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A Scalable CSMA and Self-Organizing TDMA MAC for IEEE 802.11 p/1609.x in VANETs

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Abstract vehicular ad hoc networks (VANETs) have been a key topic for research community and industry alike. The wireless access in vehicular environment standard employs the IEEE 802.11p/1609.4 for the Medium Access Control (MAC) layer implementation for VANETs. However, the carrier sense multiple access (CSMA) based mechanism cannot provide reliable broadcast services, and the multi-channel operation defined in IEEE 1609.4 divides the available access time into fixed alternating control channel intervals (CCH) and service channel (SCH) intervals, which may lead to the low utilization of the scarce resources. In this paper, a novel multichannel MAC protocol called CS-TDMA considering the channel access scheduling and channel switching concurrently is proposed. The protocol combines CSMA with the time division multiple access (TDMA) to improve the broadcast performance in VANETs. Meanwhile, the dwelling ratio between CCH and SCH changes dynamically according to the traffic density, resulting in the improvement of resource utilization efficiency. Simulation results are presented to verify the effectiveness of our mechanism and comparisons are made with three existing MAC protocols, IEEE MAC, SOFT MAC and VeMAC. The simulation results demonstrate the superiority of CS-TDMA in the reduction of transmission delay and packet collision rate and improvement of network throughput.

Keywords VANETs · CSMA · TDMA · Channel switching

1 Introduction

A VANET is formed by the connection and communication between a set of vehicles without central scheduling. Dedicated short range communication (DSRC) refers to the use of vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communications in a VANET. The former one is realized by connection through on-board units (OBUs) equipped in each vehicle and

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the latter one is for communication between vehicles and the set of roadside units (RSUs). Based on these two modes of communications, VANETs can support mainly three types of applications, namely safety applications, infotainment services and traffic management applications [1]. Motivated by the enormous potential of the applications in VANETs, both the United States and Europe have allocated a 75 MHz spectrum in the 5.9 GHz band for DSRC. The spectrum is further divided into seven 10MHz channels out of which one control channel (CCH) is dedicated for control and safety messages and six service channels (SCHs) for non-safety infotainment services data.

Among various applications, safety related applications have been considered as the most critical ones in VANETs. Basic safety messages, also known as beacons, should be transmitted by each vehicle in a frequency of typically 5–10 Hz to discover nearby vehicles and share its position, speed, direction with its neighbors. It is vital that event-driven messages should be transmitted within its lifetime that is usually bounded within 500 ms [2] so as to realize the crash warning, traffic signal violation avoidance and calling ambulance, etc. In a word, safety messages have stringent requirements on real-time and highly reliable transmission. Broadcast is considered as the primary traffic for safety applications, because all vehicles are stakeholders for the safety of the transportation system. However, due to the lack of feedback messages, broadcasting suffers from the hidden terminal problem, high collision probability and the lack of collision detection. The fast-changing network topology and vehicle mobility make the real-time and reliable broadcasting more challenging. Therefore one of the most important issues before the actual success of VANETs appears to be the design of an efficient medium access control (MAC) protocol [3].

Various MAC protocols have been proposed for VANETs. In particular, the wireless access in vehicular environment (WAVE) standard employs the IEEE 802.11p/1609.4 [4,5] for the MAC layer implementation. The IEEE 802.11p is derived from IEEE 802.11e enhanced distributed channel access (EDCA) function. Since the lack of RTS/CTS exchange and acknowledgements for broadcast messages results in the hidden terminal problem and collisions, the IEEE 802.11p cannot provide guaranteed quality-of-service (QoS), particularly for the safety applications in dense VANETs. As for the upper layer, the IEEE 1609.4 conceives an alternating scheme for a synchronization interval of fixed 100 ms, consisting of equal duration CCH and SCH intervals. All the vehicles must monitor the CCH for safety messages and WAVE Service Advertisement (WSA) exchange, and during the SCH interval, they can switch to one of the SCHs optionally to perform non-safety applications. Time synchronization can be realized based on the Coordinated Universal Time (UTC) provided by the global navigation satellite system. The multichannel operation enhances the IEEE MAC layer performance. Nevertheless, the fixed dwelling ratio between CCH and SCH is not adaptive to the fast changing traffic density of VANETs. When the network traffic is dense, the limited duration of CCH is not enough for all vehicles to transmit their safety messages. When the network is sparse, the bandwidth of CCH will be wasted, consequently large size streaming files cannot get enough bandwidth on the SCHs.

