Directional Multi-channel MAC for VANETs

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Abstract. The important goal in designing the Medium Access Control (MAC) layer in Vehicular Ad hoc Networks (VANETs) is to provide reliable safety message broadcast and efficient non-safety message transmissions to vehicles. This paper proposes the Directional Multi-channel MAC protocol for VANETs, named DMV protocol, which provides safety message broadcast reliability and high service channel utilization. Both TDMA and CSMA access schemes are supported, and directional antennas are employed in the DMV protocol. The simulation results show that DMV outperforms IEEE 1609.4 in terms of packet delivery ratio of safety messages and throughput of non-safety messages at the price of complex data structures.

Keywords: Multi-channel · MAC protocol · Directional antenna · Safety message · Reliable broadcast · Vehicular Ad Hoc Networks · VANETs

1 Introduction

VANETs are primarily designed to improve the quality, effectiveness and safety of the future transportation systems. VANETs support Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications to provide safety and non-safety applications for driving more efficiency, comfort and safety. Safety applications, such as collision avoidance, have strict requirements on communication reliability and delay whereas non-safety applications like infotainment are more throughput-sensitive.

Dedicated Short Range Communications (DSRC) is defined in 5.9 GHz with 7 channels of 10 MHz: one Control CHannel (CCH) and six Service CHannels (SCHs). IEEE 1609.4 [1] supports multi-channel operations for VANETs.

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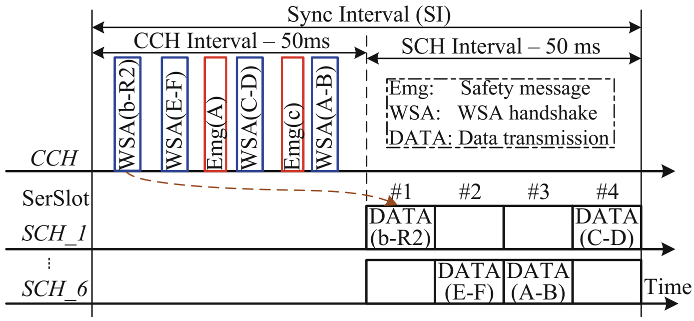

Fig. 1. The operation of IEEE 1609.4

In Fig. 1, each 100-ms Sync Interval (SI) consists of a 50-ms CCH Interval (CCHI) and a 50-ms SCH Interval (SCHI). During the CCHI, nodes broadcast periodic/event-driven safety (Emg) messages or exchange control packets like WAVE Service Announcement (WSA) packets for SCH negotiations on the CCH. Then, nodes switch to the negotiated SCHs for their non-safety message transmissions during the SCHI. This channel access scheme has a high contention on CCH, and the CCH and SCH resources cannot be utilized during the SCHI and CCHI, respectively. The VER-MAC protocol [4] improves the broadcast reliability of safety message by allowing nodes to retransmit safety messages. VER-MAC utilizes the SCH resources during the SCHI efficiently.

The TDMA-based MAC protocols [2,3,5,8,9] proposed in literature provide collision-free and delay-bounded transmissions for safety messages. VeMAC [8] proposed new techniques of accessing the available time slots and detecting transmission collisions to provide a reliable broadcast service without the hidden-terminal problem and a high throughput on the CCH. CAH-MAC [2] allows neighbor nodes to utilize the unreserved time slots for retransmitting the failed packet due to a poor channel condition. The TDMA and CSMA access schemes are used in Hybrid Efficient and Reliable MAC (HER-MAC) [3]. TDMA-based Reservation Period (RP) provides collision-free transmissions for safety messages and CSMA-based Contention Period (CP) is used for vehicles to reserve time slots in the RP or to perform the 3-way handshake for service slots selection. The performance of VeMAC, CAH-MAC and HER-MAC can be degraded as the number of nodes increases because of the limitation of the number of time slots. To overcome this, RMSB-MAC [5] defined Multi-hop Forwarders (MFs) which are allowed to reserve time slot for broadcasting the collected safety messages.

