

HER-MAC: A Hybrid Efficient and Reliable MAC for Vehicular Ad hoc Networks

Duc Ngoc Minh Dang*, Hanh Ngoc Dang[†], VanDung Nguyen*, Zaw Htike* and Choong Seon Hong*

*Department of Computer Engineering, Kyung Hee University, 446-701, Korea

[†]Department of Telecommunications Engineering, Ho Chi Minh City University of Technology, Vietnam

Email: dnmduc@khu.ac.kr, hanhndn@hcmut.edu.vn, ngvandung85@khu.ac.kr, htike@khu.ac.kr, cshong@khu.ac.kr

Abstract—Vehicular Ad hoc NETWORKS (VANETs) should provide the vehicles with reliable safety message broadcasts and efficient non-safety message transmissions. The IEEE 1609.4 MAC is designed for VANETs to support multi-channel operations, but the safety message broadcast is not much reliable and the Service CHannel (SCH) resources are not fully utilized. In this paper, we propose a new multi-channel MAC for VANETs, named HER-MAC, which supports both TDMA and CSMA multiple access schemes. The HER-MAC allows vehicle nodes to send safety messages without collision on the Control CHannel (CCH) within their reserved time slots and to utilize the SCH resources during the control channel interval (CCHI) for the non-safety message transmissions. Compared to the current IEEE 1609.4, the proposed HER-MAC protocol is more reliable in the safety message broadcast, efficient in the service channel utilization.

Keywords-VANETs, Multi-channel MAC, TDMA, CSMA.

I. INTRODUCTION

The main goal of the Intelligent Transportation System (ITS) is to improve the quality, effectiveness and safety of the future transportation systems. VANETs have been considered to be an important part of the ITS. VANETs consist of two communication types: Vehicle-to-Vehicle (V2V) communication and Vehicle-to-Infrastructure (V2I) communication, and provide a variety of safety applications and non-safety applications for more driving efficiency, comfort and safety. Safety applications have strict requirements on communication reliability and delay whereas non-safety applications are more throughput-sensitive instead of delay-sensitive. The requirements for different applications are shown in Table. I.

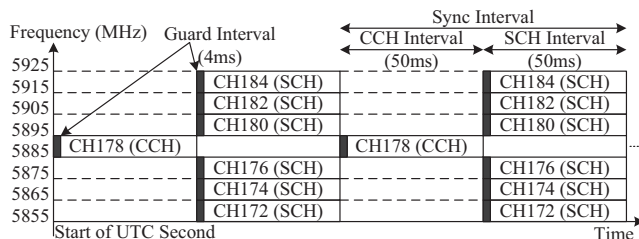


Figure 1: Frequency channel layout of a 5.9 GHz WAVE system.

Wireless Access in Vehicular Environment (WAVE) is designed for an ITS on 5.9 GHz band with the IEEE

802.11p [1] and IEEE 1609 standard family. The IEEE 1609.4 [2] 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 Control Channel Interval (CCHI) and 50 ms for the Service Channel Interval (SCH), including 4 ms Guard Interval for switching between the CCH and the SCHs. Nodes broadcast safety messages 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 SCH resources cannot be utilized during this interval. It means that the IEEE 1609.4 cannot provide the broadcast reliability for safety applications and the high throughput for non-safety applications.

In this paper, we propose the HER-MAC as a new dynamic TDMA slot assignment technique for VANETs. Unlike the IEEE 1609.4, the HER-MAC allows vehicle nodes to broadcast their safety messages in the reserved time slot to improve the reliability. Moreover, the throughput of the non-safety message is enhanced by utilizing the SCH resources during the CCHI and providing the collision-free services on the SCHs.

The rest of the paper is organized as follows. Section II reviews the related work. Section III presents the design of the HER-MAC protocol. The performance evaluation is presented in Section IV. Section V finally concludes the paper.

II. RELATED WORKS

Different multi-channel MAC protocols ([4]–[8]) have been proposed for wireless ad hoc networks. In Dynamic Channel Access (DCA) [4], nodes have two transceivers: one is on the control channel, and another can switch to any other data channels. Nodes use the control transceiver to exchange control messages on the control channel to negotiate the data channel, and then use the data transceiver to exchange data on the data channel. This scheme does not require time synchronization, but it may suffer from the bottleneck on the control channel if the ratio of the control message transmission duration and the data transmission duration is not chosen properly. Multi-channel MAC (MMAC) [5] and Hybrid Multi-channel MAC (H-MMAC) [6] adopt the Power Saving Mechanism of IEEE 802.11 (IEEE 802.11 PSM) in

Table I: DSRC application requirements [3]

