# An Efficient and Reliable MAC in VANETs

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***Abstract*—Vehicular Ad hoc Network (VANET) is developed to enhance the safety, comfort and efficiency of driving. The IEEE 802.11p/WAVE and IEEE 1609.4 family are standards intended to support wireless access in VANETs. In this paper, we propose an Efficient and Reliable MAC protocol for VANETs (VER-MAC) which allows nodes to broadcast safety packets twice during both the control channel interval and service channel interval to increase the safety broadcast reliability. By using the additional data structures, nodes can transmit service packets during the control channel interval to improve the service throughput.**

***Index Terms*—Multi-channel, MAC protocol, Vehicular Ad Hoc Networks, VANETs.**

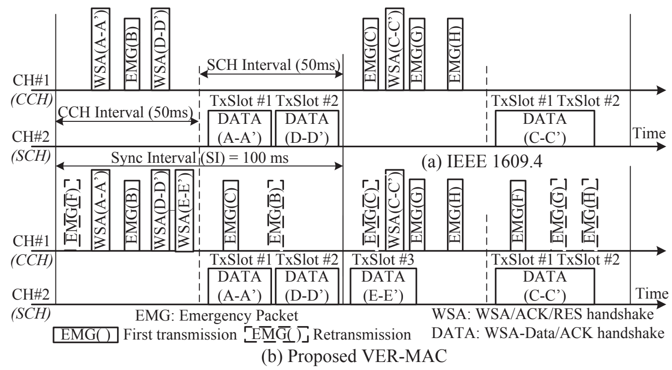


Fig. 1: The IEEE 1609.4 and proposed VER-MAC.

## I. Introduction

THE applications of VANETs fall into two categories, namely safety applications and non-safety applications. Since the safety applications provide drivers information about critical situation in advance, they have strict requirements on communication reliability and delay. On the other hand, the non-safety applications are used for improving driving comfort and the efficiency of transportation system which are more throughput-sensitive instead of delay-sensitive.

Seven 10MHz channels in 5.9GHz have been located for Dedicated Short Range Communications (DSRC): one Control CHannel (CCH) and six Service CHannels (SCHs). The IEEE 1609.4 [1] is a MAC extension of the IEEE 802.11p [2] to support multi-channel operations. As shown in Fig. 1(a), the channel access time is divided into Sync Interval (SI) consisting of a CCH Interval (CCHI) and a SCH Interval (SCHI). All nodes have to tune to the CCH during the CCHI for exchanging emergency (EMG) packets and other control packets like WAVE Service Announcement (WSA) packets. Nodes might switch to one of six SCHs to exchange non-safety application data packets during the SCHI. So, the IEEE 1609.4 cannot utilize all SCH resources during the CCHI.

A variable CCH interval (VCI) multi-channel MAC [3] can dynamically adjust the duration of the CCHI to improve the service saturation throughput. Dedicated Multi-channel MAC (DMMAC) [4] employs the hybrid channel access to provide the collision-free and delay-bounded transmission for safety traffic. However, the SCH resources are still wasted during the CCHI in both VCI and DMMAC. The proposal [5] only enhances the broadcast reliability with preemptive priority in safety services, dynamic receiver-oriented packet reception for one-hop emergency broadcast and a multifrequency busy tone. In the VEMMAC [6], the SCH resources are fully utilized by using the extended transmission mode of the IEEE 1609.4 and the safety packet broadcast reliability is improved through the retransmission mechanism. Nevertheless, the VEMMAC cannot avoid the high collisions at the beginning of the CCHI or SCHI and nodes might lose the EMG packets on the CCH due to the extended transmission mode. Different from above synchronous schemes, a distributed TDMA mechanism is applied in Asynchronous Multi-channel MAC Distributed (AMCMAC-D) [7] to reduce the high contention level on the CCH and enhance the service differentiation.

For the performance analysis, Campolo *et al.* [8] and Ghandour *et al.* [9] proposed analytical models for periodic and event-driven safety message broadcasting, respectively. Recently, Han *et al.* [10] analyzed the IEEE 802.11p with four different Access Categories by taking into account different Contention Window, Arbitration Inter-frame Space values and the internal collision while Misic *et al.* [11] modeled CCH and SCH channel management with multiple traffic classes.

The multi-channel MAC designs for VANET not only ensure the reliability of safety packet transmission, but also provide the high throughput for non-safety packet transmission. In this paper, we propose an efficient and reliable VER-MAC protocol for VANETs. The VER-MAC employs the EMG retransmission and utilizes the CCH during the SCHI for the EMG transmissions to improve the EMG broadcast reliability. Moreover, the VER-MAC utilizes the SCH resources during the CCHI efficiently to enhance the service throughput. We use the 2-D Markov model to analyze the performance of both the IEEE 1609.4 and the VER-MAC protocol. The analytical model is validated through the extensive simulation.

