A Reliable Multi-hop Safety Message Broadcast in Vehicular Ad hoc Networks

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***Abstract*—Vehicular Ad hoc NETworks (VANETs) should provide the reliable safety message broadcasts and the efficient non-safety message transmissions to vehicles. The IEEE 1609.4 MAC, which supports multi-channel operations in VANETs, is not reliable enough for the safety message broadcast and not efficient in the Service CHannel (SCH) resources utilization. In this paper, we propose a MAC protocol which supports a Reliable Multi-hop Safety message Broadcast (RMSB-MAC) in VANETs. Each Multi-hop Forwarder (MF) collects the safety messages from the neighbor vehicle nodes, and then the MF uses its reserved time slot to broadcast them to all vehicle nodes in its transmission range as well as to forward them to the next MF. Moreover, by allowing vehicle nodes to exchange non-safety messages during the Control CHannel Interval (CCHI), the RMSB-MAC utilizes the SCH resources more efficiently.**

***Index Terms*—VANETs, Multi-channel MAC, TDMA, CSMA, multi-hop broadcast**

I. Introduction

Vehicular Ad hoc NETworks (VANETs) have been considered to be an important part of the Intelligent Transportation System (ITS) to improve the quality, effectiveness and safety of the future transportation systems. VANETs support both Vehicle-to-Vehicle (V2V) 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 whereas non-safety applications are more throughput-sensitive.

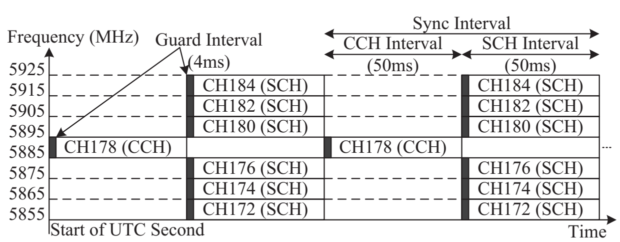

Fig. 1: Frequency channel layout of a WAVE system.

Wireless Access in Vehicular Environment (WAVE) is designed for an ITS on 5.9 GHz band with IEEE 802.11p [1] and IEEE 1609 standard family. IEEE 1609.4 [2] is the standard of the multi-channel operation for WAVE MAC. As shown in Fig. 1, the overall bandwidth is divided into seven 10 MHz channels. One Control CHannel (CCH), i.e. CH 178, can only be used to send safety relevant applications, system control and management with high priorities. The other six Service CHannels (SCHs) are mainly used to support non-safety relevant applications. Time is divided into Sync Intervals (SIs) and each SI consists of a Control Channel Interval (CCHI) and a Service Channel Interval (SCHI). There is a Guard Interval for switching between the CCH and the SCH. All nodes have to tune to CCH during the CCHI for exchanging safety messages and other control messages. During the SCHI, nodes can optionally switch to SCHs to exchange non-safety application data. IEEE 1609.4 cannot provide the high broadcast reliability for safety applications and the high throughput for non-safety applications.

The rest of this paper is organized as follows. The related works on multi-channel MAC protocols for VANETs are discussed in Section II. Section III describes the operation of RMSB-MAC. We evaluate the performance of the RMSB-MAC in section IV. We conclude our work in Section V.

II. Related Works

A variable CCH interval (VCI) multi-channel MAC scheme [3] dynamically tunes the time duration ratio between CCHI and SCHI. However, the SCH resources are still wasted during the CCHI in the VCI. The Broadcast Sequence (BS) in [4] allows the vehicle nodes to rebroadcast the safety messages sequentially without any channel contention. An Efficient and Reliable MAC protocol for VANET (VER-MAC) [5] allows nodes to broadcast safety messages twice and to exchange non-safety messages during the CCHI. Therefore, the reliability of safety message broadcast is improved and the SCH resources are utilized efficiently.