Due to the inherent drawback of CSMA access scheme, there have been many works considering time division multiple access (TDMA) [6–9], space division multiple access (SDMA) [8–10] and code division multiple access (CDMA) [11] based MAC protocols to improve the channel access reliability and efficiency. Recently, TDMA based MAC mechanisms have been paid much attention for VANETs. The distributed time scheduling MAC was initially proposed by the Reliable Reserved-ALOHA (RR-ALOHA), which is an extension of Reserved-ALOHA (R-ALOHA). The R-ALOHA based mechanisms rely on time slot partition and reservation to access channel. By including the time slot occupancy status in each packet and by assigning different time slots to those nodes that are situated closest to each other, RR-ALOHA can solve the hidden terminal problem and mitigate exposed terminal problem. However, RR-ALOHA is initially for traditional mobile networks. Based on RR-ALOHA, in Ref. [6], the authors proposed a distributed TDMA MAC protocol called ADHOC MAC particularly for VANETs. Later then, some literatures demonstrate that the mechanism still has drawbacks. In Ref. [12], the author pointed out that a fixed length frame was not adaptable to the varying traffic density; an Adaptive ADHOC (A-ADHOC) protocol was proposed to adjust the number of time slots per frame according to the vehicle density. The other drawback of ADHOC MAC is that it is single-channel operating, not compatible with the seven channel DSRC standard. VeMAC [7] has dealt with this problem. It has been proved through simulations that VeMAC can provide deterministic access delay and good scalability for VANETs. However, each vehicle needs to listen to the channel for duration of one frame length to determine the slot assignment and randomly select an available slot. Therefore access collisions are not avoidable because two or more vehicles may reserve the same slot [13]. Moreover, VeMAC assumes that each vehicle is equipped with two transceivers: one is tuned to the control channel and the other to the service channel, so that the channel switching problem is neglected by it.

In SDMA schemes, a vehicle's access decision is based on its location on the road [8]. SDMA schemes usually divide the road into small areas named as cells. Each cell will be assigned a unique set of time slots based on a mapping function. Then each vehicle accesses the channel by choosing a time slot from the subset assigned for the cell where the vehicle is currently located. The main problem of SDMA based schemes is that they require much effort for the time scheduling for all the road segments. Moreover, the unbalanced traffic density and dynamic network topology may degrade the resource utilization efficiency. In [11], the authors proposed to apply CDMA in the MAC mechanisms for VANETs because of its robustness against noise and interference. However, the allocation of the pseudo noise (PN) codes for each vehicle in a fully distributed and dynamic way is the bottleneck problem to implement CDMA MAC protocols. In Ref. [10], a Space-Orthogonal Frequency Time MAC (SOFT MAC) protocol that combines TDMA, SDMA and orthogonal frequency division multiple access (OFDMA) is proposed. SOFT MAC is contention free and it can provide reliable and QoS support for message broadcast in VANETs. However, the protocol allocates different sub-carriers for close clusters and it is single channel operating, which are incompatible with the DSRC standard.

There are also some works considering the channel switching between the control channel and service channel. In [14], the dwelling time ratio of CCH and SCH for single transceiver vehicles has been investigated, indicating that the dwelling ration between CCH and SCH has a significant influence on the network performance. While in [15], a deterministic MAC scheme called Vehicular Deterministic medium Access (VDA) is proposed, which points out that the dwelling ratio of CCH and SCH can be dynamically adjusted based on the traffic condition. However, it has not shown the implementation procedure. In Ref. [16], the authors introduce a multichannel coordination mechanism to adjust the length ratio between CCH and SCH dynamically. This scheme also introduces a multichannel coordination mechanism for the service channels. However, the coordination is performed by the RSUs rather than vehicles. Therefore the mechanism is not applicable for VANETs where RSUs have not been widely deployed.

The existing protocols have either worked on a reliability-based access scheme or dealt with the channel switching problem between CCH and SCH to improve the throughput on the service channel. However, very few works have combined these solutions into an integrated work. This paper proposes a scalable CSMA and TDMA based MAC mechanism that considers the channel access and channel switching simultaneously. The contributions of our work can be summarized as follows: 1) this mechanism combines SDMA, TDMA with CSMA for channel accessing so that it can provide reliable one-hop broadcast service; 2) the dwelling time ratio between the control channel and service channel changes dynamically according to the traffic density; 3) the mechanism is compared with three existing MAC protocols, the IEEE MAC, SOFT MAC and VeMAC in terms of transmission delay, throughput and collision rate.

The rest of this paper is organized as follows: Sect. 2 briefly examines the broadcasting performance of the MAC protocol defined in IEEE standard. Section 3 presents the proposed MAC mechanism in detail. Performance evaluation and simulation results are presented in Sect. 4. Section 5 concludes the paper.

2 Broadcast Modeling in IEEE 802.11p/1609.4

2.1 System Model

In this section, we evaluate the broadcasting performance of the MAC protocol defined in IEEE 802.11p/1609.4 in terms of two important metrics: i.e., transmission delay and packet loss probability. As defined in IEEE 802.11p, before accessing the channel, a node has to ensure that the channel has been *idle* for duration of DCF Inter-Frame Space (DIFS). If the channel is sensed to be idle, the node is allowed to transmit immediately. Otherwise, the node has to wait for the channel to become free and then performs a *backoff* procedure by randomly selecting a backoff counter from [0,W-1], where W is the size of the Contention Window (CW). The backoff counter is decremented at the end of each idle slot σ. When the counter is decreased to zero, the node will access the channel.