To improve the spatial reuse, several proposed MAC protocols employ directional antennas. The Directional Virtual Carrier Sensing (DVCS) [10] employs a steerable antenna system which can point to any specified direction. The Directional Network Allocation Vector (DNAV) is used for channel reservation to increase the network capacity 3 to 4 times. Circular Directional RTS (CDR-MAC) [7] uses the circular directional RTS in which the RTS is transmitted directional consecutively in circular way. Upon receiving RTS, the receiver replies with directional CTS at the direction of the sender. MMAC-DA [6] employs the directional antenna to multi-channel MAC protocol to exploit multiple channels as well as improve spatial reuse of wireless channel.

The rest of this paper is organized as follows. The antenna model is presented in Sect. 2. Section 3 describes the operation of DMV. Section 4 presents the performance evaluation. We conclude our work in Sect. 5.

2 Antenna Model

In DMV, the antenna operates in either *Omnidirectional* mode or *Directional* mode. The omnidirectional mode is used when nodes exchange control messages or safety messages on CCH. In directional mode, the antenna can beamform to one of M fixed directions. The directional mode is used on SCH to transmit service messages. The antenna gain in omnidirectional and directional modes are G^o and G^d (usually $G^d > G^o$), respectively (Fig. 2).

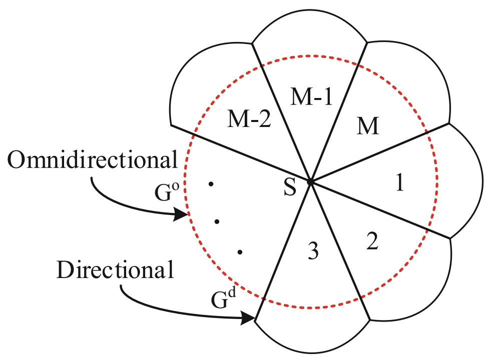

Fig. 2. Antenna model.

3 The Proposed DMV Protocol

Each vehicle node is equipped with a half-duplex transceiver. We define the MF as the node in charge of collecting, broadcasting and forwarding the safety messages. Like IEEE 1609.4, all vehicles are assumed to be time-synchronized using GPS. The location and moving direction information are shared among vehicles. Each 100-ms SI consists of a TDMA-based Reservation Period (RP) and a CSMA-based Contention Period (CP) on the CCH (Fig. 5). However, a 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) on CCH which are only used by the MFs to broadcast/forward the safety messages. To prevent the merging collision, some EmgSlots are dedicated for Road Side Units (RSUs) while the left and right side moving vehicles [8] reserve the odd and even EmgSlots, respectively. The CP is used for a vehicle to nominate itself as an MF or to send the safety messages to the MF. Moreover, vehicles perform 3-way WSA(Sender,Receiver,Beam,SerSlot,SCH) handshake in the CP to reserve SerSlots for the non-safety message transmissions.

3.1 Main Idea

The proposed DMV supports multi-hop reliable safety message transmissions as well as high efficient service data transmissions. During the CP, the MFs cooperate to receive the safety messages from the neighbor vehicles. Then, the MFs forwarded the received safety messages using their reserved EmgSlots in the RP. By using the cooperative transmissions and TDMA access scheme, the DMV protocol provides high reliability of safety message broadcast. Also, during the CP, vehicle nodes can perform 3-way WSA/RFS handshake to negotiate SerSlots of SCHs for the directional service transmissions on SCHs in the next SI. Since the DMV protocol implements directional antenna, the spatial reuse of wireless channel is improved, i.e. the service data transmissions of vehicle nodes D-f and b-B can be done in the same SerSlot on the same SCH.

3.2 Multi-hop Forwarder Nomination

In DMV, Hello(ID,Front,Rear) message (Fig. 3(a)) is sent in the CP to reserve an EmgSlot or sent periodically in the RP to maintain the EmgSlot occupancy. The furthest Front MF and the Rear MF of an MF are indicated in Hello message. The EmgSlot occupancy helps to prevent MFs which are in the two-hop transmission range from using the same EmgSlot.