Applications	Packet size/Bandwidth	Latency (ms)	Network Data Type	Application Range (m)	Priority
Intersection Collision Warning/Avoidance	100 bytes	100	Event	300	Safety of life
Cooperation Collision Warning	100 bytes/10 Kbps	100	Periodic	50-300	Safety of life
Work Zone Warning	100 bytes/1 Kbps	1000	Periodic	300	Safety
Transit Vehicle Signal Priority	100 bytes	1000	Event	300-1000	Safety
Toll Collections	100 bytes	50	Event	15	Non-Safety
Service Announcements	100 bytes/2 Kbps	500	Periodic	0-90	Non-safety
Movie Download (2 hours of MPEG 1)	>20Mbps	NA	NA	0-90	Non-Safety

which time is divided into beacons. Each beacon has an Ad hoc Traffic Indication Message (ATIM) window followed by a data window. Nodes exchange control messages during the ATIM window, and switch to agreed data channels for data transmissions. The data transmission duration may be extended to the next ATIM window in H-MMAC protocol in order to fully utilize the data channel resources. The E-MMAC is proposed in [7] to exploit the multiple channels and improve the spatial reuse of the wireless channel. The ATIM window is used to transmit the control messages containing the transmission power information used in the data window.

A variable CCH interval (VCI) multi-channel MAC scheme [9] tries to improve the saturation throughput and to provide the reliable transmission for the safety messages. 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. Similar to the IEEE 1609.4, the SCH resources are still wasted during the CCHI in the VCI. The Vehicular Enhanced Multi-channel MAC (VEMMAC) [10] allows nodes to broadcast safety messages twice and to exchange non-safety messages during the CCHI. Therefore, the VEMMAC improves the reliability of safety message broadcast and utilizes the SCH efficiently. Since the VEMMAC still uses CSMA access scheme for safety message broadcast, it cannot guarantee the QoS of the safety message or other real-time applications. The VER-MAC [11], an enhancement on the VEMMAC, allows the vehicle nodes to rebroadcast the safety messages sequentially by using the Broadcast Sequence (BS). However, the vehicle nodes which are in the same two-hop range might broadcast the safety messages simultaneously.

A clustering-based multi-channel MAC protocol is proposed in [12]. 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) [13] uses directional antennas to improve the spatial reuse. The Vehicular MESH Network (VMESH) MAC [14] proposes the coordination function for contention-free channel access on SCHs. The proposal in [15] enhances the broadcast reliability includes preemptive

priority in safety services, dynamic receiver-oriented packet reception for one-hop emergency broadcast, a multifrequency busy tone and robust distance-based relay selection for multi-hop emergency message broadcast.

Based on ADHOC MAC [16], some TDMA-based MAC protocols ([17]–[19]) are proposed to provide the collision-free and delay-bounded transmissions for safety messages. The Dedicated Multi-channel MAC (DMMAC) [17] adopts the Basic Channel reservation from RR-ALOHA [16]. 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 safety messages successfully in order to reserve a slot and can transmit safety messages only within the reserved time slot. The VeMAC [18] is proposed with new techniques of accessing the available time slots and detecting transmission collision to provide a reliable broadcast service without the hidden-terminal problem and a high throughput on the control channel. By combining the cooperative scheme and the TDMA-based MAC, the Cooperative ADHOC MAC (CAH-MAC) [19] 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.

Different from above synchronous schemes, Asynchronous Multi-channel MAC Distributed (AMCMAC-D) is proposed in [20]. Some nodes make rendezvous with their receivers or broadcast the safety messages 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.

III. THE PROPOSED HER-MAC PROTOCOL

In this protocol, we assume that each vehicle node has one half-duplex transceiver which can either transmit or receive but cannot do both simultaneously. All vehicle nodes are time-synchronized using the Global Positioning System (GPS). Time is divided into 50ms Sync Interval (SI) as shown in Fig. 2. On the CCH, each SI is further divided into Reservation Period (RP) and Contention Period (CP). The RP includes many Emergency Slots (EmgSlots), and the duration of each EmgSlot is τ . The EmgSlot is used to broadcast the safety messages (emergency messages). The number of EmgSlots in the RP is dynamically adjusted according to the number of vehicle nodes in the two-hop

