An Efficient Time Slot Acquisition on the Hybrid TDMA/CSMA Multichannel MAC in VANETs

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***Abstract*—The multichannel MACs increase the throughput and reduce the collision probability compared to the single-channel MACs. However, coordination of multiple nodes across multichannels is nontrivial. Recently, a multichannel MAC, called HER-MAC, uses both TDMA and CSMA schemes to improve reliability in broadcasting safety messages and efficiency in service channel utilization. Nevertheless, HER-MAC suffers a high collision probability for a large number of vehicle nodes. In this letter, we propose a hybrid TDMA/CSMA multichannel MAC protocol for VANETs that allows efficient broadcasting of messages and increases throughput on the control channel. Furthermore, our proposed MAC eliminates unnecessary control packet such as HELLO and SWITCH packets in HER-MAC. Analysis and simulation results show that the proposed MAC can provide faster time slot acquisition on the control channel than HER-MAC.**

***Index Terms*—VANET, HER-MAC, multi-channel MAC.**

I. Introduction

ONE purpose of the Intelligent Transportation System (ITS) is to improve the quality and effectiveness of safety messages in the future transportation systems. Vehicular Ad Hoc Networks (VANETs) are an important component of ITS. Each vehicle is equipped with a radio interface, called an on-board unit (OBU). A set of stationary units along the road called Road Side Units (RSUs) allows vehicles to connect to the Internet. VANETs support two communication types: Vehicle-to-Vehicle (V2V) and Vehicle-to-RSU (V2R). They can support a variety of safety applications and non-safety applications, and provide comfort to drivers and passengers. Dedicated Short Range Communications (DSRC) is exclusively used by V2V and V2R communications. The DSRC spectrum is divided into seven channels: one Control CHannel (CCH) and six Service CHannels (SCHs). The CCH is used for high priority safety applications and network management. Service Channels mainly support the non-safety information and entertainment applications.

To provide timely and effective safety applications, the Medium Access Control (MAC) protocol needs an efficient broadcast service for safety messages. In addition, the multi-channel MAC protocol is proposed to ensure reliable transmission of safety messages by using interleave operation CCH and SCH and priority access parameter. Some multichannel protocols are proposed to increase the safety broadcast reliability in [1]–[6]. Performance matrices for multi-channel protocol are the collision probability and the throughput. A collision probability is defined as an event where more than one node transmit at the same time slot. When a collision occurs, the nodes must re-transmit the collided packets. This causes more delay. Thus, the collision probability is important of safety message application and in this letter, we focus on the reducing the collision probability of safety messages on the control channel.

The basic multi-channel MAC is similar to IEEE 802.11 Distributed Coordination Function (DCF) and Enhance Distributed Channel Access (EDCA) [1]. The EDCA can map the traffic which has different priorities or different virtual stations and assign different channel access parameters to each virtual station. However, this schemes has a drawback in supporting throughput-sensitive non-safety applications.

IEEE 1609.4 [2] has been proposed for a default multichannel MAC standard for VANETs, as shown in Fig. 1c. In IEEE 1609.4, nodes broadcast safety messages or negotiate the SCHs on the CCH during the Control Channel Interval (CCHI). In the Service Channel Interval (SCHI), nodes switch to the negotiated SCHs for their non-safety messages transmissions. This scheme has a high contention rate during the CCHI and the SCHI resources cannot be utilized during this interval.

The VMESH protocol [3] was proposed to solve the drawback of EDCA. By using VMESH protocol, the SCH resources are fully utilized. Nevertheless, the VMESH cannot avoid the high collision at the beginning the CCHI and SCHI.

Similarly, Wang *et at.* [4] proposed a variable CCH interval (VCI) multi-channel MAC scheme. The proposed VCI MAC scheme can provide efficient channel utilization with high saturation throughput and low service packet delay when transmitting large service packet. However, the SCH resources are wasted during the CCHI.

To solve the utilization of SCH resource problem, the VER-MAC protocol [5] allows that nodes can broadcast safety application data twice during both the CCHI and SCHI to increase the safe broadcast reliability. However, the VER-MAC requires additional complex data structures and suffers from a longer delay in transmitting safety messages.

