An Efficient and Reliable MAC for Vehicular Ad Hoc Networks

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***Abstract*—The IEEE 1609.4 is a MAC extension of IEEE 802.11p to support multi-channel operations. All nodes have to tune to the Control Channel (CCH) during the CCH Interval (CCHI) for exchanging safety messages (SMsgs) and other control messages. Nodes can optionally switch to the Service Channels (SCHs) to exchange non-safety messages during the SCH Interval (SCHI). The IEEE 1609.4 cannot utilize all SCHs resource during the CCHI. This paper proposes an Efficient and Reliable MAC protocol for Vehicular Ad hoc Networks, named VER-MAC, which allows nodes to transmit non-safety messages during the CCHI to improve the non-safety throughput and broadcast SMsgs twice during both the CCHI and SCHI to increase the safety broadcast reliability.**

***Index Terms*—MAC protocol, Vehicular Ad Hoc Networks, VANETs, Intelligent Transportation Systems.**

I. INTRODUCTION

The main goal of the Intelligent Transportation System (ITS) is to improve the quality, effectiveness and safety of the future transportation systems. Vehicular ad hoc networks (VANETs) have been considered to be an important part of the ITS. The VANETs focus on Vehicle-to-Vehicle (V2V) communications and Vehicle-to-Infrastructure (V2I) communications. The applications of VANETs fall into two categories, namely safety applications and non-safety applications. Safety applications have strict requirements on communication reliability and delay while non-safety applications are more throughput-sensitive instead of delay-sensitive. The US Federal Communication Commission allocated 75 MHz of the spectrum in the 5.9 GHz band, including one control channel (CCH) and six service channels (SCHs) for safety and non-safety applications, respectively. The requirements for different DSRC (Dedicated Short Range Communication) applications are presented in [1].

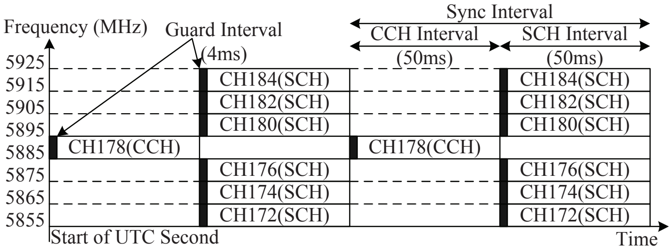

Fig. 1. Frequency channel layout of a 5.9 GHz WAVE system.

Wireless Access in Vehicular Environment (WAVE) is designed for an ITS on 5.9 GHz band with the IEEE 802.11p [2] and IEEE 1609 standard family. The IEEE 1609.4 [3] is the standard of the multi-channel operation for WAVE MAC. As shown in Fig. 1, each 100 ms Sync Interval (SI) allocates 50 ms for the CCHI and 50 ms for the SCHI, including 4 ms Guard Interval for switching between CCH and SCH. This scheme is similar to some multi-channel MAC proposals [4]–[7] in Wireless Ad hoc Network which have control interval and data interval. Nodes broadcast SMsgs or negotiate the SCHs on the CCH during the CCHI. Then, nodes switch to the negotiated SCHs for their non-safety message transmissions. This channel access scheme has a high contention during the CCHI, and the resource of SCHs cannot be utilized during this interval.

A variable CCH interval (VCI) multi-channel MAC scheme [8] tries to improve the saturation throughput and provide the reliable transmission for the SMsgs. The CCHI is further divided into the safety interval and WAVE Service Announcement (WSA) interval. The WSA interval is adjusted according to the network condition. On the other way, a hybrid channel access is employed in Dedicated Multi-channel MAC (DMMAC) [9] to provide the collision-free and delay-bounded transmission for SMsgs. The DMMAC adopts the Basic Channel reservation from RR-ALOHA [10]. Each node has to transmit a packet containing the Frame Information (FI), which specifies the status of each slot observed by node itself. Node has to transmit a SMsg successfully in order to reserve a slot and can only transmit SMsgs within reserved time slot. Some nodes may not reserve the slots because of the limited number of slots. Furthermore, the SCH resources are still wasted during the CCHI in both the VCI and DMMAC.