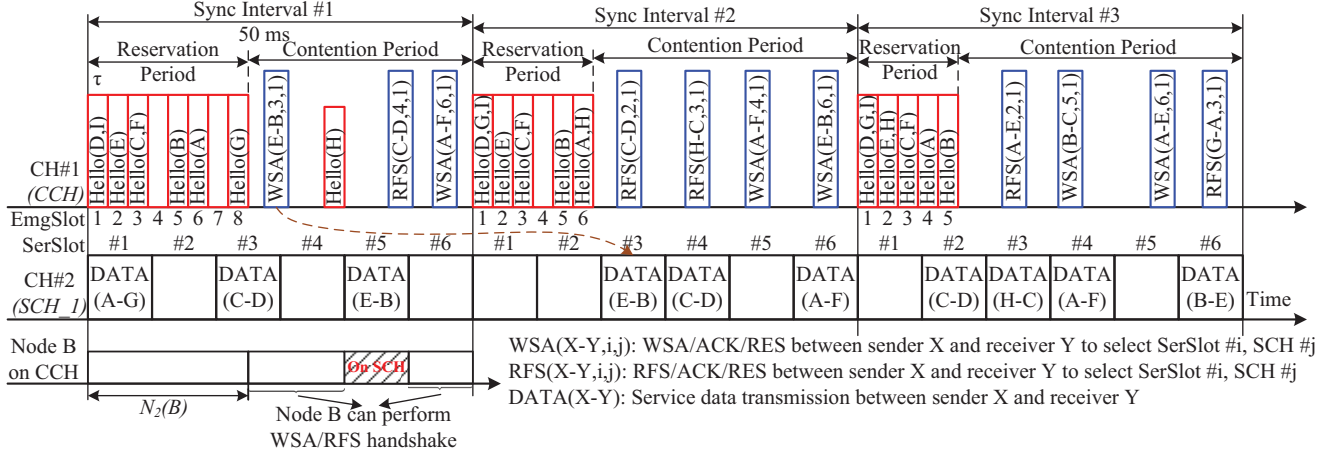


Figure 2: The operation of HER-MAC protocol.

range of the reference node. The CP is used for the vehicle node to reserve an EmgSlot or to exchange control messages for 3-way WSA/RFS handshake. During the CP, the service provider broadcasts the WSA (WAVE Service Announcement) message, and the node that needs this service can reply by sending the ACK message and the service provider confirms by sending the RES message. Moreover, a node can send the RFS (Request For Service) to the service provider for the needed service, and the service provider replies with the ACK message followed by the RES from the node. The SI is divided into M Service transmission Slots (SerSlots) on each SCH for the non-safety message transmissions. We define the one-hop neighbor nodes and two-hop neighbor nodes as those nodes which can be reached at one hop and two hops of transmission from a reference node, respectively. The neighbor nodes of a node include one-hop and two-hop neighbor nodes.

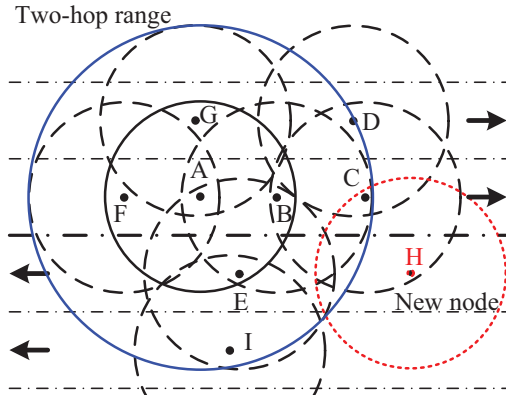


Figure 3: Network topology.

The main concepts of HER-MAC are as follows:

- Each vehicle node has to send the Hello message in its EmgSlot. The Hello message contains the information

about the status of the one-hop neighbors' EmgSlots. Based on the received Hello messages from the neighbor nodes, a node can know the status of the two-hop neighbors' EmgSlots.

- When a new vehicle node joins the network, it has to listen the whole RP to collect the status of all EmgSlots of its two-hop neighbors. Then, it tries to send a Hello message in the CP to reserve the next available EmgSlot after the last EmgSlot occupied by its two-hop neighbor node.
- The node in the two-hop range nodes occupying the last EmgSlot tries to switch to the available EmgSlot before its current EmgSlot by sending a Switch message. The purpose of EmgSlot switching is to minimize the number of the EmgSlot in the RP (the length of the RP) according to the changing network topology.
- A vehicle node broadcasts its safety messages in its EmgSlot without any collision. Each safety message is broadcast twice in two consecutive EmgSlots.
- If nodes want to exchange non-safety messages, they have to contend the CCH to perform 3-way WSA/RFS handshake in order to select a SerSlot for their non-safety message transmissions. Then, nodes switch to the selected SCH during the selected SerSlot to exchange non-safety messages.

The details of the proposed HER-MAC is described as follows:

A. EmgSlot reservation

Each node has to maintain a Frame Information Map (FIM), for example as given in Fig. 4, to store the status of EmgSlots occupied by all neighbor nodes. Each EmgSlot in the FIM can be empty or occupied (marked as "1" or a node ID). If an EmgSlot is occupied by a one-hop neighbor node, this EmgSlot is marked by the one-hop neighbor's ID in the FIM. The EmgSlot occupied by a two-hop neighbor

Node	N_1	N_2	1	2	3	4	5	6	7	8
A	8	8	1	E	F		B	A		G
B	6	8	1	E	C		B	A		1
C	5	6	D	1	C		B	1		
D	3	5	D		C		1			
E	6	8	I	E	1		B	A		1
F	6	8		1	F		1	A		1
G	8	8	1	1			1	A		1
H	6	5	1		C		1	1		
I	2	6	I	E			1	1		

Node	N_1	N_2	1	2	3	4	5	6
A	6	6	G	E	F	1	B	1
B	6	6	1	E	C		B	A
C	6	6	D	1	C		B	H
D	3	6	D		C		1	1
E	6	6	1	E	1		B	A
F	6	6	1	1	F		1	A
G	6	6	G	1	1		1	A
H	6	6	1	1	C		1	1
I	2	6	I	E			1	1

Node	N_1	N_2	1	2	3	4	5
A	5	5	G	E	F	A	B
B	5	5	1	E	C	A	B
C	5	5	D	H	C	1	B
D	3	5	D	1	C		1
E	5	5	I	E	1	A	B
F	4	5	1	1	F	A	1
G	4	5	G	1	1	A	1
H	3	5		H	C	1	1
I	2	5	I	E		1	1