The HER-MAC [6] employs both TDMA and CSMA multiple access schemes, as shown in Fig. 1b. The CCH is divided into two parts: Reservation Period (RP) and Contention Period (CP). The RP consists of a number time slots, called Emergency slots (Emgslots). Nevertheless, in the contention

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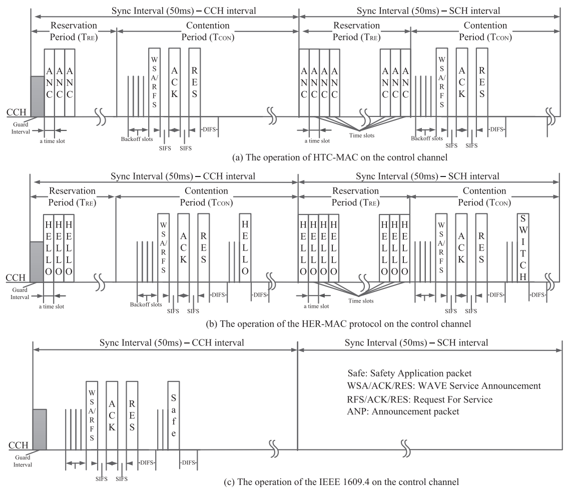

Fig. 1. The HTC-MAC, HER-MAC and the IEEE 1609.4 on the control channel.

				Neighbor information		
ID	Reserved time slot	Switched time slot	A number of time slots	IDs of neighbor nodes	Time slots are allocated by neighbor nodes	Safety Application packet

Fig. 2. Format of an ANC packet.

period, many types of packets are broadcast such as HELLO packet, SWITCH packet, and WSA/RES/ACK packet. There is a higher probability of collision due to the number of packets transmitted. Hence, the throughput on the control channel will be decreased by the control overhead.

To solve drawbacks of HER-MAC, we present a hybrid TDMA/CSMA multi-channel MAC protocol (HTC-MAC) for VANETs. HTC-MAC not only eliminates unnecessary control overhead but also increases the throughput on the control channel, as shown in Fig. 1a.

II. HTC-MAC Protocol

We assume that each node has one transceiver which can switch between CCH and SCHs. Each node must be on the CCH in order to broadcast safety message or exchange WSA/RFS message. For safety application, each node must acquire exactly one time slot in the TDMA-based reservation period. As such, each node must transmit an announcement packet (ANC) on the reservation period. As shown in Fig. 2, the ANC packet contains seven fields: (i) Node ID, (ii) its reserved time slot, (iii) switched time slot, (iv) a number of time slots, (v) IDs of neighbor nodes, (vi) time slot are allocated by neighbor nodes, (vii) safety application packet. Once a node acquires a time slot, it keeps accessing the same slot on the TDMA-based reservation period if its transceiver is not tuned to the service channel to receive or transmit non-safety application packets.

Considering ANC payload size of S bytes and a transmission rate of R Mbps, the ANC packet requires a transmission time of $t_{payload} = (S * 8)/R$. The sum of the guard periods, the preamble and the physic layer header is t_{add}. Then, a time slot is $t_{slot} = t_{payload} + t_{add}$. We assume that there are K nodes which broadcast in the reservation period. Hence, the reservation period is $T_{RE} = K * t_{slot}$. When the node density is high, the payload size S increases because the neighbor information field becomes bigger. The reservation period T_{RE} also increases and the contention period ($T_{CON} = 50\text{ms} - T_{RE}$) will be decreased. Consequently, the collision probability will increase due to many nodes attempt to broadcast packets in a small contention period.

Based on ANC packets transmitted on the TDMA-based reservation period, neighbor nodes will decide which time slots they can access. The operation of HTC-MAC is as follows.

1) A node chooses a random time slot in order to access on the TDMA-based reservation period.
2) At each time slot, each node broadcasts its ANC packet including its neighbor information.
3) Upon receiving the ANC packets from neighbor nodes, each node learns about neighbor nodes.
4) After one period of sync-interval (50 ms), each node checks ANC packets broadcast by neighbor nodes. If all neighbor nodes broadcast ANC packets including its information in the neighbor information field, it successfully acquires its reserved time slot.