A clustering-based multi-channel MAC protocol is proposed in [11]. Each node has two transceivers which can operate simultaneously on different channels. The cluster head uses one transceiver to collect and deliver emergency messages and control messages within its cluster, and uses another transceiver to exchange consolidated safety messages among cluster heads. And a VANET Multi-channel MAC (VMMAC) [12] uses directional antennas to improve the spatial reuse. The Vehicular MESH Network (VMESH) MAC [13] proposes the coordination function for contention-free channel access on SCHs.

Different from above synchronous schemes, Asynchronous

Multi-channel MAC Distributed (AMCMAC-D) is proposed in [14]. Some nodes make rendezvous with their receivers or broadcast the SMsgs on the CCH while the others are exchanging non-safety messages on the SCHs. A distributed TDMA mechanism is applied to reduce the high contention level on the control channel and enhance the service differentiation.

Similar to the H-MMAC [5], which allows nodes to transmit data packets during the control interval in wireless ad hoc network, the VEMMAC [15] allows nodes to extend their non-safety message transmissions to the upcoming CCHI according to the network load. Besides that, the SMsgs are broadcast twice to increase the reliability. Since the reliability of the broadcast transmission without the acknowledgement is very low, the higher reliable broadcast can be achieved using the reservation mechanism, especially for periodical SMsg broadcasts. If a node broadcasts a SMsg successfully at the first time, it will rebroadcast this SMsg at the second time and also broadcast the new SMsgs followed by this SMsg successfully. Moreover, the contention-based throughput of the non-safety messages is not high compared to the reservation-based throughput. In the reservation-based method, nodes exchange WSA/ACK/RES (WAVE Service Announcement/Acknowledgement/Reservation) or RFS/ACK/RES (Request for Service/Acknowledgement/Reservation) to reserve the SCH for their non-safety message transmissions during the reserved time. So, the reservation mechanism is also used for non-safety message transmissions. The VER-MAC is proposed based on the reservation mechanism to improve the saturation throughput of non-safety applications while guaranteeing the high SMsg broadcast reliability. The details of the VER-MAC protocol are described in the following sections.

II. THE PROPOSED VER-MAC PROTOCOL

First, we assume that a node is equipped with a half-duplex transceiver which is capable of switching the channel dynamically. The control channel and six service channels are numbered from CH #1 through #7. Moreover, all nodes are time-synchronized as in the IEEE 1609.4. Each SI consists of a CCHI and an SCHI. The CCHI and SCHI are further divided into Reservation Period (RP) and Contention Period (CP) on the CCH. The RP is used for nodes to rebroadcast the SMsgs sequentially without any channel contention. When a node broadcasts a SMsg at the first time in the CP, this node also reserves the CCH for broadcasting the SMsg at the second time. Now, we divide the CCHI and SCHI into many transmission slots (TxSlot) on the SCHs. In case of the non-safety message transmissions, a node tries to access the CCH to reserve a TxSlot on a certain SCH by exchanging WSA/ACK/RES or RFS/ACK/RES messages (the WSA or RFS messages for short) only during the CP of the CCHI. Nodes will be on the selected SCH only during the selected TxSlot according to the negotiation on the CCH they made during the CCHI. Since the SMsgs are broadcast twice during both the CCHI and SCHI, node always receives the SMsgs broadcast by its neighbor nodes.

Fig. 2 shows the network topology and the operation of VER-MAC protocol with four TxSlots in each SI. Nodes try to contend the CCH for broadcasting the SMsg at the first time during the CP of the CCHI or SCHI, and rebroadcast without any collision during the RP of the next SCHI or CCHI. The service provider can also broadcast the WSA packets with the information of the available TxSlots of each SCH. Nodes that need the service can reply with the ACK indicating which TxSlot and which SCH are going to be used. Then, the service provider confirms the selected TxSlot and SCH by sending the RES. Moreover, a service user can request service data from service provider by sending the RFS with the information of available TxSlots on each SCH. The service provider replies with the ACK and receives the confirmation via the RES from the service user.