The MF stores the EmgSlot occupancy of its one-hop MFs and two-hop MFs in Frame Information Map (FIM), shown in Table 1. An MF updates its FIM

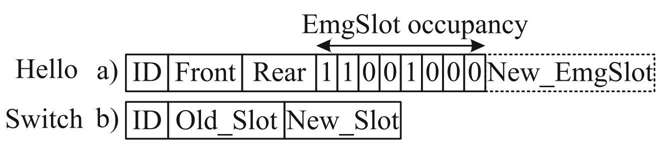

Fig. 3. Frame format.

Table 1. The frame information map

Multi-hop forwarder C											
EmgSlots	1	2	3	4	5	6	7	8	9	10	...
1-hop MFs	C	B	A	D			E				
2-hop MFs					1	1			1		

through the overheard Hello messages from the neighbor MFs. FIM prevents the vehicle nodes in two-hop transmission range from using the same EmgSlot.

The following rules present how a vehicle can nominate/retire itself as an MF.

Rule 1: There are at least two MFs which are moving in the same direction in the front and in the rear of a vehicle or an MF. Based on the overheard Hello message, a vehicle knows about the neighbor MFs and it can nominate itself as an MF.

Rule 2: Since only the furthest MFs are specified in the Hello message, the MF which is not specified in all Hello messages of its neighbor MFs retires its MF role by not sending Hello message in its reserved EmgSlot.

Rule 3: Based on the FIM, the last MF in its FIM can switch its EmgSlot to the earliest empty EmgSlot. However, only the last MF in the FIM is allowed to switch the EmgSlot to prevent vehicle nodes in two-hop transmission range from switching to the same EmgSlot.

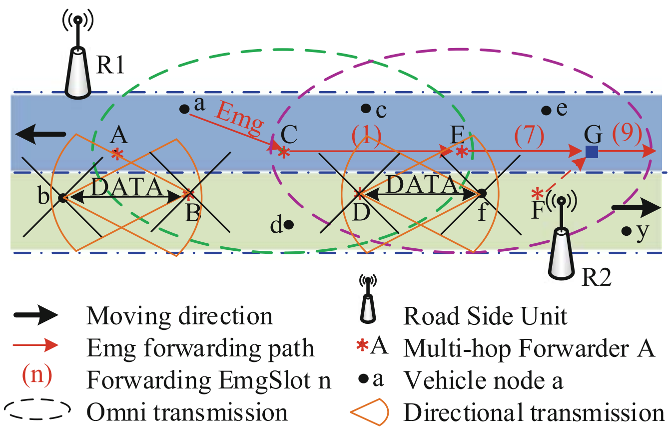

Fig. 4. Network topology.

3.3 Safety Message Broadcast

In the design of DMV, all MFs have to be connected, thus there are at least 4 MFs in both directions around a vehicle. The vehicle has to broadcast its safety messages in omnidirectional mode during the CP. Once the safety messages are received successfully by at least one neighbor MF, they are forwarded among MFs in omnidirectional mode during the RP. Since each MF reserves an EmgSlot of the RP, it can broadcast/forward the received safety messages without any collision. Consider an example given in Fig. 5, vehicle node a transmits its safety message to the MF C. Upon receiving that safety message successfully, the MF

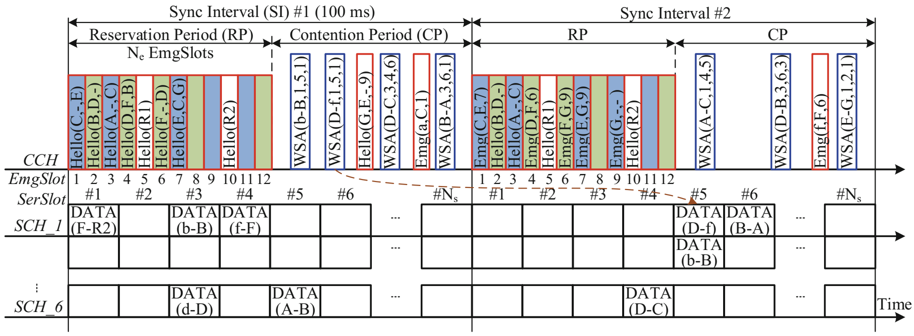

Fig. 5. The operation of the DMV protocol.