Based on ADHOC MAC [6], the TDMA-based MAC protocols [7]–[10] are proposed to provide the collision-free and delay-bounded transmissions for safety messages. The Dedicated Multi-channel MAC (DMMAC) [7] adopts the Basic Channel reservation from RR-ALOHA [6]. Each node has to transmit a packet containing the Frame Information (FI), which specifies the status of each slot observed by the node itself. A node has to transmit a safety message successfully in order to reserve a slot and can only transmit the safety messages within the reserved time slot. The VeMAC [8] decreases the probability of transmission collisions caused by node mobility by assigning disjoint sets of time slots to vehicles moving in opposite directions and to road side units. There are Reservation Period (RP) and Contention Period (CP) on the CCH of the Hybrid Efficient and Reliable MAC (HER-MAC) [9]. The RP consists of many emergency slots which are used to transmit the safety messages without any collision while the CP is used for vehicle nodes to reserve time slots in the RP or to perform the 3-way handshake for the service slots selection. The Cooperative ADHOC MAC (CAH-MAC) [10] allows neighbor nodes to utilize the unreserved time slots for retransmitting a packet which failed to reach the target receiver due to a poor channel condition.

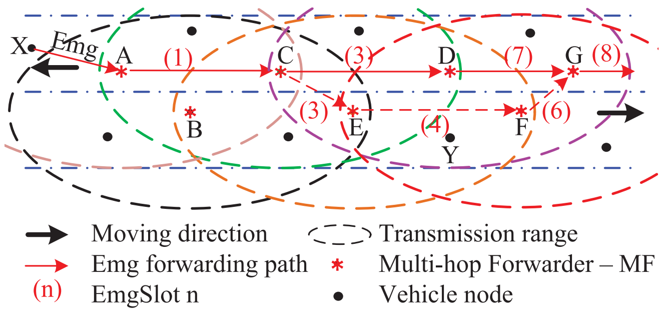

Fig. 2: Network topology.

We propose the RMSB-MAC protocol in which the dynamic TDMA slot assignment technique and the CSMA access mechanism are used. The vehicle node transmits the safety message to the Multi-hop Forwarder (MF) using the CSMA access mechanism. Then, the MF uses the TDMA technique to broadcast/forward the safety message in the reserved time slot without any collision. To reduce the probability of the merging collision caused by node mobility, the vehicle nodes moving in opposite directions reserve the different sets of time slots. Furthermore, the SCH resources are utilized during the CCHI for the non-safety message transmissions.

III. The proposed RMSB-MAC protocol

We assume that each vehicle node has one half-duplex transceiver and all vehicle nodes are assumed to be time-synchronized using the Global Positioning System (GPS). Based on the GPS signal, a vehicle node retrieves its location and moving direction. The information about the location and moving direction is shared among vehicle nodes. The network topology is given in Fig. 2. The dashed circle is the transmission range of the reference node. We define the Multi-hop Forwarder (MF) as the node which is in charge of collecting and forwarding the safety messages within their life time. For easy understanding of our proposal, we use the term vehicle nodes as the normal nodes which are not the MFs. A vehicle node is in the two-hop transmission range of another vehicle node when they are not in the transmission range of each other but in the transmission range of a common vehicle node. For example, vehicle nodes A and E are two-hop neighbors in Fig. 2.

Like IEEE 1609.4, time is divided into 100 ms Sync Intervals (SIs) in our proposed protocol, as shown in Fig. 4. Each SI is further divided into Reservation Period (RP) and Contention Period (CP) on the CCH whereas the SI is divided into N_s Service transmission Slots (SerSlots) on each SCH for the non-safety message transmissions. The RP includes N_e Emergency Slots (EmgSlots), and the duration of each EmgSlot is τ. The EmgSlots are only used by the MFs to broadcast/forward the safety messages. To prevent the merging collision, the left side moving vehicles reserve the odd EmgSlots while the right side moving vehicles reserve the even EmgSlots. The MFs B, E and F reserve the EmgSlots #2, 4 and 6, respectively. The CP is used for the vehicle node to nominate as the MF or to send the safety messages to the MF. Also, vehicle nodes perform 3-way WSA/RFS handshake in the CP to reserve SerSlots for the non-safety message transmissions.

Now, we describe the details of the RMSB-MAC protocol.

A. Multi-hop Forwarder Nomination

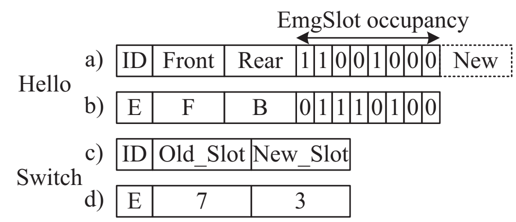

Fig. 3: Frame format.

