sub-carriers again. The advantages of PMRA/CS are reducing alarm message loss and improving the channel utilization rate in every cycle period.

### 3.3 Analysis on Sending Success Rate and Sending Delay

Compared with the traditional CSMA/CA method, PMRA/CS takes resource reuse and delay time $T_m$ into account. The carrier utilization is improved significantly and the message loss caused by delay is avoided. The improvements are critical for emergency scene.

Assume that $x$ vehicles compete in one sub-carrier. Each vehicle selects a certain back-off time. We order their back-off time from the smallest to the largest: $[T_1, T_2, \ldots, T_x]$. Suppose there is no same back-off time, so that the vehicle with the smallest back-off time always gets the channel resource in PMRA/CS. However, in CSMA/CA, channel conflict occurs if $T_2 < T_1 + T_m$. The vehicle with back-off time $T_2$ will send the message because it doesn't receive any signal when its back-off time is over. In the sending process, wireless nodes cannot sense the channel. The vehicles cannot realize the conflicts until the end of the transmission. The warning information would be lost owing to collision. It also brings a serious wastage of channel slots.

At first, without considering vehicle priority, we assume that total of $K$ vehicles with alarm probability $p$ per cycle. $N$ sub-carriers are allocated to these vehicles. In one cycle, $P_m$ is the probability that m vehicles need to send an alert.

$$P_m = C_K^m p^m (1-p)^{K-m} \tag{1}$$

Let $\mathrm{D}(m, N, l)$ denote the possible combinations that $m$ vehicles randomly compete $N$ sub-carriers and eventually $l$ sub-carriers are used in one competition.

$$\mathrm{D}(m, N, l) = \begin{cases} 1 & l = N = 0,\ or\ l = m = 0 \\ C_N^l \left( l^m - \sum\limits_{i=0}^{l-1} D(m, l, i) \right) & N \geq l > 0,\ m \geq l \\ 0 & elsewhere \end{cases} \tag{2}$$

When repeating PMRA/CS competitive strategy, the average sending success rate becomes to $P_{\mathrm{PMRA/CS-2}}$ in one cycle.

$$P_{\text{PMRA/CS}-2} = \frac{\sum_{m=0}^{K}\left(P_m \cdot \sum_{l=0}^{\min(m,N)}\left(l \cdot \frac{D(m,N,l)}{N^m} + \sum_{i=0}^{\min(m-l,N-l)} i \cdot \frac{D(m-l,N-l,i)}{(N-l)^{m-l}}\right)\right)}{Kp} \tag{3}$$

Simply make sure the sum time of contention period and data period is no more than a cycle time $T$ and the PMRA/CS system supports contention counts as many as possible. The sending success rate will improve with the increase of competition count.

In terms of transmission delay, it includes a random back-off time, sending detecting frame and waiting time. When s vehicles compete in one sub-carrier, the average value of the minimum back-off time $T_{min}$:

$$T_{min} = T_m \int_{t=0}^{1} t(1-t)^{s-1} dt = \frac{T_m}{s+1} \tag{4}$$

Let $\overline{T}_{\text{PMRA/CS}}$ be the average delay which is based on the unit of $T_{m.}$

$$\overline{T}_{\text{PMRA/CS}} = \frac{\sum_{m=0}^{K}\left(P_m \cdot \sum_{l=0}^{\min(m,N)}\left(l \cdot \frac{D(m,N,l)}{N^m} \cdot \sum_{s=0}^{m-l+1} \frac{(2s+3)T_m}{s+1} K(m,l,s)\right)\right)}{KpP_{\text{PMRA/CS}}} \tag{5}$$

$K(m,l,s)$ is the probability of $s$ vehicles in one channel when $m$ vehicles choose a total of $l$ sub-carriers.

$$K(m,l,s) = \begin{cases} 1 & m = s = 0,\ or\ l = s = 0 \\ \frac{C_m^s \cdot D(m-s,l-1,l-1)}{D(m,l,l)} & m \geq s > 0,\ m \geq l > 0,\ m \geq s + l - 1 \\ 0 & elsewhere \end{cases} \tag{6}$$