If a new node wants to access a time slot, it must listen for ANC packets for one sync-interval (50ms) staring its. Upon receiving ANC packets, a new node has full neighbor's information. Based on the received information, a new node will decide which time slots they can access on the TDMA-based reservation period. However, in HER-MAC, if a new node wants to access a time slot, it must listen for one reservation period to obtain the full information of all time slots acquired by all neighbor nodes. Then, this node attempts to send HELLO packet in the contention period. Nonetheless, as the number of new nodes increases, the collision probability increases, and the probability that all nodes successfully acquire time slots decreases [9]. In HTC-MAC, in order to minimize the length of the reservation period, the switched node broadcasts an ANC packet including the TDMA-based reservation period. Note that, in HER-MAC, the switched node will broadcast a SWITCH packet including new time slot on the contention period. However, this protocol has a high collision probability when there is a large number of nodes that broadcast their safety messages on the contention period. In both protocols, if all neighbor nodes confirm its information in the neighbor information field, it successfully switches its time slot.

III. Analytical Model for Time Slot Acquisition

A. Markov Chain in HTC-MAC

For comparison with HER-MAC, we determine the average number of nodes which acquire a time slot within a sync interval and the probability that all the nodes acquire a time slot within n frames. Let K denotes the number of contending nodes in 2-hop neighborhood because if nodes are located at least three hop away, they can reuse the same time slot [7].

The Markov chain of HTC-MAC is inherited from the VeMAC [8], as shown in Fig. 3a. Let N be the number of initially available time slots in a sync-interval, and X_n be the total number of nodes which acquire a time slot within n sync interval. X_n is a stationary discrete-time Markov chain with the transition probabilities illustrated in Fig. 3a.

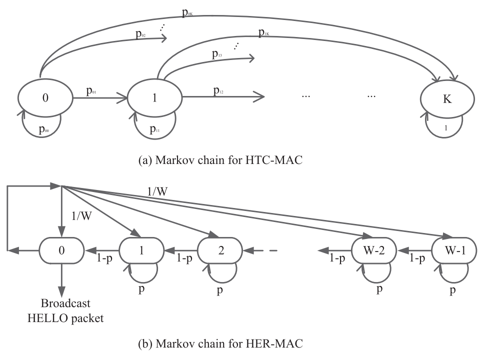

Fig. 3. Markov chain.

In this letter, we consider the case where $K \leq N$. For the case $K > N$, it is useful to determine an optimal value for a number of time slots on the reservation period. Let P be the one-step transition probability matrix, and P^n be the n-step transition probability matrix. Then,

$$p(X_n = i) = P^n_{1,i+1}, \quad i = 0, \ldots, K. \tag{1}$$

The probability that all nodes acquire a time slot within n sync interval is

$$F^{all}_{n,HTC-MAC} = p(X_n = K) = P^n_{1,K+1}. \tag{2}$$

Let Y be the average number of nodes which successfully acquire a time slot within n frames. Then, we have

$$E[Y_n] = \sum_{i=0}^{K} i P^n_{1,i+1}. \tag{3}$$

B. Markov Chain in HER-MAC

In this section, we determine formulas of the average number of nodes which acquire a time slot within a sync interval and the probability that all the nodes acquire a time slot within n frames in HER-MAC. From the Markov chain [9] in Fig. 3b, it is clear that the probability τ that a node transmits a HELLO or safety application packet in an arbitrary time slot can be expressed as

$$\tau = \frac{2(1-p)}{1-2p+W}. \tag{4}$$

Let p be the collision probability when more than one node transmit at the same time slot. Hence, we have

$$p = 1 - (1-\tau)^{K-1}. \tag{5}$$

Consequently, based on (4) and (5), variable τ and p can be solved by the numerical methods as in [9]. Note that $0 \leq p \leq 1$ and $0 \leq \tau \leq 1$.

In every time slot during the HELLO interval, an agreement will be successfully made with probability p_{suc}, thus, we have

$$p_{suc} = K\tau(1-\tau)^{K-1}. \tag{6}$$

In the p-persistent CSMA/CA, the backoff interval is based on the geometric distribution with probability p_{suc} [10]. Based on the Bernoulli trial, let X be the number of successful nodes that participate in contention window size. We can calculate $p(X = i)$ in on a single frame as follows:

$$p(X = i) = \binom{i}{W} {p_{suc}}^i (1-p_{suc})^{W-i}. \tag{7}$$

From the Bernoulli trial, we can solve for X as follows:

$$E[X] = W p_{suc}. \tag{8}$$

In each frame, we can compute $E[X_i]$ and $p_{i,suc}$ with variable number of unsuccessful nodes at the i^{th} frame by replacing K to number of unsuccessful nodes at the $(i-1)^{th}$ frame into (5) and (6). Thus, the average number of nodes which acquire a time slot within n frames is

$$E[Y_n] = E[X_0] + \ldots + E[X_n] = W \sum_{i=0}^{n} p_{i,suc}. \tag{9}$$

The probability that all nodes acquire time slots within n frames is shown in (10), shown at the bottom of the page.