The rest of this paper is organized as follows. Section

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TABLE I: Two data structures in the VER-MAC

(a) Node A's NIL

| Node | SCH | Tx_slot |
|---|---|---|
| D | 2 | 2 |
| E | 2 | 3 |
| X | 3 | 4 |

(b) Node A's CUL

| SCH | Avail_slot |
|---|---|
| 2 | 4 |
| 3 | 3, 4 |
| 4 | 4 |

II describes the operation of VER-MAC. The performance analysis is presented in Section III. Section IV presents the performance evaluation. We conclude our work in Section IV.

## II. The Proposed VER-MAC

The operation of the VER-MAC is illustrated in Fig. 1(b). The VER-MAC utilizes the CCH during the SCHI for broadcasting the EMG packet and each periodic/event-driven EMG packet is broadcast twice a SI to increase the packet delivery ratio. If an EMG packet is broadcast in the CCHI (or SCHI), the copy of this EMG packet is scheduled to be broadcast in the upcoming SCHI (or CCHI) by delaying a CCHI (50ms). The purpose of the delay is to avoid the high congestion at the beginning of the CCHI or SCHI. On each SCH, the CCHI and SCHI are divided into $M$ transmission slots (TxSlots) which are used for the collision-free service data transmissions. Each node pair performs a WSA handshake to select a TxSlot of a SCH. With six SCHs, the maximum number of TxSlots/SI that can be utilized in the IEEE 1609.4 and the VER-MAC are $6M$ and $12M$, respectively. Nodes only switch to the selected SCH during the selected TxSlot in order to broadcast their own EMG packets and avoid missing the EMG packets on the CCH in another time. Nodes maintain the Neighbor Information List (NIL) and Channel Usage List (CUL). The NIL (Table Ia) stores the SCH and TxSlot used by the neighbors while the CUL (Table Ib) shows the available TxSlots of each SCH. Based on the NIL, a node knows when its neighbor is on the CCH in order to perform a WSA handshake. The CUL is used to select the common TxSlot during the WSA negotiation. Since nodes can be on the SCHs during the CCHI, they might miss the WSA messages used to update their NILs and CULs.

The operation of the VER-MAC is as follows

1) If an EMG packet arrives at the MAC layer, nodes try to broadcast it on the CCH in the current CCHI (or SCHI) and then rebroadcast it in the next SCHI (or CCHI).
2) When a node has service packets to exchange, it sends the WSA including its CUL.
3) Upon receiving the WSA, the receiver selects the common TxSlot and SCH based on the CULs of both sender and receiver. Then, the receiver sends the ACK indicating the selected [TxSlot,SCH] to the sender.
4) The sender sends the RES (Reservation) to confirm the [TxSlot,SCH] selected by the receiver.
5) Both sender and receiver switch to the selected SCH in the selected TxSlot to exchange their service packets.
6) Neighbor nodes, which overhear the ACK or RES messages, update their NILs and CULs.

## III. Analytical Model

In our analytical model, there are $N$ vehicle nodes in the network. We assume that the generated packet arrives the MAC layer in a Poisson manner with rate $\lambda$. According to the IEEE 1609.4, the EMG packets and WSA packets are sent on the CCH only in the CCHI. If the packets are generated during the SCHI, they have to wait in the MAC buffer until the next CCHI to be transmitted. It may lead to the synchronized collision because many nodes start contending the CCH at the beginning of the CCHI. To avoid the synchronized collision, the considered application layer has to schedule these packets to arrive at MAC layer by delaying a time of CCHI (50 ms). There are two queues with the same arrival rate $\lambda$ during the CCHI: CCHI and SCHI queues. The sum of two independent Poisson processes with rate $\lambda$ is the Poisson process with rate $2\lambda$. Similarly, for each EMG packet in the VER-MAC, when it arrives directly at the MAC layer, the considered application layer also stores a copy of it and schedules it to arrive at MAC layer after a CCHI (50 ms). Therefore, the packet arrival rate of emergency and service traffics at each node during the CCHI are $2\lambda_e$ and $2\lambda_s$, respectively for both the IEEE 1609.4 and VER-MAC. And the packet arrival rate of emergency traffic is $2\lambda_e$ during the SCHI for the VER-MAC only.

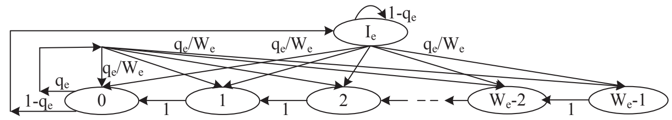

Fig. 2: Markov chain of the emergency traffic.