Figure 4: Frame Information Map.

node is marked by "1". N_1 and N_2 are the last EmgSlots occupied by the one-hop neighbor nodes and by all neighbor nodes, respectively. N_1 is included in the Hello message (Fig. 5) to help the one-hop neighbor nodes know the length of the reserved slot map in the Hello message while N_2 represents the RP's length of the corresponding node. N_2 is also included in the Hello message to help the neighbor nodes know when the corresponding node is available on the CCH for the WSA/RFS handshake. Let us consider the FIM of node B in the first SI. From Fig. 3, nodes A, C and E are the one-hop neighbor nodes of node B, while nodes D, F, G and I are the two-hop neighbor nodes of node B. Nodes E, C and A reserve the EmgSlot #2, 3 and 6; the EmgSlot #2, 3 and 6 in the FIM of node B store the corresponding one-hop neighbor node ID (nodes E, C and A), respectively. Nodes D and I are two-hop neighbor nodes of node B and they reserve the same EmgSlot #1, the EmgSlot #1 in node B's FIM is marked as "1". In case of node F, nodes C and F reserve the same EmgSlot #3, but node C is the one-hop neighbor of node B. The one-hop neighbor has higher priority than the two-hop neighbor. Therefore, the EmgSlot #3 is marked as node C. Similarly, the EmgSlot #8 is marked as "1" since the two-hop neighbor node, node G, reserves the EmgSlot #8. Based on the status of EmgSlots, node B can get the last EmgSlots N_1 and N_2 reserved by the one-hop neighbor nodes and all neighbor nodes are 6 and 8, respectively.

In every SI, each vehicle node has to transmit a Hello message including the status of its one-hop neighbors' EmgSlots. By overhearing the Hello messages from the one-hop neighbor nodes, a vehicle node updates its FIM. The format and an example of Hello message are given in Fig. 5(a). The *SerSlot* field in the Hello message indicates which SerSlot is used by the corresponding node to exchange the non-safety messages in the current SI. This information helps the one-hop neighbor nodes to update their Neighbor Information Lists (explained in next subsection). The Hello message contains the last EmgSlots' index N_1 used by one-hop neighbor nodes, the last EmgSlots' index N_2 used by all neighbor nodes, the status of EmgSlots only occupied by

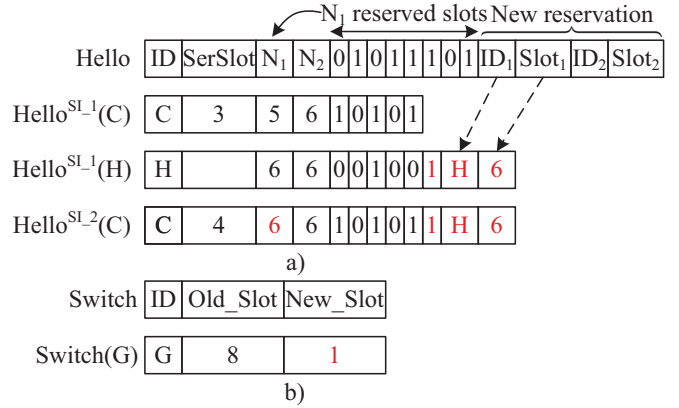


Figure 5: Frame format.

one-hop neighbor nodes (0 or 1). According to the topology (Fig. 3), nodes B and D are one-hop neighbor nodes of node C while nodes A and E are two-hop neighbor nodes of node C. From the operation of HER-MAC (Fig. 2), nodes D and B reserve EmgSlot #1 and 5, respectively. Among one-hop neighbor nodes, node B is the node that occupied the last EmgSlot. Therefore, the maximum number of Emgslots used by one-hop neighbors N_1 is 5 and node C sends its Hello message (the $Hello^{SL-1}(C)$ message in Fig. 5(a)). By overhearing the Hello message sent by node C, node B knows that node C occupies EmgSlot #3 and EmgSlots #1, 5 are occupied by node C's one-hop neighbors. EmgSlot #1 in node B's FIM will be marked as "1" because node D is the two-hop neighbor node of node B.

When a new node joins the network, it has to listen the whole RP to obtain the complete information of all EmgSlots occupied by all neighbor nodes. Then, this node tries to send the Hello message during the CP to reserve the EmgSlot #($N_2 + 1$), where N_2 is the last EmgSlots used by the all neighbor nodes. This time, the Hello message includes the information of the new reservation: new node's ID and EmgSlot. And also, when a node receives a Hello message from a new node, it has to inform a new reservation

to its one-hop neighbor nodes. For example, node H is a new node in the network from the beginning of the SI #1 and it tries to reserve one EmgSlot in the RP. Node H has to listen the whole RP of the SI #1. Based on the Hello message overheard from node C, node H knows the current length of the RP is 5 slots and it will send a Hello message to reserve EmgSlot #6 (the $Hello^{SI-1}(H)$ in Fig. 5(a)). Node C overhears the node H's Hello message, it informs the new reservation by sending its Hello message (the $Hello^{SI-2}(C)$ in Fig. 5(a)).