In the VANET, each vehicle is supposed to have either a beacon message or WAVE Service Advertisement (WSA) ready to transmit at the beginning of each CCH interval. Since non-zero IEEE 802.11 backoff counters are given to the safety services and the guard interval declares the wireless medium as busy to prevent multiple nodes from attempting to access the channel simultaneously upon switching, all the vehicles need to backoff a random counter before accessing the channel. Due to the nature of beacon messages, the information it contains will be out of date when the next beacon is generated. It is reasonable to limit the lifetime of a beacon message within one CCH interval. Therefore, in our analytical model, the expired beacon will be dropped when a fresh one is generated. It is also assumed that the channel condition is perfect for data transmission. The communication links are assumed to be symmetric and each vehicle in the network has the same and fixed communication range. The carrier sensing range is assumed to be the same as the communication range.

2.2 Mean Time to Accomplish CCH Transmissions

Assume there are N vehicles within the two-hop transmission range of each other so that messages are irretrievably corrupted if their transmissions overlap in time. The backoff process of each vehicle is independent from other nodes. The probability $P(l, n, w, k)$ [17] computed in (1) represents the probability that when the n vehicles generate the beacon message at the beginning of a CCH interval and select the backoff counters from a contention window of w slots, $(l-1)$ empty slots have passed before the first transmission attempt, and $k (k \leq n)$ vehicles transmit in the lth slot.

$$P(l,n,w,k)=\left(1-\frac{l-1}{w}\right)^{n}\cdot\binom{n}{k}\left(\frac{1}{w-l+1}\right)^{k}\left(1-\frac{1}{w-l+1}\right)^{n-k} \tag{1}$$

Given that at most w slots left at the backoff counter and when n have not attempted to transmit, the mean maximum time to complete the beacon transmission for all vehicles during a synchronization interval is derived as in (2).

$$T(w,n)=\sum_{l=1}^{w}\left\{\begin{array}{l} P\left(l,n,w,1\right)\left[T_s+T(w-l,n-1)\right] \\ +\sum_{k=2}^{n}P(l,n,w,k)\left[T_c+T(w-l,n-k)\right]\end{array}\right\} \tag{2}$$

where $T_s=L/R_d+DIFS+\delta$ represents the duration of a successful transmission,where L is the average packet size, R_d is the system transmission rate and δ denotes the propagation delay. And $T_c=L/R_d+EIFS+\delta$ is the duration of a corrupted transmission, where EIFS (Extended IFS) instead of DIFS is used when the physical layer detects an unsuccessful transmission event.

In (2), the first term represents the time spent on occasions that each time there is only one node out of the n vehicles choosing to backoff from w slots succeed to transmit the packet in the lth slot; and the last term represents how long the channel is occupied when more than one vehicle transmits in the lth simultaneously. Suppose the size of the contention window is W, then the mean maximum time of $T(W,N)$ can be obtained by (1) and (2) from calculating $T(w,n)$.

Through analyzing $T(W,N)$ in detail, some problems can be discovered for IEEE MAC protocol. When the value of W and n is relatively small, $T(W,N)$ is much shorter than 50 ms. For example, $T(16,20)$ is close to 17.14 ms, then the rest of CCH interval will be wasted in this situation. On the other hand, when the traffic is heavy, meaning that W and N will be large, then T(W,N) will exceed 50 ms. T(128,50) is almost 62 ms, implying that many safety-related packets will be dropped caused by channel switching every 50 ms. Thus, it is necessary to find a more adaptive channel switching scheme that can guarantee the reliability as well as make better use of the valuable wireless resource.

2.3 Packet Loss Probability on the CCH

We define $L(W,N)$ as the mean number of the collided beacon messages because of accessing the channel simultaneously during a synchronization interval. The closed-form expression of $L(w,n)$ is derived as (3).

$$L(w,n)=\sum_{l=1}^{w}\left\{\begin{array}{l} P(l,n,w,1)\cdot L(w-l,n-1) \\ +\sum_{k=2}^{n}P(l,n,w,k)\left[k+L(w-l,n-k)\right]\end{array}\right\} \tag{3}$$

Based on (1) and (3) and starting from $L(W,N)$, all the possible numbers are recursively computed. Consequently, the probability of packet loss can be computed as:

$$P(W,N)=\frac{L(W,N)}{N} \tag{4}$$

Through calculating (4) with different W and N values, we get the packet loss probability under different network conditions. Results show that P(W,N) is considered to be even unacceptable upon most occasions. For example P(16,10) is about 45.1 %, meaning that almost half of the safety-related packets are dropped because of collision. What's worse, P(16,20) sharply increases to 71.2 %, which is unacceptable for safety concerns. Moreover, the result will be disastrous if the number of vehicle keeps increasing. We find that through increasing the contention window, the probability of successful packet delivery can be increased to some extent. However, large contention window results in the increment of delay accordingly. The random access characteristic of CSMA leads to these results. Therefore, a MAC mechanism that is more adaptable and reliable for the vehicular environment is needed.