If all TxSlots of all SCHs in the SCHI are used up, nodes will choose the TxSlots in the next CCHI for their non-safety message transmissions. In Fig. 2, nodes E and E' select TxSlot #3 when they found that all TxSlots of SCHI are already reserved by their neighbors. During the SCHI, nodes also exchange the non-safety messages on the CCH through the channel contention if they find the CCH idle, e.g non-safety message transmission of nodes B and B'. Due to the fairness among nodes, each node pairs can reserve one TxSlot for each successful WSA/ACK/RES or RFS/ACK/RES handshake. If nodes have many non-safety messages to exchange, they have to make more WSA/ACK/RES or RFS/ACK/RES handshake. They may extend their transmissions if the SCH is idle after they finish their reserved TxSlot, e.g the non-safety message transmissions of nodes C and C' is extended during the second SCHI. The transmission extension depends on the information about the neighbor nodes and the SCHs that they have in their data structures.

In details, each node maintains three data structures, such as Broadcast Sequence, Neighbor Information List and Channel Usage List as follows.

A. Broadcast Sequence (BS)

A node uses the BS to know the sequence of SMsg retransmissions: which node rebroadcasts the SMsgs before or after it. The BS contains the Predecessor, Node, Successor and the Time t when Node transmits SMsgs successfully at the first time in the CP. The Predecessor and Successor are the nodes broadcast the SMsgs before and after the Node currently broadcasts the SMsg. The BS is updated whenever the node receives a SMsg from its neighbor during the CP.

TABLE I
BROADCAST SEQUENCE

	Predecessor	Node	Successor	Time (t)
Node A	G	-	-	-
Node B	-	B	G	t_B
Node C	G	C	-	t_C
Node G	B	G	C	t_G

Let us consider the CP of the first SI in Fig. 2 when nodes B, G and C broadcast their SMsgs. Table. I shows the BS of

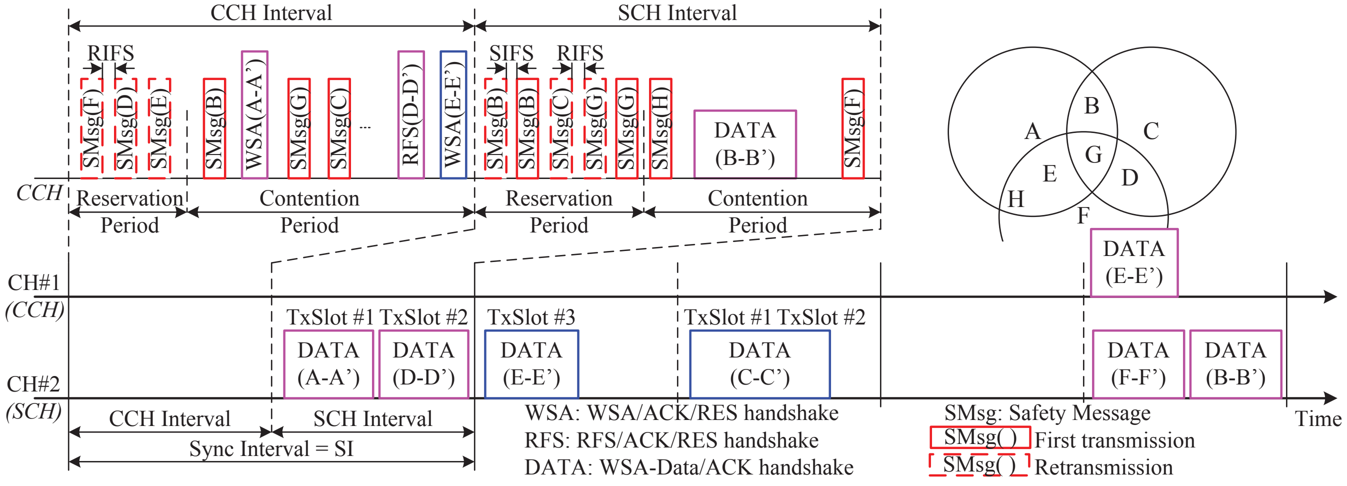

Fig. 2. The operation of VER-MAC protocol.

some nodes at the end of the first CCHI. In point of view of node A, only node G which is in the transmission range of node A broadcasts a SMsg and node A does not broadcast any SMsg, so node A only updates node G to the Predecessor of its BS. In case of node G, nodes B and C are in its transmission range. When node B broadcasts its SMsg, node G updates the Predecessor. Node G broadcasts its SMsg and updates its BS accordingly. And when it overhears the SMsg from node C, it updates the Successor of its BS.