Due to the changing topology, some EmgSlots will be empty. In order to keep the minimum length of the RP, the node which occupies the last EmgSlot will switch to another available EmgSlot before its current EmgSlot. Let us consider the first SI as given in Fig. 2. Based on the FIM, node G finds that EmgSlot #1 is available within its two-hop neighbor set. Node G transmits a Switch message (the $Switch(G)$ in Fig. 5(b)) indicating that it will switch from EmgSlot #8 to EmgSlot #1 in the second SI. Similarly, nodes A and G will switch from EmgSlot #6 to EmgSlot #4 and from EmgSlot #6 to EmgSlot #2 in the third SI.

Once a vehicle node reserves an EmgSlot successfully, it can broadcast its safety messages within its EmgSlot without any collision. Since some one-hop neighbor nodes may be on the SCHs for the non-safety message transmissions, they cannot receive the safety message. That is why each safety message has to be broadcast again in the next SI. Using the TDMA scheme and retransmission mechanism, the safety broadcast in the HER-MAC becomes more reliable.

Similar to ADHOC MAC [16], the HER-MAC has two types of collision on EmgSlots which can happen on the CCH [21]: access collision and merging collision. An access collision happens when two or more vehicle nodes in the two-hop range of each other try to reserve the same EmgSlot. On the other hand, a merging collision occurs when two or more vehicle nodes reserving the same EmgSlot become the two-hop neighbor node of each other. A vehicle node can detect the access collision if at least one of its one-hop neighbor nodes confirm about its EmgSlot reservation. In that case, that vehicle node has to reserve the EmgSlot again until all one-hop neighbor nodes confirms about its EmgSlot reservation. In order to detect the merging collision easily, each vehicle node broadcasts its Hello message randomly within its EmgSlot. In some cases, the one-hop neighbor node of colliding nodes helps to detect the merging collision. When the merging collision occurs, the colliding nodes also have to reserve new EmgSlots again.

B. Non-safety message transmissions

For the non-safety message transmissions, node has to maintain the status of its one-hop neighbor nodes and the availability of the SerSlot of each SCH through Neighbor Information List (NIL) and SerSlot Usage List (SUL), respectively. The NIL shows the SerSlots that the one-hop

neighbor nodes use to exchange the non-safety messages in the current SI and the next SI. The current CP is used to exchange the WSA/RFS messages to reserve a SerSlot of the next SI for non-safety message transmissions. It means that when a node overhears its one-hop neighbor node's WSA/RFS messages, it updates the reserved SerSlot of the next SI for the corresponding one-hop neighbor node. At the beginning of each SI, all records of the "Next SerSlot" are copied to the "Current SerSlot", and clear the record "Next SerSlot" in the NIL of each node. For some cases of missing the WSA/RFS messages, a node can update the records of the "Current SerSlot" by listening the Hello message from its one-hop neighbor node. In additions, the NIL stores the maximum number of EmgSlots N_2 of its one-hop neighbor nodes. The N_2 indicates the time that the neighbor node can perform the WSA/RFS handshake. In Fig. 2, node B can perform the WSA/RFS after the time of $N_2(B)$ and except the time node B is on the SCH for the non-safety messages transmissions (SerSlot #5). Based on the NIL, a node knows when its one-hop neighbor node is available on the CCH during the CP of the current SI in order to perform WSA/RFS handshake. Table. II shows the NIL of node A at the end of the first SI. Based on that, node A knows when node F is on the CCH in the current SI and begins its WSA handshake with node F.

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

Node	N_2	Current SerSlot	Next SerSlot
B	8	5	3
E	8	5	3
F	8	4	6
G	8	1	-

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. Since a node has to be on the CCH during its reserved EmgSlot to send its Hello message and its safety messages, a node cannot choose a SerSlot that includes its EmgSlot for non-safety message transmissions. Note that a node is not allowed to reserve the same SerSlot consecutively to avoid missing the safety messages on the CCH because each safety message is broadcast twice in two consecutive EmgSlots. An example is given in Fig. 2, while nodes A and G are exchanging non-safety messages during the SerSlot #1 on the SCH_1, node D broadcasts its safety messages. Since node D will rebroadcast its safety messages in the next SI, nodes A and G are not allowed to reserve the SerSlot #1 of any SCHs in the next SI. Similar to NIL, the SUL is updated whenever a node overhears the WSA/RFS messages from its neighbor nodes.

Table. III shows the SULs of both nodes A and F. If node A wants to exchange non-safety messages with node F, it sends WSA message including its SUL to node F.

Table III: The SULs of nodes A and F

(a) Node A		(b) Node F	
Channel	Avail_slot	Channel	Avail_slot
2	2, 4, 6	2	2, 3, 4, 5, 6
3	3, 4	3	1, 5
4	4	4	2, 3
...

Upon receiving the WSA from node A, node F chooses the common available SerSlot, for example SerSlot #6 of CH #2 (SCH_1), and sends the ACK to node A. Node A confirms the selected SerSlot by sending the RES to node F.