Table 2. Explanation for the notation in Fig. 5

Notation	Description
Hello(ID,Front,Rear)	The MF *ID* sends the Hello message including the *Front* and *Rear* MFs
Hello(ID,Front,Rear,New)	The Hello message is sent in the CP to nominate as an MF and reserves the *New* EmgSlot
Emg(Sender,MF,EmgSlot)	The *Sender* sends the safety message Emg to the *MF* and the *MF* will forward the received safety message in the upcoming *EmgSlot*
WSA(Sender,Receiver,Beam,SerSlot,SCH)	The 3-way WSA handshake between *Sender* and *Receiver* to select *Beam*, *SerSlot* and *SCH*
RFS(Sender,Receiver,Beam,SerSlot,SCH)	The 3-way RFS handshake between *Sender* and *Receiver* to select *Beam*, *SerSlot* and *SCH*
DATA(Sender,Receiver)	The non-safety messages are exchanged between the *Sender* and *Receiver* on the selected SCH during the selected SerSlot
* *Beam* in WSA/RFS handshake is $Sender's$ antenna beam index	

confirms that it is going to forward that safety message in the next EmgSlot #1. If the MF C is not on the CCH or there is a collision at the MF C, the other MFs A, B or D cooperate to receive that safety message and forward it in the RP (Table 2).

Table 3. Node A's NIL

Node	MF	Current SerSlot	Next SerSlot
B	1	3,5	6
b	0	3	3
C	1	-	4

Table 4. Node A's SUL

SCH	SerSlot #1	SerSlot #2		SerSlot #N_s
1	1,2,4	2,3	...	2,M
...	..., ...	...	...	...
6	1,3	2,4	...	1,2

3.4 Non-safety Message Transmission

For WSA/RFS handshake before any non-safety message transmission, each vehicle has to keep track of the status of their neighbor nodes and the availability of beam and SerSlot of each SCH via Neighbor Information List (NIL) and SerSlot Usage List (SUL), respectively. In the NIL (Table 3), the "Current SerSlot" and "Next SerSlot" indicate which SerSlot the neighbor node uses in the current SI and the next SI. In the 3-way WSA handshake, the service provider (source) sends a WSA including its SUL (Table 4). The service user (destination) selects a common available SerSlot based on the sender's SUL and its SUL and replies with an Acknowledgment (ACK) including the selected beam, SerSlot and SCH. The service provider sends a Reservation (RES) to confirm the selected transmission parameters.

3.5 The Operation of the DMV Protocol

Vehicle nodes must always be on the CCH except the time they exchange non-safety messages on SCHs.

1. During RP, vehicles listen to Hello messages on CCH to know which nodes are their MFs.
2. A vehicle node attempts to transmit its safety message to an MF based on the forwarding direction of safety message in CP. After that, the safety message will be broadcast by MF in RP.
3. When a vehicle node has non-safety messages to send or request for the non-safety messages, it has to perform the WSA/RFS handshake on the CCH by sending the WSA or RFS message including its SUL.
4. Upon receiving the WSA or RFS message from the sender, the receiver sends the ACK message indicating the selected SerSlot, SCH and Beam index to the sender.

5. The sender confirms the selected SerSlot, SCH and Beam index by sending the RES message to the receiver.
6. All neighbor nodes update their NILs and SULs according to the overheard ACK or RES messages.
7. In the next SI, the sender and receiver only switch to the agreed SCH during the selected SerSlot and use the negotiated Beam index for their non-safety message transmissions.

3.6 Synchronization Collision Reduction

In DMV, nodes perform the WSA/RFS handshake before any data transmission only during the CP. If a node has data packets (safety or non-safety) to send during the RP, it has to wait until the upcoming CP to perform the handshake. So, at the beginning of CP, there are many nodes contending CCH for WSA/RFS handshake. That high contention leads to the high collision probability. This kind of collision is synchronization collision. To reduce synchronization collision, each node can start contending the CCH with the probability p. On the other hand, the CP can be divided into many sub-slots. At the beginning of each CP, each node chooses a limited number of sub-slots randomly and it only contends the control channel during the selected sub-slots.