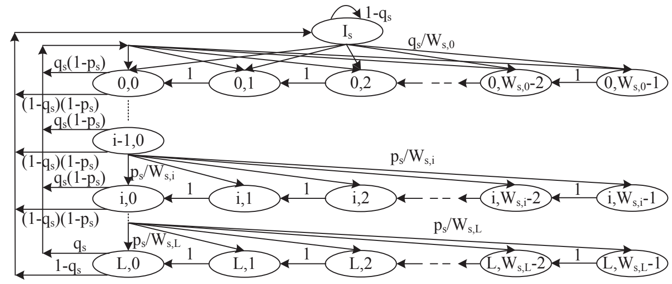

Fig. 3: Markov chain of the service traffic.

Let $b_e(t)$ be the stochastic process representing the backoff counter value at slot time $t$; $W_e$ be the contention window (CW), $p_e$ be the collision probability, $I_e$ be the idle state with an empty buffer and $q_e$ be the probability of at least one emergency packet in the buffer. Let $b_{e,k}$ and $b_{I_e}$ be the stationary distribution of the backoff state and the idle state. From the Markov chain in Fig. 2 and the normalization condition $1 = b_{I_e} + \sum_{k=0}^{W_e-1} b_{e,k}$, we derive $b_{e,0}$ and the probability $\tau_e$ that a node transmits an EMG packet in a slot time as follows

$$\tau_e = b_{e,0} = \left[\frac{1-q_e}{q_e} + \frac{W_e+1}{2}\right]^{-1} \quad (1)$$

Let $b_s(t)$ and $s_s(t)$ be the stochastic processes representing the backoff counter and backoff stage for the service data at slot time $t$. Let $L$ be the retry limit, and $W_{s,i} = 2^i W_{s,0}$ be the CW of $i^{th}$ backoff stage. We assume the collision probability $p_s$ is constant and independent. Let $I_s$ be the idle state with an empty buffer for service traffic and $q_s$ be the probability of at least one new service packet in the buffer, as shown in

Fig. 3. Let $b_{s,i,k}$, where $i \in [0, L]$, $k \in [0, W_{s,i} - 1]$ be the stationary distribution of the Markov chain, and we can obtain

$$b_{s,0,0} = \left[\frac{1-q_s}{q_s} + \frac{1}{2}\left(\frac{1-p_s^{L+1}}{1-p_s} + \frac{1-(2p_s)^{L+1}}{1-2p_s}W_{s,0}\right)\right]^{-1} \quad (2)$$

Since a WSA packet is transmitted when the backoff counter is zero, regardless of the backoff stage, the probability $\tau_s$ that node transmits a WSA packet in a slot time is

$$\tau_s = \sum_{i=0}^{L} b_{s,i,0} = \frac{1-p_s^{L+1}}{1-p_s} b_{s,0,0} \quad (3)$$

A collision occurs when one more node also transmits during a slot time. The collision probabilities $p_e, p_s$ are given

$$\begin{aligned} p_e &= 1-(1-\tau_e)^{N-1}(1-\tau_s)^N \\ p_s &= 1-(1-\tau_e)^N(1-\tau_s)^{N-1} \end{aligned} \quad (4)$$

From Eqs. 1, 3 and 4, we can solve the unknowns $\tau_e, \tau_s$. The probability $P_b$ that the channel is busy

$$P_b = 1-(1-\tau_e)^N(1-\tau_s)^N \quad (5)$$

Let $P_{e,suc}$ and $P_{s,suc}$ be the probabilities of successful transmission for an emergency packet and a service packet, respectively. And let $P_{e,col}$, $P_{s,col}$, and $P_{es,col}$ be the probability of collision transmission from only emergency packet; only service packet and both, respectively.

$$\begin{aligned} P_{e,suc} &= N\tau_e(1-\tau_e)^{N-1}(1-\tau_s)^N \\ P_{s,suc} &= N\tau_s(1-\tau_e)^N(1-\tau_s)^{N-1} \\ P_{e,col} &= (1-\tau_s)^N\left(1-(1-\tau_e)^N - N\tau_e(1-\tau_e)^{N-1}\right) \\ P_{s,col} &= (1-\tau_e)^N\left(1-(1-\tau_s)^N - N\tau_s(1-\tau_s)^{N-1}\right) \\ P_{es,col} &= P_b - P_{e,suc} - P_{s,suc} - P_{e,col} - P_{s,col} \end{aligned} \quad (6)$$

Let $\sigma$ be the duration of an empty slot time and $\delta$ be the propagation delay. Let $T_{e,suc}$ and $T_{s,suc}$ be the time the channel is sensed busy because of the successful transmission of emergency and service traffics, respectively. Let $T_{e,col}$ and $T_{s,col}$ be the time the channel is sensed busy during the collision caused by the emergency and service traffics.