3 CSMA and Self-Organizing TDMA MAC Mechanism

In this section, we provide a multichannel MAC protocol named CS-TDMA for VANETs. The main contributions of the mechanism include: 1), it combines the advantages of CSMA and TDMA as well as SDMA to provide a reliable broadcast service and avoid the hidden terminal problem 2), it adjusts the dwelling time ratio between CCH and SCH dynamically according to the traffic density. Consequently, an integrated MAC mechanism is proposed.

3.1 The Preliminaries of CS-TDMA

To make the protocol compatible with the IEEE standard, we assume that the VANET has one control channel denoted as c_1 and six service channels denoted as $s_1, s_2, \ldots, s_6$. The control channel is used to transmit safety messages and control messages whereas service channels are used to transmit service data. As the CS-TDMA MAC is distributed and self-organized, it does not require central management from RSUs. The RSUs can access the channel via the same approach as vehicles. Each vehicle is recognized by its MAC address and an identifier number (ID)that is shorter than the MAC address.The MAC mechanism requires time synchronization among the nodes. A simple solution is to utilize the 1PSS signal on the GPS receiver. When the GPS signal is lost, other distributed synchronization methods [18,19] to locally generate synchronization pulse can be employed. In our mechanism, we define a concept of "*Chip*" for the control channel. It is composed of a transmission (TS) period and reservation (RS) period. The TS period is TDMA based, which contains a sequence of time slots denoted T_s that is used for transmission of safety messages and control messages. It can be accessed only via reservations. The RS period is CSMA based, which is used for new T_s reservations, or transmissions of high priority safety messages. The chip structure is shown as Fig. 1. For simplicity, we assume the duration of each T_s is consistent as 1ms. To make the protocol more adaptable and efficient, the duration of each time slot can be dynamically adjusted according to the traffic density. This issue is out of scope in this paper and will be discussed in the future. For safety concerns, each vehicle must acquire at least one time slot on the TS

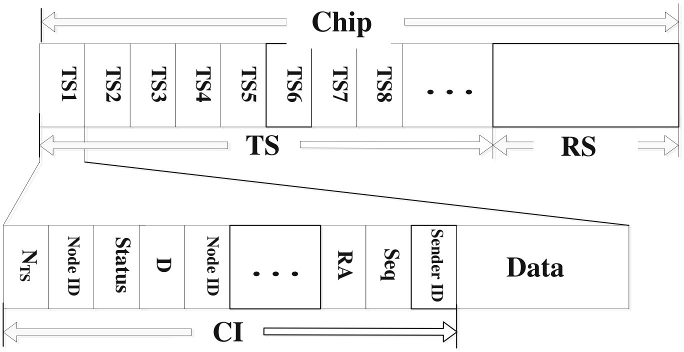

Fig. 1 The chip structure

Table 1 The meaning and size of the header fields

Header	Size (bit)	Meaning
N_{TS}	8	The number of T_s on the TS period
Node ID	8*Nts	The identifiers of the occupiers of the Ts slots, which are listed in sequence
STATUE	Nts	The status of each T_s , to be BUSY(1) or IDLE(0)
D	Nts	The Delete flag of each T_S. When the T_s can be rearranged for another vehicle, the flag is set to 1
MR	1	The MR flag is set when a vehicle receives multiple reservation requests on the RS period
Seq	1	The sequence number of the current T_s on the RS period

period to broadcast safety messages and control messages on the CCH. All the transmissions must carry the current number of TS slots (N_{TS}) and other information for accomplishing the protocol, namely the *Chip Information (CI)* shown in Fig. 1. For vehicles in the same subset, $ID(i)$ is defined as the node ID of whom reserves the ith TS slot ($i = 1, 2 \ldots N_{TS}$). Assuming each vehicle in the same cluster has reserved a TS slot, the number of N_{TS} equals the number of vehicles in the cluster. The set of ID(i) contains IDs and MAC addresses of all the vehicles within the cluster. The STATUS field contains the status of each T_s, BUSY or IDLE.If a node is inactive for other nodes, the status will be set to IDLE. Otherwise it will be set to BUSY. And the D flag of a T_s will be set when the slot can be rearranged. The meaning and size of the header fields defined in the CS-TDMA MAC are listed in Table 1.

The time scheduling procedure in the CS-TDMA MAC mechanism is detailedly described in the following subsection.

3.2 Time Scheduling on the CCH

In CS-TDMA MAC, the service area is divided into a set of region units that are named as clusters. Each cluster covers a limited number of vehicles for channel contention and associates with a set of non-overlapping frequency subcarriers. The subcarrier allocation maps are pre-installed in each vehicle. The region based clustering idea has been proposed by some existing works [8,9].