4 Performance Evaluation

In this section, we perform the simulations on the event-driven simulation tool in Matlab to compare the performance of DMV and IEEE 1609.4. The simulation parameters are summarized in Table 5. We vary the number of nodes N to evaluate the packet delivery ratio (PDR) of safety messages and the throughput of non-safety messages.

Table 5. Simulation parameters

Parameters	Value
Data rate	6 Mbps
Safety/WSA packet arrival rate	10/100 packets/s
Safety/Non-safety packet size	100/1024 bytes
WSA/ACK/RES	100/14/14 bytes
Hello/Switch	20/10 bytes
Slot time/SIFS/DIFS	13/32/58 μs
Number of EmgSlots (N_e)	6 EmgSlots/RP
Number of SerSlots (N_s)	4 SerSlots/SI
Number of beams	2

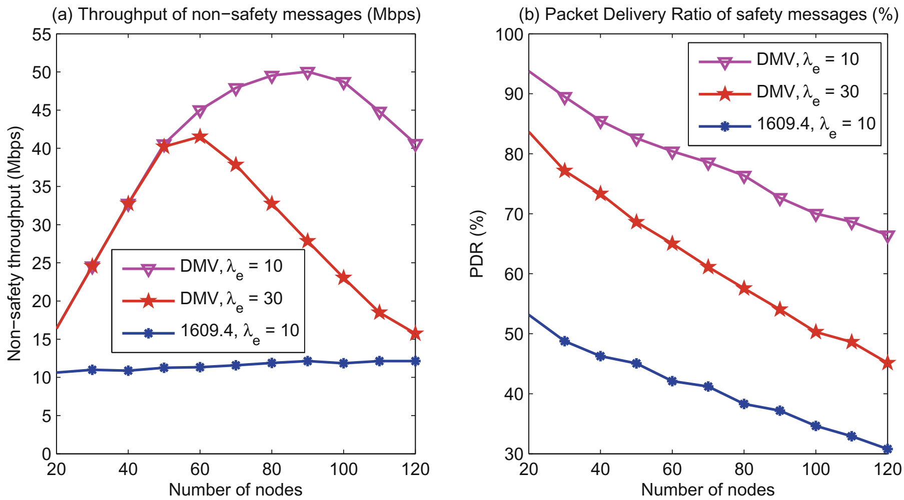

Fig. 6. Performance comparison of the IEEE 1609.4 and DMV protocols.

Figure 6 shows the performance comparison between IEEE 1609.4 and DMV with the topology in Fig. 4. The packet arrival rate of safety message (λ_e) is set to 10 and 30 packets/s in the DMV protocol. Since DMV utilizes SCH resources in both CCHI and SCHI, and employs directional antennas for non-safety message transmissions, the maximum non-safety message throughput is higher than that of IEEE 1609.4. In Fig. 6(a), the non-safety message throughput of DMV increases as the number of nodes increases until saturation. After saturation, the throughput decreases due to the high collision probability. When the number of nodes increases, the time taking for a WSA handshake increases. Therefore, the number of successful WSA handshakes within a SI is reduced. The packet delivery ratio of safety messages decreases as the number of nodes increases, as shown in Fig. 6(b). When the number of nodes increases, the number of nodes contending the CCH for transmitting safety messages or doing WSA handshakes increases. It leads to high collision probability on CCH, the number of failed safety messages increases. However, the MFs in the proposed DMV protocol can cooperate to receive safety messages from their neighbors and broadcast these safety messages in their TDMA-based EmgSlots. That is why DMV is more reliable in safety message broadcast.

5 Conclusion

In this paper, we propose the DMV protocol in which TDMA and CSMA access schemes are employed. The directional antennas also are used for spatial reuse improvement. All SCH resources are utilized in both CCHI and SCHI to provide more concurrent non-safety message transmissions. The DMV protocol can provide reliable safety message broadcast and high SCH utilization with the complex data structures compared with IEEE 1609.4.

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