In CSMA/CA, let us assume the back-off time is a random time in $(0, iT_m]$. If $s$ vehicles compete in one sub-channel, $P_c(s,i)$ means the conflict-free rate of this channel and $T_c(s,i)$ is the average delay of the message.

$$P_c(s,i) = \begin{cases} 1 & s = 1 \\ \frac{(i-1)^s}{i^s} & s > 1,\ i > 1 \\ 0 & elsewhere \end{cases} \tag{7}$$

$$T_c(s,i) = \begin{cases} \frac{iT_m}{2} & s = 1 \\ \frac{(i-1)T_m}{s+1} & s > 1,\ i > 1 \\ 0 & elsewhere \end{cases} \tag{8}$$

The average sending success rate and delay are computed as in Eqs. (9) and (10).

$$P_{CSMA/CA} = \frac{\sum_{m=0}^{K} P_m \cdot \sum_{l=0}^{\min(m,N)}\left(l \cdot \frac{D(m,N,l)}{N^m} \cdot \sum_{s=0}^{m-l+1} P_c(s,i)K(m,l,s)\right)}{Kp} \tag{9}$$

$$\overline{T}_{CSMA/CA} = \frac{\sum_{m=0}^{K} P_m \cdot \sum_{l=0}^{\min(m,N)} \left( l \cdot \frac{D(m,N,l)}{N^m} \cdot \sum_{s=0}^{m-l+1} P_c(s,i) T_c(s,i) K(m,l,s) \right)}{KpP_{CSMA/CA}} \tag{10}$$

The success probability of PMRA/CS is significantly higher than that of CSMA/CA. However, the average delay time in CP is longer than in PMRA/CS because sending short detecting frame and carrier-sense time needs at least $2T_m$. In addition, repeating competitive strategy also increases the delay. In other words, PMRA/CS sacrifices sending delay for success rate in transmission. The message delay time is so short that it has a minimal impact on the vehicular system. Nevertheless, the improvement of message sending success rate is significant. Therefore, PMRA/CS can provide safety and reliability in theory for improving the performance of the vehicular networks.

## 4 Simulation

In this section, we compare the performance of multi-carrier CSMA/CA and PMRA/CS using MATLAB.

To better explain research achievement, we did a simulation to compare four strategies: N_PMRA/CS, P_PMRA/CS, N_CSMA/CA and P_ CSMA/CA. N means to consider the vehicle priority. Special vehicles will have exclusive sub-carriers, and ordinary vehicles use competitive strategies to access. P indicates that all vehicles compete all sub-carriers. We will verify the proposed algorithm using the parameters in Table 1. If vehicles which need to alarm fail to access the channel in the first cycle, they will try to retransmission at most two times. In other words, every alarm message has three opportunities to be sent. Once failed three times in a row, alarm messages will be discarded.

**Table 1.** Simulation parameters

| Parameter | Value |
|---|---|
| Duration of contention period | 5 $T_m$ |
| Maximum message retransmission count | 2 |
| Competition count in PMRA/CS | 2 |
| Total simulation cycle number | 10000 |
| Number of special vehicle ($K_s$) | 2 |
| Message sending probability of special vehicle ($p_s$) | 0.6 |
| Message sending probability of ordinary vehicle ($p_o$) | 0.3 |

Figure 3(a) shows the success rate of sending messages using four strategies mentioned above with a different total number of vehicles or channel resource. N_PMRA/CS and P_PMRA/CS are always superior to others. Even the vehicles surge, N-PMRA/CS and P_PMRA/CS still maintain a success rate of ninety percent. When channel resource is in severe shortage, dedicating sub-carriers for special vehicles causes performance degradation. If accessible sub-carriers are relatively plentiful, this approach is very unlikely to have any effect on sending success rate. Although exclusive channels may impact the whole system, it is reasonable and practical. In a word, PMRA/CS greatly improves the success rate of sending messages compared to CSMA/CA.

The average transmission count of four strategies is shown in Fig. 3(b). The average number becomes higher with vehicle number increasing or sub-carrier number decreasing. It can be seen that PMRA/CS cannot stay ahead of the other two CSMA/CA strategies, particularly when the ratio of vehicle number to resource number is great. The primary cause of this phenomenon is the collision due to message delay $T_m$. In PMRA/CS, message loss only happens when a vehicle failed the competition for channel 3 times in a row. But beyond that the channel collision will directly raise data packet loss in CSMA/CA. Message dropping makes the demand for retransmission decrease, and it brings a high rate of packet loss.