To make the following description clearer, we consider only one lane in the geographical area. All vehicles are distributed uniformly and independently on the lane. Each vehicle occupies a space of w that has taken the vehicular gap into account. The communication links are assumed to be symmetric and each vehicle in the network has the same and fixed communication range, R. The size of a cluster is adjusted such that all vehicles in the same cluster are able to hear from each other. Therefore the cluster size L must satisfy $L \leqslant R$.

The number of vehicles that can reside in a cluster is calculated as $k = \left\lfloor \frac{L}{w} \right\rfloor$. In CS-TDMA, the maximum number of T_s slots is N_{max}, therefore L must satisfy $\left\lfloor \frac{L}{w} \right\rfloor \leqslant N_{\max}$.

Besides these two conditions, a lager cluster size means less handoff processes when vehicles move between clusters; however it also means more vehicles within a cluster, resulting in more traffic and contention. Therefore, the cluster size should be optimized to provide the best performance according to the traffic density. In this paper, the cluster size is assumed to the same as the communication range R.

Suppose a vehicle x powers on or is newly entering a cluster, it needs to acquire a Ts in the CCH. It starts listening to the channel for one complete synchronization period. There are three time scheduling scenarios. Through analyzing the chip information, the vehicle x determines the corresponding reservation operation.

Initial transient state is the case that vehicle x receives a Hello-New message. Then vehicle $x$assumes that no vehicle in the cluster has a reserved T_s successfully; the value of N_{TS} is set to zero and the synchronization period only consists of the RS period for the control channel. Then vehicle x transmits a Hello-New message via CSMA in the RS period. Similarly, other vehicles that need to reserve T_s will also transmit the Hello-New messages on the RS period. The nodes within the cluster will update their CI based on the received Hello-New messages and T_s arrangement for each node. The arrangement sequence is set according to the MAC address of each node. For example, the node with the smallest MAC address will be assigned the first T_s.Then the time scheduling process will be repeated by all the nodes throughout the Chip duration to obtain a complete time scheduling map for each node. Given a synchronized duration of 100 ms, the simplified assumption of invariant vehicle set in the same cluster is acceptable, since it is reasonable to assume that the mobility of vehicles can be neglected during the short period of time.

The transition state is triggered when the listening time expires before vehicle x receives any message. The reason is that there is no other vehicle in the cluster or the number of T_s has reached the maximum. If the number of T_s has reached the maximum number, then all the vehicles have to release the reserved T_s slot and transmit a Hello-New message in the RS period. The system goes back to the initial transient state. If vehicle x can receive message during the listening process, the system is regarded to be in the steady state. Vehicle x will analyze the chip information in the packets it receives to determine the current number of N_{TS}. It will set the sequence of the T_s slot it will reserve to: $Seq = N_{TS} + 1$. Then it attempts to reserve a T_s slot period via broadcasting a Reservation-Request (Res-Req) packet based on the CSMA access scheme in the RS period. After vehicle x broadcasts the Res-Req packet, it will listen for another Chip interval to determine whether the reservation is successful. If no other vehicles access channel in the RS period at the same time as vehicle x, then other vehicles in the cluster can receive the reservation request from vehicle x and increment the N_{TS}, put the ID of vehicle x to the time slot reservation set. However, during the RS period, there may be more than one vehicle that broadcast the Res-Req. If an active node detects $n(n > 1)$ reservation requests in the cluster, it will set the Multiple-Reservations (MR) flag and assign n T_s lots to the n newly entering vehicles, plus n to the current N_{TS}, update the CI and broadcast in the next chip. To avoid the effect of the case that some nodes cannot sense some reservation(s) but other nodes within the cluster can, a node updates the CI to include any new T_s slot that has been assigned in other CIs. Then all the nodes can have a complete map of the N_{TS} set. This rule aims to avoid the hidden terminal problem. There is an example shown Fig. 2. We assume vehicle B and vehicle D are new entrants to the cluster, but they cannot sense each other. And vehicle A, C, E all have reserved their own T_s. Then N_{TS} is 3 before B and D reserving T_s successfully. Then both B and D will reserve new T_s with the sequence number of 4 in the RS period. If both the two requests are received by A, then A will assign T_s for both of the two and set its RA flag, plus 2 to the current N_{TS}. During the TS period of next chip, it will broadcast the assignment to others. All the vehicles will update their CIs according to the received packet. However, the reservation process in the RS is still contention-based. If two or more vehicles counter down the backoff counter to zero and access the channel at the same time, then all the reservation requests will fail and these vehicles need to request again.