C. The operation of the HER-MAC protocol

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

- 1) Each vehicle node has to send its Hello message within its reserved EmgSlot to inform its one-hop neighbor nodes about its EmgSlot reservation status in every SI. The one-hop neighbor nodes which overhear the Hello message update their FIMs.
- 2) Whenever a vehicle node has a safety message, it broadcasts this safety message after the Hello message in its reserved EmgSlot without any collision. This safety message will be rebroadcast in the next SI.
- 3) When a node has non-safety messages to send or request for the non-safety messages, it contends the CCH during the CP to send the WSA or RFS message including its SUL.
- 4) Upon receiving the WSA or RFS from the sender, the receiver selects the "best" SerSlot of the corresponding SCH based on the sender's SUL and receiver's SUL. Then, the receiver sends the ACK indicating the selected SerSlot and SCH to the sender.
- 5) The sender sends the RES to confirm the SerSlot and the SCH selected by the receiver.
- 6) The one-hop neighbor nodes, which overhear the ACK and/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 the IEEE 1609.4 [2] and our proposed HER-MAC protocol on our developed event-driven simulation tool in Matlab.

In the simulations, all vehicle nodes are in the two-hop range of each other. Each vehicle node generates two traffics: safety and non-safety traffics. By giving the high priority

to the Hello message when a vehicle try to send a Hello message for the EmgSlot reservation, the contention window for the Hello message transmission and the WSA message transmission are set to 8 and 16, respectively. Since the safety message has the strict delay, we consider the highest priority safety message with 100 ms latency (Table I) in our simulations. That means we set 100 ms time-out for the safety message. When the safety message is generated, a vehicle node has to contend the control channel and broadcast the safety message within 100 ms, otherwise this safety message is dropped. The other simulation parameters in our simulations are listed in Table IV. Each simulation was performed for 10 seconds, and the simulation results are the average of 20 runs.

Table IV: Simulation Parameters

Parameters	Value
EmgSlot duration (τ)	1000 μ s
Hello message duration	100 μ s
Switch message duration	100 μ s
3-way WSA handshake duration	400 μ s
Number of SerSlots (M)	5
Safety message transmission time	200 μ s
Non-safety message transmission time	1000 μ s
Safety message time-out	100 μ s

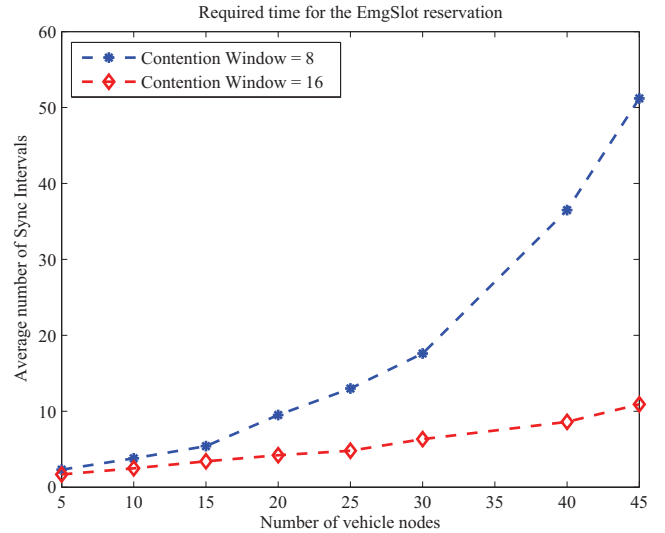


Figure 6: Required time for the EmgSlot reservation versus the number of vehicle nodes.

First, we performed the simulation to show how many Sync Intervals needed until all vehicle nodes reserved the EmgSlots successfully. Fig. 6 shows the comparison of the required time for the EmgSlot reservation according to different number of vehicle nodes. Vehicle nodes have to contend the control channel to send the Hello message for the EmgSlot reservation. When the number of vehicle nodes increases, the collision probability increases and the success-

ful Hello message transmission probability decreases. So, it takes long time until all vehicle nodes reserved the EmgSlots successfully. Fig. 6 also shows that the larger contention window reduces the required time for EmgSlot reservation because of the decrease of the collision probability.

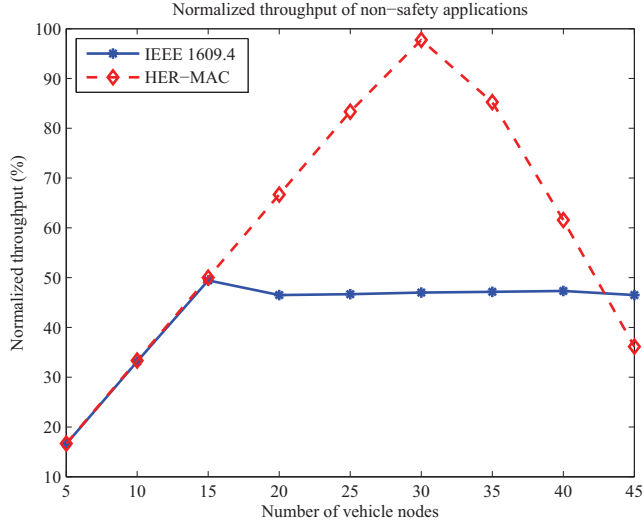


Figure 7: Non-safety normalized throughput comparison of different protocols.