First, we describe the Hello and Switch messages used by the MF in the RMSB-MAC protocol. The frame format of the Hello and Switch messages are given in Fig. 3. In the Hello message, the Front and Rear fields specify the furthest MFs in the front and rear sides in the same moving direction of a vehicle node. The following bit map indicates the EmgSlot occupancy of the one-hop MFs: "1" means occupied, "0" means empty. To guarantee the safety message reception without any collision, the MFs which are within the two-hop range cannot use the same EmgSlot. The bit map helps the MFs to avoid using the same EmgSlot. If a vehicle node sends the Hello message in the CP for an MF nomination, it specifies the EmgSlot which it wants to reserve in the "New" field.

The safety message should be broadcast as soon as possible. Therefore, in our proposed protocol, the MFs have to switch their EmgSlots to the earlier empty EmgSlots: from Old_Slot to New_Slot. In Fig. 3(d), the MF E broadcasts the Switch message in EmgSlot #7 to announce other MFs that it is going to switch from the EmgSlot #7 to the EmgSlot #3 from the next SI (refer to Fig. 5(c)).

TABLE I: The Frame Information Map of the MF E

EmgSlot - SI #1							
1	2	3	4	5	6	7	8
1	B	C	E	1	F		

The MF uses the Frame Information Map (FIM) to store the EmgSlot occupancy, as given in Table I. Each EmgSlot can be either empty or occupied. The FIM is updated from the overheard Hello messages of the neighbor MFs. If an EmgSlot is reserved by the one-hop neighbor MF, that EmgSlot is marked by the MF's ID. If an EmgSlot is reserved by a two-hop neighbor MF (exacted from the EmgSlot occupancy bit

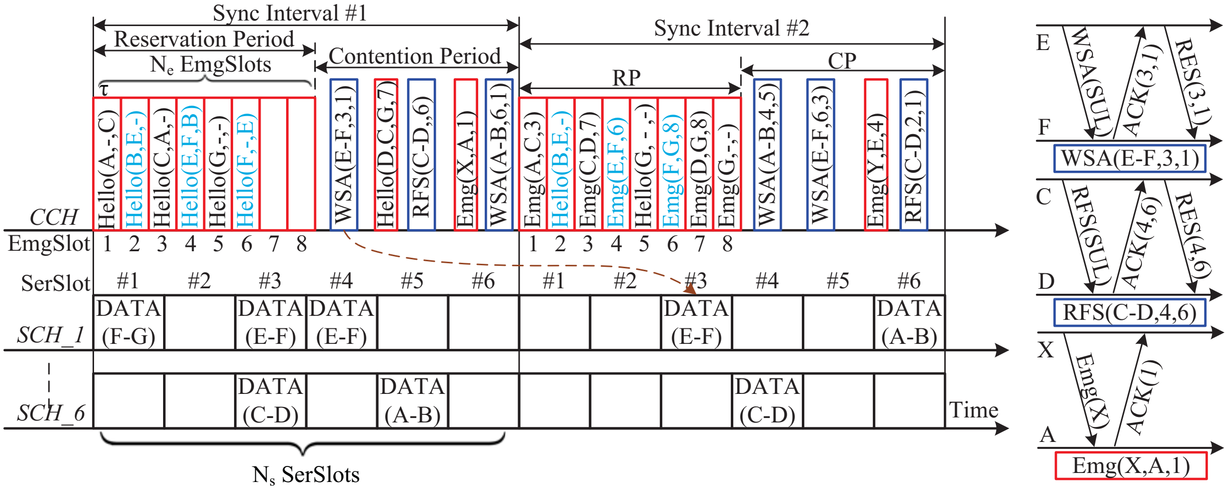

Fig. 4: The operation of RMSB-MAC protocol.

map of the overheard Hello message), that EmgSlot is marked as "1" which indicates that EmgSlot is not empty.

Next, we present how a node can nominate/retire itself as a Multi-hop Forwarder (MF). We give an example for each rule in Fig. 5. The left side is the network topology in which all vehicles are moving to the left side. The right side is the time line of the CCH where the RP consists of 5 odd EmgSlots (reserved by left side moving vehicles). All nodes are assumed to be moving to the left side. The transmission range covers up to two hops, e.g. nodes A and E are in the transmission range of node C.