To handle the vehicles when they leave the cluster, a T_s re-arrangement strategy is proposed. If a vehicle that occupies a certain T_s slot is inactive to other vehicles in the cluster for q consecutive chips, the vehicle is considered to be out of the cluster, and the D flag for

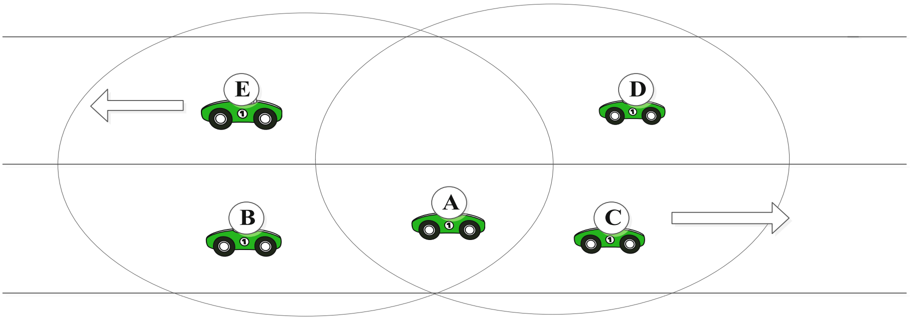

Fig. 2 Illustration of multiple reservations

the T_s will be set, and the ID of the vehicle will be removed from the set. Then the T_s slot will be available to other vehicles. As the TS period is consecutive, a simple algorithm to adjust the reservation allocation is: if there is no new reservation request, then the vehicle that occupies the last T_s slot will move to the idle slot, decrement N_{TS} by 1 and update the CI. By this means, the time slots can be guaranteed to be fully utilized. To avoid the case that some vehicles are incidentally disconnected with the cluster, the value of q should be set large enough. However, a too large q value will cause a waste of time slots. In this paper, the value of q is set to 10, which means that if a vehicle is inactive for one second the vehicle is considered to be driving out of the cluster. Otherwise it is just incidentally disconnected with the cluster.

3.3 Channel Switching Between CCH and SCH

As we have described in the aforementioned subsection, the number of TS slots needs to be at least the number of vehicles so that each vehicle has at least one dedicated time slot to guarantee a reliable transmission for the safety messages and control messages. As for the RS period, we adjust its length according to the current N_{TS} that manifest the latest traffic density. When the traffic density is high, the number of vehicles which may enter the system is relatively large, so the duration of RS should be longer. Considering that one Chip only lasts for less than one tenth of a second, within the period, the number of new vehicles is much smaller than that of the existing ones. In CS-TDMA, we make sure that our RS period is long enough for ten percent of the number of the existing vehicles to accomplish their transmissions. Thus, the length of our Chip is self-adapting depend on the traffic density of vehicles. In order to comply with the DSRC protocols, we also define 100 ms as the length of the frame of the synchronization interval in our mechanism.

When the traffic density is low, the duration of CCH is reduced to leave more time for SCH to improve the throughput. When the traffic density is high, the duration of the CCH is extended to guarantee the safety message transmission so that the high collision problem in CSMA is much alleviated. All in all, safety-related messages should have higher priority. Therefore, it is reasonable to guarantee the safety-related transmissions at the cost of lowering the throughput of non-safety related transmissions. By adapting the duration of CCH and SCH based on the traffic density, the transportation of safety messages becomes more reliable and the wireless resources can be utilized more efficiently. Considering all the features above comprehensively, the implementation of our mechanism is shown in Fig. 3. By adapting the duration of CCH and SCH to the traffic density, the transportation of safety messages becomes more reliable and the wireless resources can be utilized more efficiently.

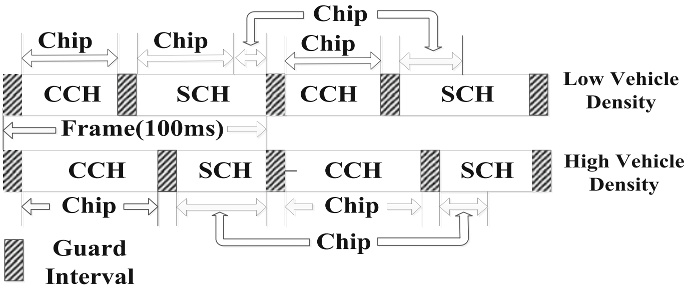

Fig. 3 Dynamic dwelling time ratio between CCH and SCH

4 Simulations and Comparisons

We have carried out extensive simulations to validate the performance of the CS-TDMA and compare it with IEEE802.11p/1609.4 MAC, VeMAC defined in [7] and SOFT MAC defined in [8]. In VeMAC, the channel access mechanism for the control channel is TDMA based. Time is partitioned into synchronized same-duration frames. Each frame is divided into a constant number of fixed duration time slots. In VeMAC, each frame contains 100 time slots each of which lasts for 0.35 ms. To compare fairly with our mechanism, we adjust the duration of each time slot in VeMAC to be 1ms and the frame duration is 100 ms. VeMAC mechanism is multi-channel operating; however it assumes each node has two transceivers. To compare the performance more fairly, the duration of the control channel per frame is set to 100 ms and the duration of SCH is set to zero in VeMAC in the simulations. The SOFT MAC divides the control channel into a period of transmission slots and reservation slots. However, the SOFT MAC doesn't consider the multi-channel operation. As we are mainly concerned with the broadcast performance on the control channel, the SCH duration in SOFT MAC is considered to be zero as well. The simulation is conducted using the MATLAB and the simulation parameters are listed in Table 2 in detail.