IV. Performance Evaluation

To validate HTC-MAC, we use an event-driven simulation program written in Matlab. For comparison with HTC-MAC, we also simulate HER-MAC where a HELLO packet configured to use Access Class 3 ($AC3$) with $CW = 8$ and $CW = 4$ due to it is a safety message using the highest priority scheme [11]. In Fig. 4, we compare HTC-MAC with HER-MAC for $CW = 8$ and $CW = 4$ in a dense scenario ($N = 20$, $K = 10$). In HER-MAC, if nodes use $CW = 8$, all nodes can successfully acquire a time slot after 6 frames. However, nodes using $CW = 4$ need 12 frames to successfully acquire a time slot. In the same condition, in HTC-MAC, after 5 frames, all nodes have successfully acquired their time slots. Using Eq. (10) and

$$p[X_i = E[X_i]] = \begin{cases} 0, \quad i = 0 \; or \; \lfloor E[X_i] \rfloor < 1 \\ (1 - p[X_0 = E[X_0]] - \ldots - p[X_{i-1} = E[X_{i-1}]]) \binom{\lfloor E[X_i] \rfloor}{W} {p_{i,suc}}^{E[X_i]} (1-p_{i,suc})^{W-E[X_i]}, \\ i \geq 1 \; and \; \lfloor E[X_i] \rfloor \geq 1 \end{cases}$$

$$F^{all}_{n,HER-MAC} = p\left(\left\lfloor \left(\sum_{i}^{n} E[X_i]\right)\right\rfloor = K\right) = p[X_0 = E[X_0]] + p[X_1 = E[X_1]] + \ldots + p[X_n = E[X_n]]$$
$$= \sum_{i=0}^{K} (1 - \sum_{j=0}^{i-1} p[X_j = E[X_j]]) \binom{\lfloor E[X_i] \rfloor}{W} {p_{i,suc}}^{E[X_i]} (1-p_{i,suc})^{W-E[X_i]} \tag{10}$$

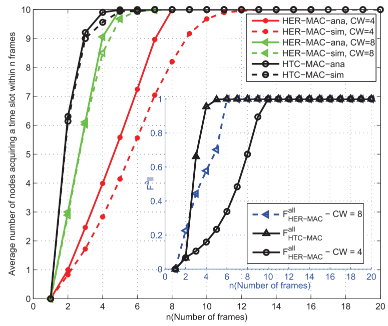

Fig. 4. The average number of nodes which acquire a time slot within n frames and F^{all} with $CW = 4$, 8, and 10 nodes.

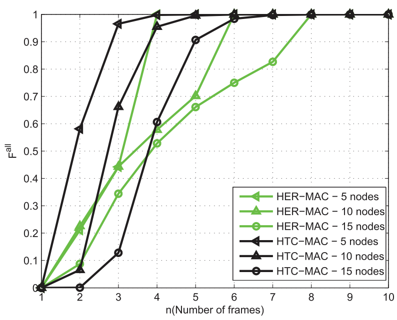

Fig. 5. Probability that all nodes acquire a time slot within n frames.

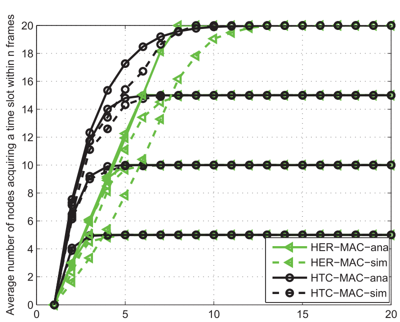

Fig. 6. The average number of nodes which acquire a time slot within n frames with $CW = 8$.

(2), the probability that all nodes acquire time slots within n frames is presented in Fig. 4. The average number of nodes which successfully acquire a time slot and F^{all} have same results. Hence, the rate of successful time slot acquisition can be shown by using the probability or average number of nodes which acquire a time slot.