Rule 1 In order to support multi-hop safety message forward, any vehicle node must have at least two MFs which are moving the same direction in the front and in the rear of it. If there is no MF in the front and/or in the rear of a vehicle node, the vehicle node can send the Hello message to nominate itself as an MF and reserve an earliest available EmgSlot of the RP. In Fig. 5(a), nodes E and G are the MFs and reserve the EmgSlots #1 and 3. At the end of the RP of the SI #1, nodes A, B, C and D satisfy the Rule 1 and they contend the CCH to send the Hello message. But node C is the first node which transmits the Hello message successfully. According the Hello message received from node E, EmgSlots # 1 and 3 are already reserved. So, node C reserves EmgSlot #5. From the SI #2, nodes E, G and C reserve the EmgSlots #1, 3 and 5, respectively.

Rule 2 If there is no MF specified in the Front and/or Rear fields of the Hello message sent by an MF, the vehicle node in the missing side (Front or Rear side) can nominate itself as an MF even though there are enough MFs around it. In Fig. 5(b), the MFs E, B and G reserve the EmgSlots #1, 3 and 5. However, there is no MF in the rear side of the MF B and in the front side of the MF E. The MFs E and B indicate the missing MF in their Hello messages. Even though vehicle nodes C and D recognize that there are enough MFs in both

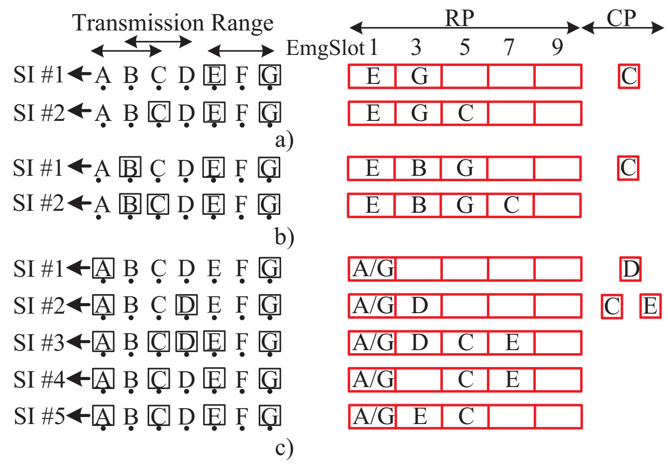

Fig. 5: Multi-hop Forwarder Selection.

sides of them, they still volunteer as an MF between the MFs B and E. Vehicle node C transmits the Hello message and reserves the EmgSlot #7 successfully. Now, we have the fully connected path among the MFs: B ↔ C ↔ E ↔ G.

Rule 3 As the MFs know the position of the neighbor MFs, they just specify the furthest MFs in their Hello messages. If an MF is not specified in the Hello messages of its neighbor MFs, that MF will retire the MF role by not sending the Hello message in the reserved EmgSlot. In Fig. 5(c), the MFs A and G can use the same EmgSlot because they are not in the two-hop range of each other. According to Rule 1, node D is the new MF which reserves the EmgSlot #3. And according to Rule 2, nodes C and E become new MFs which reserve EmgSlots #5 and 7, respectively. Fig. 6(a) shows the FIMs and the Hello messages of the MFs D, C and E in the RP of the SI #3. The MF D specifies two furthest neighbor MFs C and E in its Hello message. The MF E is the furthest MF in the rear side of the MF C. So, the MF C specifies the MFs A and E in the Hello message sent in the EmgSlot

#5 of the SI #3. Similarly, the MF E specifies the MFs C and G in its Hello message sent in the EmgSlot #7 of the SI #3. The MF D has two neighbor MFs C and E, but none of them indicate node D in their Hello messages. The MF D knows that its MF role is redundant and it does not send the Hello message in the EmgSlot #3 from the SI #4 any more.

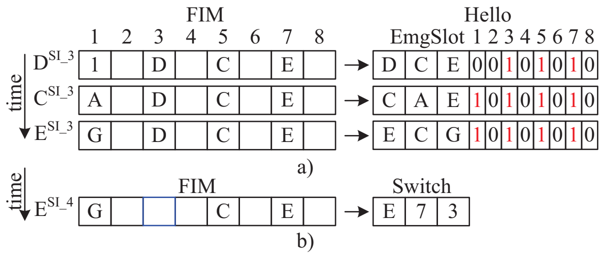

Fig. 6: Illustration for Rules 3 and 4.