We first evaluate the average access time and the number of collisions for all vehicles within a cluster to reserve successfully on the control channel to reach the steady state. This is actually the worst transient scenario for the reservation procedure. As the initial RS duration is 100 ms in both CS-TDMA and SOFT MAC, and we have neglected the point-to-

Table 2 The meaning and size of the header fields

Parameter	value
Traffic density of vehicles (Veh/km)	30–80
Distance between each vehicle on the same lane (m)	80–120
Payload size (Bytes)	500
Data rate (Mbps)	12
Contention window	32
Slot time (us)	16
T_s duration(ms)	1
Initial RS duration (ms)	100
Chip duration(ms)	100

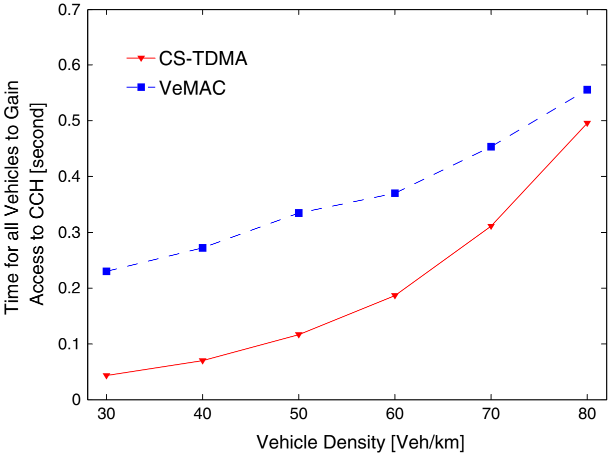

Fig. 4 Time required for all vehicles to gain access to CCH versus vehicle density

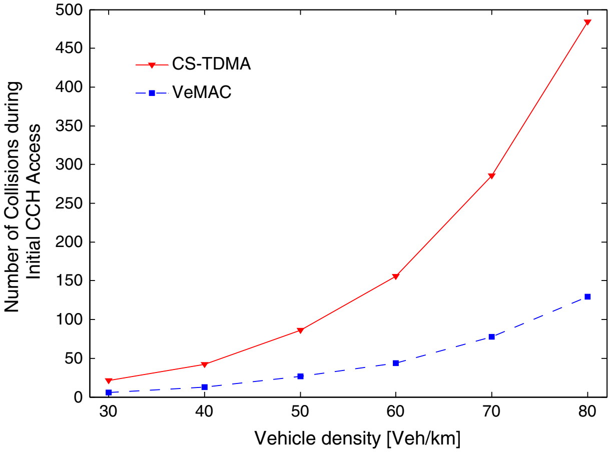

Fig. 5 Number of collisions during initial CCH access versus vehicle density

point communication in SOFT MAC, they perform identically. As for the comparison with VeMAC, the results are shown as Figs. 4 and 5.

In CS-TDMA, the reservation is based on CSMA/CA in which collisions happen when more than two or more nodes backoff their counters to zero at the same time. As there is no acknowledgement for the reservation requests, the backoff counter is constant regardless of collisions. While in VeMAC, the nodes reserve time slot by random selecting an available time slot and access collisions will happen when more than one node select the same time slot. As the traffic density goes high, the number of access collisions in CS-TDMA is rising faster than the VeMAC. The reason is that in our mechanism, the contention window is 32, which means that there are only 32 choices for vehicles to choose a counter ([0, 31]), while for VeMAC, there are 100 slots for vehicles to randomly access. However, in our mechanism the nodes can sense the collisions immediately if they are within the carrier sensing range, then the nodes can re-access in the RS period again. While in VeMAC, after an access attempt, each vehicle needs to listen for another frame interval to determine whether or not the access is successful,

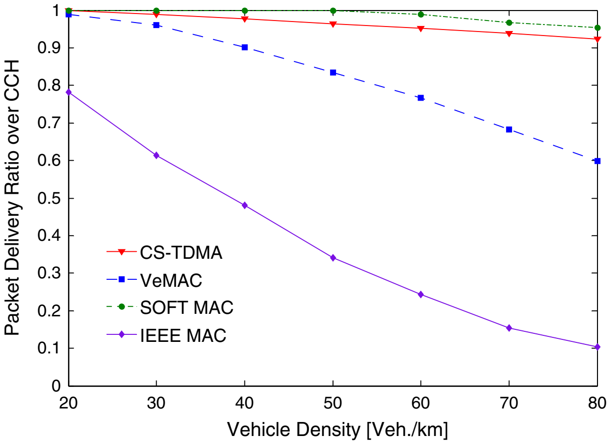

Fig. 6 Packet delivery ratio of CCH in the steady state

and if collision happens for a node, it needs to wait for the next frame to re-access. Therefore the time required for all nodes to access over the CCH is much shorter in CS-TDMA than in VeMAC. The CS-TDMA has a more efficient access performance than VeMAC.