In Fig. 5, we evaluate Eq. (5) and (10) with the same the number of available time slots, $N = 20$. We take the average number of nodes which acquire a time slot within each frame by running 100 times. In addtion, in Eq. (10), we take the floor function $\lfloor E[X_i] \rfloor$. Hence, the average number of nodes which acquire a time slot within 3 frames as shown in Fig. 6 with K = 5 and K = 10, which are close together. Consequently, the probability that all nodes acquire time slots within 3 frames is also close together as shown in Fig. 5. If we take the ceiling function $\lceil E[X_i] \rceil$, the rate of time slot acquisition is faster than taking the floor function.

In Fig. 6, we fix the number of available time slots and vary the number of contending nodes, K. For comparison, we simulate HER-MAC with its best performing parameter, $CW = 8$. If K is 5, HTC-MAC and HER-MAC have the same rate of successful time slot acquisition. When K increases, the rate of successful time slot acquisition in HTC-MAC is higher than HER-MAC. When K equals N, the collision probability when more than one node transmit at the same time slot in Eq. (5) increases. Hence, the probability that all nodes acquire time slots in HER-MAC will decrease. All nodes need 13 frames to successfully acquire time slot in HER-MAC but in HTC-MAC, they need 10 frames. When K is too small, HTC-MAC and HER-MAC have the same rate of successful time slot acquisition. However, when K increases, in all dense network scenarios, nodes in HTC-MAC show better performance results than in HER-MAC.

V. Conclusion

In this letter, we propose an efficient time slot acquisition on the hybrid TDMA/CSMA mutli-channel MAC in VANETs. HTC-MAC not only eliminates unnecessary control overhead but also increases the throughput on the control channel. The analysis and simulation results prove that HTC-MAC outperforms HER-MAC in terms of the average number of nodes which acquire a time slot. However, HTC-MAC requires a larger ANC's payload size to broadcast its neighbors' information when the node density is high.

References

[1] H. Wu, A. Wang, Q. Zhang, and X. Shen, "IEEE 802.11e enhanced distributed channel access (EDCA) throughput analysis," in *Proc. IEEE Int. Conf. Commun. (ICC'06)*, 2006, vol. 1, pp. 223–228.

[2] *IEEE Standard for Wireless Access in Vehicular Environments (WAVE) Multi-Channel Operation*, Sep. 2010.

[3] Y. Zang, L. Stibor, B. Walke, H.-J. Reumerman, and A. Barroso, "Towards broadband vehicular ad-hoc networks—The vehicular mesh network (VMESH) MAC protocol," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC'07)*, Mar. 2007, pp. 417–422.

[4] Q. Wang, S. Leng, H. Fu, and Y. Zhang, "An IEEE 802.11 p-based multichannel MAC scheme with channel coordination for vehicular ad hoc networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 2, pp. 449–458, Jun. 2012.

[5] D. N. M. Dang, C. S. Hong, S. Lee, and E.-N. Huh, "An efficient and reliable MAC in VANETs," *IEEE Commun. Lett.*, vol. 18, no. 4, pp. 616–619, Apr. 2014.

[6] D. N. M. Dang, H. N. Dang, V. Nguyen, Z. Htike, and C. S. Hong, "HER-MAC: A hybrid efficient and reliable MAC for vehicular ad hoc networks," in *Proc. IEEE 28th Int. Conf. Adv. Inf. Netw. Appl. (AINA)*, May 2014, pp. 186–193.

[7] F. Borgonovo, A. Capone, M. Cesana, and L. Fratta, "ADHOC MAC: New MAC architecture for ad hoc networks providing efficient and reliable point-to-point and broadcast service," *Wireless Netw.*, vol. 10, pp. 359–366, 2004.

[8] H. Omar, W. Zhuang, and L. Li, "VeMAC: A TDMA-based MAC protocol for reliable broadcast in VANETs," *IEEE Trans. Mobile Comput.*, vol. 12, no. 9, pp. 1724–1736, Sep. 2013.

[9] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE J. Sel. Areas Commun.*, vol. 18, no. 3, pp. 535–547, Mar. 2000.

[10] W. Alasmary and W. Zhuang, "The mobility impact in IEEE 802.11p infrastructureless vehicular networks," in *Proc. IEEE 72nd Veh. Technol. Conf. (VTC'10-Fall)*, Sep. 2010, pp. 1–5.

[11] Q. Xu, T. Mak, J. Ko, and R. Sengupta, "Vehicle-to-vehicle safety messaging in DSRC," in *Proc. 1st ACM Int. Workshop Veh. Ad Hoc Netw.*, 2004, pp. 19–28.