Rule 4 Based on the FIM whose information is collected from the neighbor MFs, the last MF in the FIM can switch its EmgSlot to the earliest empty EmgSlot. We continue considering the example in Fig. 5(c) from the SI #4. Since the MF D retires its MF role and does not send the Hello message in the EmgSlot #3 of the SI #4, the MFs C and E clear the EmgSlot #3 in their FIMs. It means that the EmgSlot #3 is empty and the MFs C and E can switch that EmgSlot by sending the Switch message. However, only the last MF in the FIM has the right to switch the EmgSlot to prevent nodes in two-hop transmission range from switching the same EmgSlot. The MF E sends the Switch message to switch the EmgSlot from the EmgSlot #7 to the EmgSlot #3.

B. Safety message broadcast

The main purpose of the MFs is to collect/broadcast/forward the safety messages for the specified region or within the life time of the safety messages. When a vehicle node has a safety message Emg to broadcast, it sends the safety message to one of its MFs during the CP. The MF confirms the successful safety message reception by an ACK message. The ACK message specifies which EmgSlot is going to be used for broadcasting/forwarding the safety message. The ACK including the EmgSlot is used to prevent other MFs from using the same EmgSlot. During the RP, the safety message is forwarded among the MFs. The empty EmgSlots are used by any MF to forward the safety messages. Let us consider two scenarios in Fig. 7. The safety message transmission between vehicle node and MF is in the CP whereas the safety message transmission between MFs is in the RP. In Fig. 7(a), vehicle node X has a safety message to broadcast. Phase 1: During the CP, vehicle node X attempts to send the Emg(A) to the MF A, then the MF A replies with ACK(1) indicating that node A will forward this safety message in the upcoming EmgSlot # 1. Phase 2: During the RP, the MF A forwards the safety message to the MF C by sending Emg(C) in the EmgSlot #1. The MF C receives the safety message and schedules to forward that safety message in the EmgSlot #3 by sending the ACK(3) to the MF A. Then, the MF C forwards the safety message to the next MF and so on.

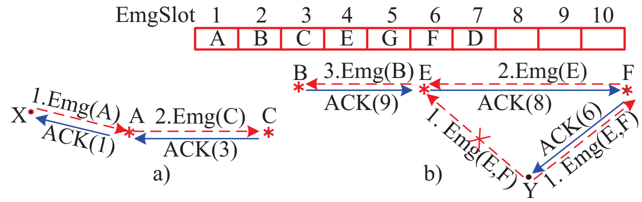

Fig. 7: Broadcast/Forward the safety messages.

When the MF forwards the safety message, the normal vehicle nodes in the MF's transmission range also receive the safety message without any collision. The reliability in the safety message broadcast depends on the transmission between the normal vehicle node and the MFs during the CP. The safety message must be transmitted to the MF. Otherwise it cannot be forwarded. To improve reliability, when the vehicle node sends the safety message to the intended MF, it also specifies another MF which acts like a back-up MF. The back-up MF is in the transmission range of the intended MF. If the back-up MF does not receive the ACK from the intended MF for a certain period, the back-up MF sends the ACK to the vehicle node. In Fig. 7(b), the vehicle node Y wants to send the safety message to the MF E. Phase 1: During the CP, vehicle node Y sends the safety message Emg(E,F) to the MF E. Assuming that the transmission between vehicle node Y and the MF E is corrupted, and the MF E does not send an ACK. After a time-out period, the MF F sends the ACK(6) to the vehicle node Y. Phase 2: The MF F forwards the safety message to the MF E in the EmgSlot #6. Since there is no collision for the transmission in each EmgSlot, the MF E confirms with the ACK(8) indicating that the MF E will use the next empty EmgSlot #8 to forward the safety message. Then, the MF E forwards the safety message to the MF B. In some cases, the MFs which are moving in the opposite direction can also help to receive the safety message from the vehicle node.

C. Non-safety message transmissions

For the non-safety message transmissions, a vehicle node has to maintain the Neighbor Information List (NIL) and SerSlot Usage List (SUL) to keep track the status of its neighbor nodes and the availability of the SerSlot of each SCH, respectively. In the NIL, if the neighbor node is the MF, the "MF" field is "1" and the "EmgSlot" field indicates which EmgSlots are reserved by the MF. The "Current SerSlot" and "Next SerSlot" indicate which SerSlot that the neighbor node uses in the current SI and the next SI, respectively. The current CP is used to reserve SerSlots of the next SI for non-safety message transmissions. When a node overhears the ACK/RES messages indicating the SerSlot, it updates the "Next SerSlot" field for the corresponding neighbor node. At the beginning of each SI, all records of the "Next SerSlot" are copied to the "Current SerSlot", and clear the record of the "Next SerSlot" in the NIL of each node. Based on the