During the RP, when a node rebroadcasts a SMsg, it also specifies the Successor in this SMsg. The neighbor node, which receives this SMsg, checks the sender of this SMsg and the Successor specified in this message. If the sender and the Successor are matched to the Predecessor and Node in its BS, that neighbor node is the next node that rebroadcasts its SMsgs after a Reservation Inter-frame Space (RIFS) where SIFS $<$ RIFS $<$ DIFS. As a sequence, all nodes transmit their SMsgs at the second time without collision. The first node does not have the Predecessor, it chooses the back-off counter based on time t in its BS to contend the CCH. The smaller time t, the smaller back-off counter value. The last node does not have the Successor in its last SMsg transmission. This helps nodes know when the RP is finished, so that they can contend for the SCH reservations or the new SMsg transmissions. If the node has a new SMsg to broadcast during the RP, it will broadcast this SMsg right after the SMsg retransmission with a SIFS. If a node has many SMsgs to send in a high traffic network, it needs to send at least one SMsg successfully in the CP to reserve the CCH in the next RP. Once that node reserved the CCH, it can rebroadcast all SMsgs without collision in the RP. This is one of the benefits of the VER-MAC.

B. Neighbor Information List (NIL)

The NIL maintains the information of the neighbor nodes, for example as given in Table II. The Channel field indicates which SCH the node uses to exchange the non-safety messages. Channel 0 means that node does not have any non-safety message to send or receive during the upcoming SCHI or CCHI. The Tx_slot shows which TxSlots are used by the corresponding node. Based on the Tx_slot, a node knows when the neighbor node will be on the CCH in order to perform the negotiation. If a node uses TxSlots of the upcoming CCHI, it will be available on the CCH in next 2 SIs. For example, node A overhears the WSA messages of node E and knows that node E uses TxSlot #3 during the CCHI #1. That means node E will not be on the CCH during the CCHI #2, but it will be on the CCH during the CCHI #3 (after 2 SIs). So, a node has to update its NIL whenever it overhears the WSA or RFS messages from its neighbor nodes to keep track of its neighbors' status.

TABLE II
NODE A'S NIL

Node	Channel	Tx_slot
D	2	2
E	2	3
X	3	4
...	...	...

C. Channel Usage List (CUL)

The CUL stores the information of the channel, for example as shown in Table III. The Avail_slot shows on which TxSlots both the corresponding SCH and a node itself are available. Table. III shows that node A and the SCH #2 are available on TxSlot #4. Based on that, nodes can choose the suitable SCH with a suitable TxSlot for their non-safety message transmissions. The sender initiates the negotiation by sending the WSA or RFS with its CUL. The receiver chooses the "best" TxSlot of the corresponding SCH among the common available TxSlots of sender and receiver based on the received CUL from sender and its CUL. The "best" TxSlot means the TxSlot which followed by the most available slots. The reason of the "best" TxSlot is that after nodes finish their reserved TxSlot, they may extend their transmission if the SCH is still available for the next TxSlots. In Fig. 2, during the SCHI #2 nodes C and C' selected the "best" TxSlot #1 of CH #2 (SCH #1) because there are maximum 2 available TxSlots #1 and #2 on SCH #1. So, after finishing the transmission in TxSlots #1, nodes may continue exchanging their non-safety messages in TxSlots #2.

TABLE III
NODE A'S CUL

Channel	Avail_slot
2	4
3	3, 4
4	4
...	...