Next, we compare the performance of the IEEE 1609.4 and our proposed HER-MAC in terms of the normalized throughput of non-safety messages (Fig. 7) and the packet delivery ratio (PDR) of the safety messages (Fig. 8). The safety packet arrival rate and the non-safety packet arrival rate are 50 packets/second and 200 packets/second, respectively. Since the HER-MAC utilizes all service channel resources and provides collision-free non-safety message transmission in each SerSlot, the maximum normalized throughput of the HER-MAC is about twice as many as that of the IEEE 1609.4 as shown in Fig. 7. In the HER-MAC, the reservation period (RP) compromises the contention period (CP). Therefore, when the number of vehicle nodes increases, the length of the RP increases and the length of the CP decreases. Moreover, vehicle nodes have to negotiate the SerSlot during the CP, the successful SerSlot negotiation decreases when the number of vehicle nodes is too large. That is why the normalized throughput of the HER-MAC decreases when the number of vehicle nodes increase from 30 to 45. For example, when the number of nodes is 45 nodes, the RP length is 45ms (each EmgSlot is 1ms), there are only 5ms for the CP. It leads to a small number of the successful SerSlot negotiation. For that reason, the HER-MAC should limit the maximum length of the RP in order to give more chance for the vehicle nodes to reserve the SerSlot.

Fig. 8 shows the comparison of the safety packet delivery ratio of the IEEE 1609.4 and the HER-MAC. The HER-

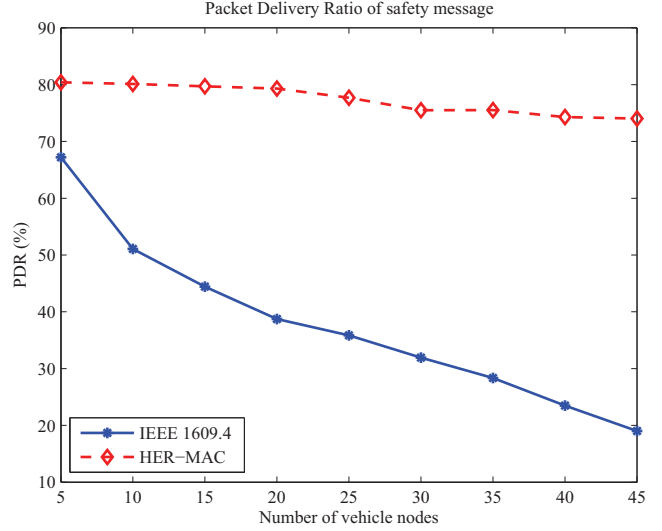


Figure 8: Safety message packet delivery ratio comparison of different protocols.

MAC uses TDMA access scheme and the retransmission mechanism for the safety message broadcast. After a vehicle node reserved an EmgSlot successfully, it can broadcast its safety messages during its reserved EmgSlot without any collision. Moreover, each safety message is broadcast twice in its EmgSlot of two consecutive Sync Intervals to ensure that all vehicle nodes receive its safety messages successfully. The IEEE 1609.4 uses the CSMA access mechanism to broadcast the safety message, and that is why the safety message broadcast is not reliable. Especially, when the number of vehicle nodes increases, the collision probability increases and the safety packet delivery ratio decreases significantly. We consider the HER-MAC simulation from the initial state when no EmgSlot is reserved; all vehicle nodes have to reserve the EmgSlots in order to broadcast the safety messages. If a node has not reserve the EmgSlot yet and it has some safety messages to send, the safety messages might be dropped due to time-out. When a number of vehicle nodes increases, it takes long time to finish the EmgSlot reservation for all vehicle nodes. During the EmgSlot reservation, some safety messages are dropped if a vehicle node cannot reserve an EmgSlot successfully. It is the reason the safety packet delivery ratio slightly decreases when the number of vehicle nodes increases. If we consider the HER-MAC simulation when all EmgSlot are reserved successfully, the safety packet delivery ratio does not decrease as the number of vehicle nodes increases.

V. CONCLUSIONS

In this paper, we proposed the hybrid multi-channel MAC for VANETs, named HER-MAC, which combines TDMA and CSMA access schemes. The HER-MAC provides the reliable safety message broadcast through the TDMA access

scheme and the retransmission mechanism. Moreover, the HER-MAC allows the vehicle nodes to exchange non-safety messages during the CCH interval to improve the throughput of non-safety applications. The simulation results have been presented to show that the HER-MAC protocol outperforms the IEEE 1609.4 in terms of the aggregate throughput for the non-safety messages and the packet delivery ratio for the safety messages. However, a vehicle node cannot send many safety messages during the limited reserved EmgSlot. The HER-MAC needs to be enhanced to help the vehicle nodes use the available EmgSlot of its neighbor if needed. We left this issue as our future work.