NIL, a node knows when its neighbor node is available on the CCH during the CP of the current SI in order to perform WSA/RFS handshake. Based on the "Current SerSlot", a vehicle node knows when it can communicate with its MFs or perform the 3-way WSA/RFS handshake with its neighbor nodes. Table II shows the NIL of node A at the beginning of the CP of the second SI. Based on that, node A knows when node C is on the CCH in the current SI and begins its WSA handshake with node C. Moreover, based on the NIL, the MF knows if the neighbor vehicle nodes are on the SCH at the time it broadcasts the safety messages. And then it can rebroadcast the safety messages in another empty EmgSlot.

TABLE II: Node A's NIL at the end of SI #1

Node	MF	EmgSlot	Current SerSlot	Next SerSlot
B	1	2	5	6
C	1	3	3	5
X	0	-	-	-

The SUL shows the availability of the SerSlot on each SCH. In the 3-way WSA/RFS handshake, the receiver has to select a common available SerSlot based on the sender's SUL and its SUL. In the SUL of the MF, the Avail_slot does not include the reserved EmgSlot. Similar to the NIL, the SUL is updated whenever a vehicle node overhears the WSA/RFS messages from its neighbor nodes.

TABLE III: The SULs of nodes E and F

(a) Node E

SCH	Avail_slot
1	2, 3, 6
2	3, 4
3	4
...	...

(b) Node F

SCH	Avail_slot
1	3, 5, 6
2	1, 5
3	2, 3
...	...

Table III shows the SULs of both vehicle nodes E and F. If vehicle node E wants to exchange non-safety messages with vehicle node F, it sends WSA message including its SUL to vehicle node F. Upon receiving the WSA message from vehicle node E, vehicle node F chooses the common available SerSlot, for example SerSlot #3 of SCH #1, and sends the ACK to vehicle node E. Vehicle node E sends the RES message to confirm the selected SerSlot and SCH.

D. The operation of the RMSB-MAC protocol

The vehicle nodes must be on the CCH in order to broadcast/listen the safety messages or exchange the WSA/RFS messages to reserve SerSlots for the non-safety data transmissions. We define the sender as the node which initiates the WSA/RFS handshake by sending the WSA/RFS message, and the receiver will reply with the ACK.

1) Every vehicle node listens the whole RP to know which nodes are the MFs. A vehicle node can be an MF according to the above-mentioned rules.
2) Whenever a vehicle node has a safety message to broadcast, it attempts to transmit this safety message to the MF based on the forwarding direction of the safety message. And the safety message will be forwarded among the MFs of the desired direction for the required distance or within the safety message's life time.
3) When a node has non-safety messages to offer or request for the non-safety messages, it initiates the 3-way WSA/RFS handshake on the CCH. During the CP, the sender tries to send the WSA or RFS message including its SUL.
4) Upon receiving the WSA or RFS from the sender, the receiver selects the common [SerSlot,SCH] based on the sender's SUL and its SUL. Then, the receiver sends the ACK message indicating the selected [SerSlot,SCH] to the sender.
5) The sender confirms the selected [SerSlot,SCH] by sending the RES message to the receiver.
6) The neighbor nodes, which overhear the ACK or RES messages, update their NILs and SULs.
7) In the next SI, the sender and receiver only switch to the agreed SCH during the selected SerSlot for their non-safety message transmissions.

IV. Performance Evaluation

In this section, we perform the simulations of IEEE 1609.4 [2] and our proposed RMSB-MAC on our developed event-driven simulation tool in Matlab.

TABLE IV: Simulation Parameters

Parameters	Value
Data rate	6 Mbps
Safety / Non-safety packet size	100 / 800 bytes
WSA / RFS	100 / 100 bytes
ACK / RES	14 / 14 bytes
Hello / Switch	20 / 10 bytes
SIFS / DIFS	32 μs / 58 μs
Slot time	13 μs
The RP length	20 EmgSlots
Number of SerSlots (N_s)	10 SerSlots/SI
EmgSlot duration (τ)	2000 μs

In the simulations, there is an average of N vehicle nodes in the transmission range of an MF. By giving the high priority to the safety message, the contention window for the Hello message transmission and the WSA message transmission are set to 8 and 16, respectively. Each vehicle node generates two traffics: safety and non-safety traffics. In the performance comparisons, RMSB-MAC is compared with IEEE 1609.4 in terms of the packet delivery ratio of the safety message in one-hop broadcast and the normalized service throughput. The other simulation parameters are listed in Table IV.