D. The operation of VER-MAC protocol

The nodes must be on the control channel in order to broadcast SMsgs or exchange the WSA or RFS messages to reserve a TxSlots on certain SCH for their non-safety message transmissions. We denote the node sending the WSA or RFS as the sender, and the receiver replies with the ACK.

1) Whenever a node has a SMsg to broadcast, it contends the CCH to broadcast in the current CCHI or SCHI. Neighbor nodes which overhear the SMsg, update their BSs. Then, the node broadcasts SMsgs again in the RP of the next SCHI or CCHI through the reservation mechanism.
2) When a node has non-safety messages to send or requests for non-safety messages, it sends the WSA or RFS which piggybacks with its CUL.
3) Upon receiving the WSA or RFS, the receiver selects the "best" TxSlot on the corresponding SCH and then sends the ACK indicating the selected TxSlot and SCH to the sender.
4) The sender sends the RES to confirm the TxSlot and the SCH selected by the receiver.
5) Neighbor nodes, which overhear the ACK or RES messages, update their NILs and CULs.
6) After the CCHI, the sender and receiver only switch to the agreed SCH in the selected TxSlot for their data transmissions.

III. PERFORMANCE EVALUATION

In this section, we evaluate the IEEE 1609.4 [3], AMCMAC [14] and our proposed VER-MAC protocol on our developed packet-level simulation tool in Matlab.

A node may have both safety and non-safety messages to transmit and it tries to contend the channel with other nodes to send only safety messages or non-safety messages at the time. So, we assume there are 10 safety nodes and 40 non-safety nodes which generate the safety traffic and non-safety traffic, respectively. Since the SMsg has strict delay, in our simulations, we consider the highest priority SMsg with 100 byte packet size and 100 ms latency [1]. That means a SMsg will be dropped if it is not transmitted within 100 ms. The other simulation parameters are listed in Table IV. Each simulation was performed for 10 seconds, and the simulation results are the average of 20 runs. The metrics used to evaluate the performance include:

TABLE IV
SIMULATION PARAMETERS

Parameters	Value
Number of nodes	10 + 40 nodes
Data rate	6 Mbps
Safety packet size	100 bytes
Non-safety packet size	1024 bytes
WSA / RFS	27 bytes
ACK	16 bytes
RES	16 bytes
AIFS[Safety]	2
AIFS[Non-safety]	9
Safety:CW(min:max)	(3:7) time slots
Non-safety:CW(min:max)	(7:1023) time slots
SIFS	16 μs
RIFS	25 μs
DIFS	34 μs
Slot time	9 μs

1) The aggregate throughput (Mbps) of non-safety traffic.
2) The average delay (msec) of non-safety traffic.
3) The packet delivery ratio (PDR) of safety traffic.
4) The SMsg broadcast efficiency (nodes/SMsg): the average number of nodes received a SMsg successfully.

Fig. 3 shows the performance of different protocols as the packet arrival rate of non-safety messages increases when the safety packet arrival rate is fixed at 20. By utilizing the SCHs during the CCHI, the aggregate throughput of the VER-MAC is almost twice as high as that of the IEEE 1609.4, and also higher than the AMCMAC as shown in Fig. 3(a). The throughput of the AMCMAC is lower than that of the VER-MAC because of the congestion on the CCH. In both the IEEE 1609.4 and VER-MAC, if a node has non-safety packets after the CCHI, it has to wait for the next CCHI to start its SCH negotiation. In the AMCMAC, a node can start its SCH negotiation whenever it has non-safety packets. That is why the AMCMAC has a lower delay than the others (Fig. 3(b)). By using the reservation mechanism for the SMsg retransmissions, the VER-MAC has higher PDR of SMsg and average SMsg broadcast efficiency than the other protocols as shown in Figs. 3(c) and (d).

The non-safety packet arrival rate is fixed at 300 and we vary the safety packet arrival rate to compare the performance of different protocols (Fig. 4). Figs. 4(a) and (b) illustrate that the VER-MAC has better non-safety application's aggregate throughput and average delay than the IEEE 1609.4. Even though the safety packet arrival rate is high, if a node can send at least one SMsg successfully in the CP, it can reserve the CCH for rebroadcasting all SMsgs successfully including the SMsgs that are collided at the first transmission. Since almost all the SMsgs are transmitted successfully and there is no collision at the second time, the VER-MAC has higher PDR of SMsg and average SMsg broadcast efficiency as shown in Figs. 4(c) and (d).