ACKNOWLEDGMENT

This research was supported by the MSIP (Ministry of Science, ICT & Future Planning), Korea, under the ITRC (Information Technology Research Center) support program (NIPA-2013-H0301-13-4006) supervised by the NIPA (National IT Industry Promotion Agency). Dr. CS Hong is the corresponding author.

REFERENCES

- [1] *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments*, Jul, 2010.
- [2] *IEEE Standard for Wireless Access in Vehicular Environments (WAVE) Multi-channel Operation*, Sep, 2010.
- [3] Q. Xu, T. Mak, J. Ko, and R. Sengupta, "Vehicle-to-vehicle safety messaging in dsrc," in *Proc. of the 1st ACM international workshop on Vehicular ad hoc networks*, pp. 19–28, ACM, 2004.
- [4] S.-L. Wu, C.-Y. Lin, Y.-C. Tseng, and J.-P. Sheu, "A new multi-channel mac protocol with on-demand channel assignment for multi-hop mobile ad hoc networks," in *Proc. of International Symposium on Parallel Architectures, Algorithms and Networks (I-SPAN)*, pp. 232–237, 2000.
- [5] J. So and N. H. Vaidya, "Multi-channel mac for ad hoc networks: handling multi-channel hidden terminals using a single transceiver," in *Proc. of the 5th ACM international symposium on Mobile ad hoc networking and computing*, pp. 222–233, ACM, 2004.
- [6] D. N. M. Dang and C. S. Hong, "H-mmacc: A hybrid multi-channel mac protocol for wireless ad hoc networks," in *Proc. of IEEE International Conference on Communications (ICC)*, pp. 6489–6493, 2012.
- [7] D. N. M. Dang, M. V. Nguyen, C. S. Hong, S. Lee, and K. Chung, "An energy efficient multi-channel mac protocol for wireless ad hoc networks," in *Proc. of IEEE Global Communications Conference (GLOBECOM)*, pp. 433–438, 2012.
- [8] D. N. M. Dang, P. L. Vo, C. K. Hwang, and C. S. Hong, "Mitigating starvation in wireless ad hoc networks: Multi-channel mac and power control," in *Proc. of 8th International Conference on Ubiquitous Information Management and Communication (IMCOM/ICUIMC)*, 2014.
- [9] Q. Wang, S. Leng, H. Fu, and Y. Zhang, "An ieee 802.11p-based multichannel mac scheme with channel coordination for vehicular ad hoc networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 13, no. 2, pp. 449–458, 2012.
- [10] D. N. M. Dang, H. N. Dang, C. T. Do, and C. S. Hong, "An enhanced multi-channel mac for vehicular ad hoc networks," in *Proc. of IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 351–355, 2013.
- [11] D. N. M. Dang, H. N. Dang, C. T. Do, and C. S. Hong, "An efficient and reliable mac for vehicular ad hoc networks," in *Proc. of Network Operations and Management Symposium (APNOMS), 2013 15th Asia-Pacific*, pp. 1–5, 2013.
- [12] H. Su and X. Zhang, "Clustering-based multichannel mac protocols for qos provisionings over vehicular ad hoc networks," *IEEE Transactions on Vehicular Technology*, vol. 56, no. 6, pp. 3309–3323, 2007.
- [13] X. Xie, F. Wang, K. Li, P. Zhang, and H. Wang, "Improvement of multi-channel mac protocol for dense vanet with directional antennas," in *Proc. of IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 1–6, 2009.
- [14] 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. of IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 417–422, 2007.
- [15] X. Ma, J. Zhang, X. Yin, and K. Trivedi, "Design and analysis of a robust broadcast scheme for vanet safety-related services," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 1, pp. 46–61, 2012.
- [16] 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 services," *Wireless Networks*, vol. 10, no. 4, pp. 359–366, 2004.
- [17] N. Lu, Y. Ji, F. Liu, and X. Wang, "A dedicated multi-channel mac protocol design for vanet with adaptive broadcasting," in *Proc. of IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 1–6, 2010.
- [18] H. Omar, W. Zhuang, and L. Li, "Vemacc: A tdma-based mac protocol for reliable broadcast in vanets," *IEEE Transactions on Mobile Computing*, vol. 12, no. 9, pp. 1724–1736, 2013.
- [19] S. Bharati and W. Zhuang, "Cah-macc: Cooperative adhoc mac for vehicular networks," *IEEE Journal on Selected Areas in Communications*, vol. 31, no. 3, pp. 470–479, 2013.
- [20] C. Han, M. Dianati, R. Tafazolli, X. Liu, and X. Shen, "A novel distributed asynchronous multichannel mac scheme for large-scale vehicular ad hoc networks," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 7, pp. 3125–3138, 2012.
- [21] F. Borgonovo, L. Campelli, M. Cesana, and L. Fratta, "Impact of user mobility on the broadcast service efficiency of the adhoc mac protocol," in *Proc. of IEEE Vehicular Technology Conference (VTC2005-Spring)*, vol. 4, pp. 2310–2314 Vol. 4, 2005.