Figure 6 shows the probability of successful packet delivery within one frame on the control channel of IEEE802.11p, VeMAC, SOFT MAC and CS-TDMA. As for the IEEE MAC, the success ratio decreases rapidly as the traffic density increases, when the vehicle number is more than 40 within one kilometer, half of the messages are lost because of serious collision. By contrast, CS-TDMA can guarantee a reliable broadcast for more than 95 percentages of the messages. The reason is that the existing vehicles within the cluster have dedicated transmission slots for reliable message broadcast, and most of the new entering vehicles' reservation requests are transmitted successfully in the RS period Consequently the reliable broadcast can be guaranteed. In terms of SOFT MAC, it can guarantee the reliable transmission of almost all the messages. However the superiority of the performance on the control channel of SOFT MAC is based on the sacrifice of the SCH performance. In VeMAC, as the traffic density become higher, the number of access collisions increases accordingly. Each access collision indicates one access failure; therefore the success ratio is lower than that in CS-TDMA.

As for the service channel, we compare the performance of these four mechanisms in terms of the throughput over the service channel within one synchronization period. The result is shown in Fig. 7. As the duration of SCH is zero of VeMAC and SOFT MAC, therefore the throughput of both mechanisms is zero. As for CS-TDMA and IEEE 802.11/1609.4 based MAC mechanism, the throughput of both mechanism decreases as the traffic density goes high. However, when the traffic density is below 40 veh/km, CS-TDMA has a better performance, this is because when the traffic density is relatively low, the time needed for vehicles to access the CCH is reduced and more time can be spared for SCH, therefore the duration of the SCH period is longer than 50 ms within one synchronization period, and the throughput will be higher accordingly. As the traffic density goes higher, the throughput in our mechanism decrease faster than the IEEE based mechanism. Two factors account for the decrement: firstly, higher traffic density results in the extension of the CCH interval, but it is a manifestation of the reliability and efficiency for the most important safety related applications; secondly, high traffic density of nodes leads to a high probability of collision, which is also the reason why the throughput also decrease as for the IEEE MAC mechanism. Thus, the decrement of throughput is in fact a manifestation of the reliability and scalability

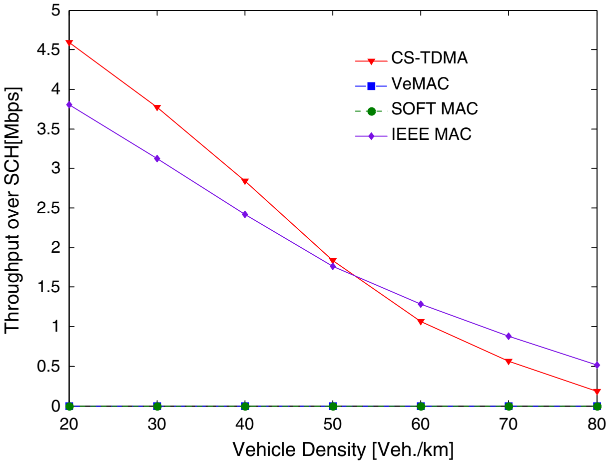

Fig. 7 Throughput of the SCH versus vehicle density

in CS-TDMA instead of the deterioration of performance. CS-TDMA can utilize the wireless resource more efficiently than the other three mechanisms.

In short, we can conclude that CS-TDMA can provide guaranteed QoS support for broadcasting on the control channel in the vehicular environment. Moreover, the wireless resource utilization efficiency is higher than the IEEE MAC, VeMAC and SOFT MAC, as they do not consider the channel switching problem. CS-TDMA has considered the access scheme and channel switching problem concurrently.

5 Conclusion and Future Work

In this paper, an adaptive and reliable multichannel MAC protocol, CS-TDMA, is proposed for VANETs. The most important contributions of it include: 1) it combines CSMA and TDMA to improve the broadcast performance for safety related messages on the control channel. 2) It dynamically adjusts the dwelling time ratio of the control channel and the service channel interval to improve the channel resource utilization. The simulation results show that, compared with the IEEE MAC, SOFT MAC and VeMAC protocols, the CS-TDMA MAC is more adaptive and reliable in the reduction of transmission delay and packet loss rate, and improvement of network throughput.

In the future, the effect of the existence of RSUs on the performance of the CS-TDMA protocol will be investigated via both theoretical analysis and simulations. As for the clustering, we plan to work out an optimized clustering scheme for the CS-TDMA so that the cluster allocation is more adaptive to the traffic condition. Concerning the service channels, the MAC protocol will be extended to support reliable unicast and broadcast on the SCHs.

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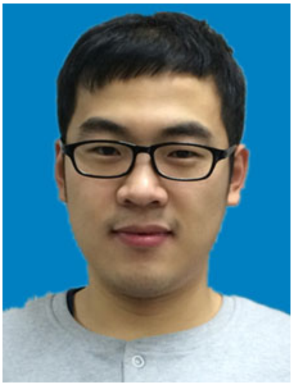

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