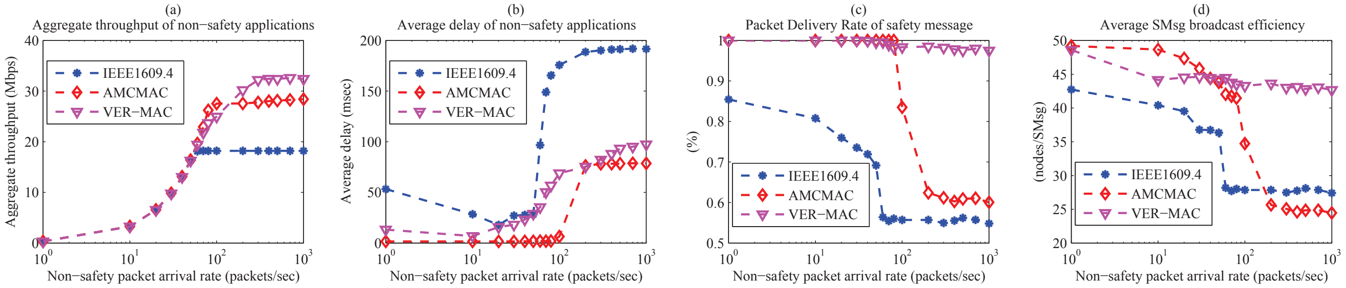

Fig. 3. Performance comparisons of different protocols as the non-safety packet arrival rate varies.

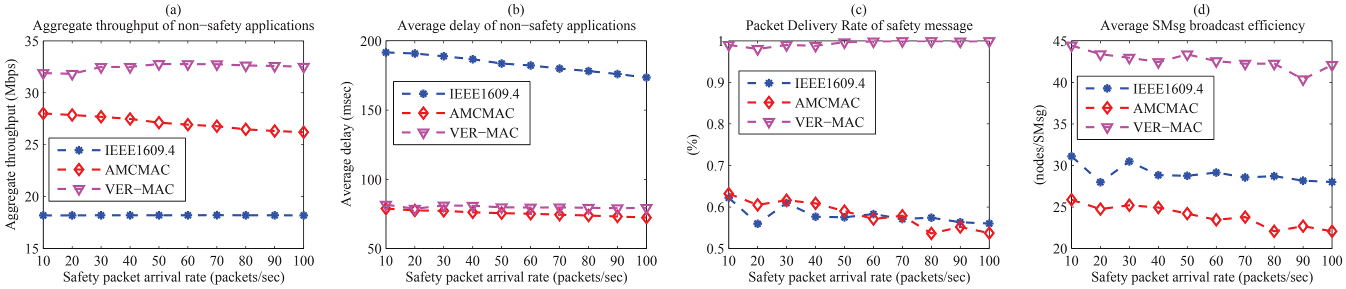

Fig. 4. Performance comparisons of different protocols as the safety packet arrival rate varies.

IV. CONCLUSIONS

This paper proposed the Efficient and Reliable multi-channel MAC for VANETs (VER-MAC) which allows nodes to exchange non-safety messages during the CCH interval to improve the throughput of non-safety applications. Moreover, using the reserved retransmission mechanism, the SMSg broadcast efficiency of the VER-MAC also increases significantly. The simulation results has been presented to show that the VER-MAC protocol outperforms the IEEE 1609.4 in terms of the aggregate throughput and average delay for the non-safety messages; the packet delivery rate and broadcast efficiency for the safety messages.

ACKNOWLEDGMENT

This research was supported by the MKE(The Ministry of Knowledge Economy), Korea, under the ITRC(Information Technology Research Center) support program supervised by the NIPA(National IT Industry Promotion Agency)" (NIPA-2013-(H0301-13-2001)). Dr. CS Hong is the corresponding author.

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