From the results in Fig. 3, it can be seen that PMRA/CS has a higher success rate of sending messages. For the transmission time, PMRA/CS functions well for six sub-channels, while performing poorly in four sub-channels when the vehicle number is large. To better explain the relationship between sending success rate and average sending time, we will give one specific example with more detailed information.

We choose experiment of twelve ordinary vehicles and two special vehicles as an example. In the simulation, the transmission time of each alarm message is counted. The simulation result is shown in Fig. 4. PMRA/CS for four sub-carriers has a relatively high proportion of two or three times transmissions, while the failure rate is high in CSMA/CA. However, when computing an average transmission time, a failure message will be excluded. This is the reason that CSMA/CA method is sometimes better than PMRA/CS in respect of average transmission time.

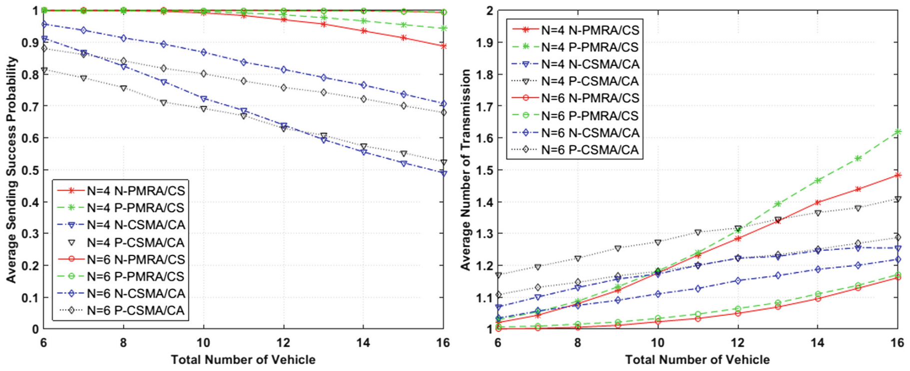


**Fig. 3.** (a) The average sending success rate. (b) The average number of transmission.

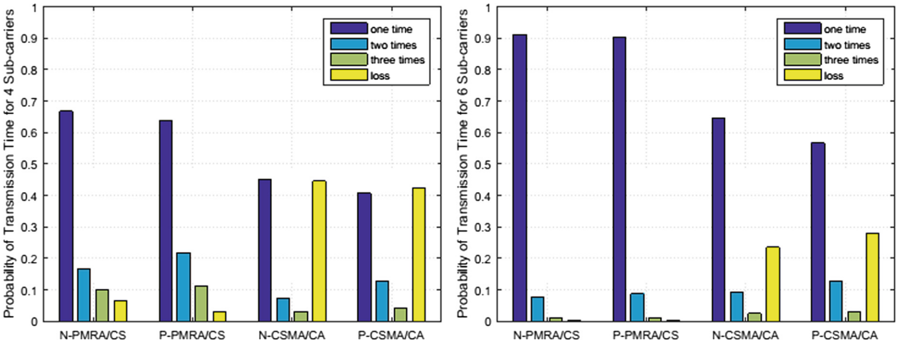


**Fig. 4.** (a) Probability of transmission time for 4 sub-carriers. (b) Probability of transmission time for 6 sub-carriers.

## 5 Conclusion

In this paper, we proposed a vehicular priority-based channel allocation and sub-carrier access scheme for LTE-V networks. Vehicle priority changes the original vehicle alarm model, thus making full use of the channel resource. Then, the PMRA/CS scheme modifies the traditional contention access in wireless communication systems by adding detecting frame and carrier-sense stages to reuse idle resource and avoid message collision. Compared with multi-channel CSMA/CA mechanism, the message loss decreases and resource utilization rate rises. Theoretical analysis and simulation results prove the proposed method to be effective with respect to increasing sending success rate and reducing the average transmission time in heavy traffic. The achievements in this paper can improve future vehicular communication systems in the aspects of safety and reliability.

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