Figs. 8 (a) and (b) show the performance comparison between IEEE 1609.4 and RMSB-MAC when the packet arrival rate of the safety message is 10 packets/second. As the number of vehicle nodes increases, the collision probability increases; and it results in the decreasing packet delivery ratio of the safety messages. However, the RMSB-MAC

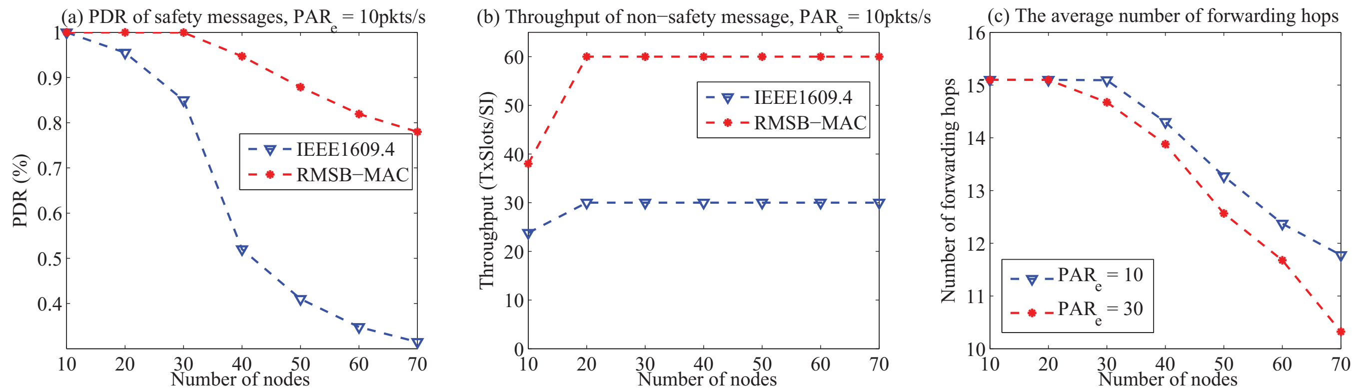

Fig. 8: Performance evaluation.

supports the cooperative transmission in the safety message transmission between the vehicle nodes and the MFs. When the intended MF does not reply the ACK message, another MF can reply the ACK message to the vehicle node and forwards the received safety message to the intended MF. Then, the intended MF broadcasts/forwards the safety message in the reserved EmgSlot without any collision. The cooperation of the MF in RMSB-MAC makes the safety message broadcast more reliable compared to IEEE 1609.4, as shown in Fig. 8(a). The number of SerSlots which are used in each SI depends on the number of successful WSA/RFS handshake and the maximum number of SerSlots that can be used in each SI. The RMSB-MAC allows vehicle nodes to use the whole SI on the SCHs for the non-safety message transmissions whereas IEEE 1609.4 allows vehicle nodes to use only the SCHI (a half of SI) for the non-safety message transmissions. That is why the maximum SCH utilization of RMSB-MAC is double compared to IEEE 1609.4, as shown in Fig. 8(b).

Fig. 8(c) shows the maximum average number of hops which are used to forward the safety messages when the packet arrival rate of the safety message is 10 packets/second and 30 packets/second. The average number of forwarding hops decreases when the number of vehicle nodes increases. It is because the successful probability of the safety message transmission from the vehicle node to the MF depends on the number of the vehicle nodes contending the CCH to send safety messages or perform the 3-way WSA/RFS handshake. Once the safety message is received successfully by the MF, the safety message is broadcast/forwarded without any collision since the MF uses the reserved EmgSlot.

V. Conclusions

In this paper, we proposed the Reliable Multi-hop Safety Message Broadcast for VANETs (RMSB-MAC) in which both TDMA and CSMA access schemes are used. The RMSB-MAC provides the reliable multi-hop safety message broadcast and utilizes the SCH resources efficiently. Moreover, the cooperative transmission is used to increase the reliability of the safety message transmission between the vehicle node and the MF. There are at least 4 MFs around a vehicle node and these MFs can help to receive and forward the safety message efficiently. The simulation results show that RMSB-MAC outperforms IEEE 1609.4 in terms of the throughput for the non-safety messages and the packet delivery ratio for the safety messages.

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