$$\begin{aligned} T_{e,suc} &= T_{e,col} = T_e = EMG + \delta + DIFS \\ T_{s,suc} &= WSA + ACK + RES + 2SIFS + 3\delta + DIFS \\ T_{s,col} &= WSA + \delta + DIFS \end{aligned} \quad (7)$$

Each state may be a successful transmission, a collision or the medium being idle. The expected time spent per state $E_S$

$$\begin{aligned} E_S = (1-P_b)\sigma &+ P_{e,suc}T_{e,suc} + P_{s,suc}T_{s,suc} + P_{e,col}T_{e,col} \\ &+ P_{s,col}T_{s,col} + P_{es,col}\max(T_{e,col}, T_{s,col}) \end{aligned} \quad (8)$$

From the average slot time $E_S$, the probability $q_e$ and $q_s$ can be approximated as

$$q_e = 1-e^{-2\lambda_e \cdot E_S}; \quad q_s = 1-e^{-2\lambda_s \cdot E_S} \quad (9)$$

The packet delivery ratio (PDR) of the emergency traffic is

$$PDR_e^{1609} = \frac{P_{e,suc}}{N_e\tau_e} = (1-\tau_e)^{N-1}(1-\tau_s)^N \quad (10)$$

The EMG packets in the VER-MAC are transmitted twice and the successful probability in the CCHI is the same with the IEEE 1609.4 (Eq. 10). During the SCHI, only the EMG packets are transmitted on the CCH. Based on Eq. 1 and $p_e = 1-(1-\tau_e)^{N-1}$, the successful probability of EMG packet transmission in the SCHI is $PDR_e^{schi} = (1-\tau_e)^{N-1}$. The PDR of the EMG packet of the VER-MAC is

TABLE II: MAC parameters

| Parameters | Value | Parameters | Value |
|---|---|---|---|
| Data rate | 6 Mbps | $\lambda_s$ | 25 pkts/sec |
| WSA | 100 bytes | ACK | 14 bytes |
| EMG | 100 bytes | RES | 14 bytes |
| Slot time $\sigma$ | 13 $\mu s$ | SIFS | 32 $\mu s$ |
| Propagation time $\delta$ | 1 $\mu s$ | DIFS | 58 $\mu s$ |
| Retry limit ($L$) | 6 | $W_e$ | 8 |
| Number TxSlots $M$ | 4 | $W_{s,0}$ | 16 |

$$PDR_e^{ver} = 1-(1-PDR_e^{1609})(1-PDR_e^{schi}) \quad (11)$$

It takes the average slot of $(W_e-1)/2$ for the node to perform the backoff. The average total service time $E_E$ of an EMG packet includes the average backoff duration $\frac{W_e-1}{2}E_S$ and the transmission time $T_e$

$$E_E = \frac{W_e-1}{2}E_S + T_e \quad (12)$$

For simplicity, a node can be modeled as an M/M/1 queue with an infinitive buffer size, the packet arrival rate $2\lambda_e$ and the mean service rate $\mu_e = 1/E_E$. The EMG packets in one queue already have the delay of $T_{cchi}$ before being transmitted in the IEEE 1609.4, the average delay of the EMG packets is

$$E_{D_e^{1609}} = \frac{1}{(\mu_e - 2\lambda_e)} + \frac{T_{cchi}}{2} \quad (13)$$

For the VER-MAC, each EMG packet is scheduled to arrive at MAC layer for the retransmission by delaying a CCHI. Similar to Eq. 12, the average service time $1/\mu_e^{schi}$ for an EMG packet during the SCHI is derived. And the average delay until the EMG packet is retransmitted is given as

$$E_{D_e^{ver}} = \frac{1}{2}\left(\frac{1}{(\mu_e - 2\lambda_e)} + \frac{1}{(\mu_e^{schi} - 2\lambda_e)}\right) + T_{cchi} \quad (14)$$

The average number of WSA packets exchanged successfully during the CCHI on the CCH is

$$N_{s,suc} = \frac{T^{cch}}{E_S}P_{s,suc} \quad (15)$$

Now, we can evaluate the aggregate throughput of the service packets via the number of selected TxSlots/SI of the IEEE 1609.4 and the proposed VER-MAC as

$$S_s^{1609} = \min\left[N_{s,suc}, 6M\right]; \; S_s^{ver} = \min\left[N_{s,suc}, 12M\right] \quad (16)$$

## IV. PERFORMANCE EVALUATION

To validate our model, we use the event-driven simulation program written in Matlab. The values of the parameters used to obtain the numerical results for both the analytical model and simulation runs, are summarized in Table. II. We fix the service packet arrival rate $\lambda_s$ at 25 packets/second, and vary the number of nodes $N$ and the EMG packet arrival rate $\lambda_e$ to evaluate the PDR and the average delay of the EMG packets; and the throughput of service packets.

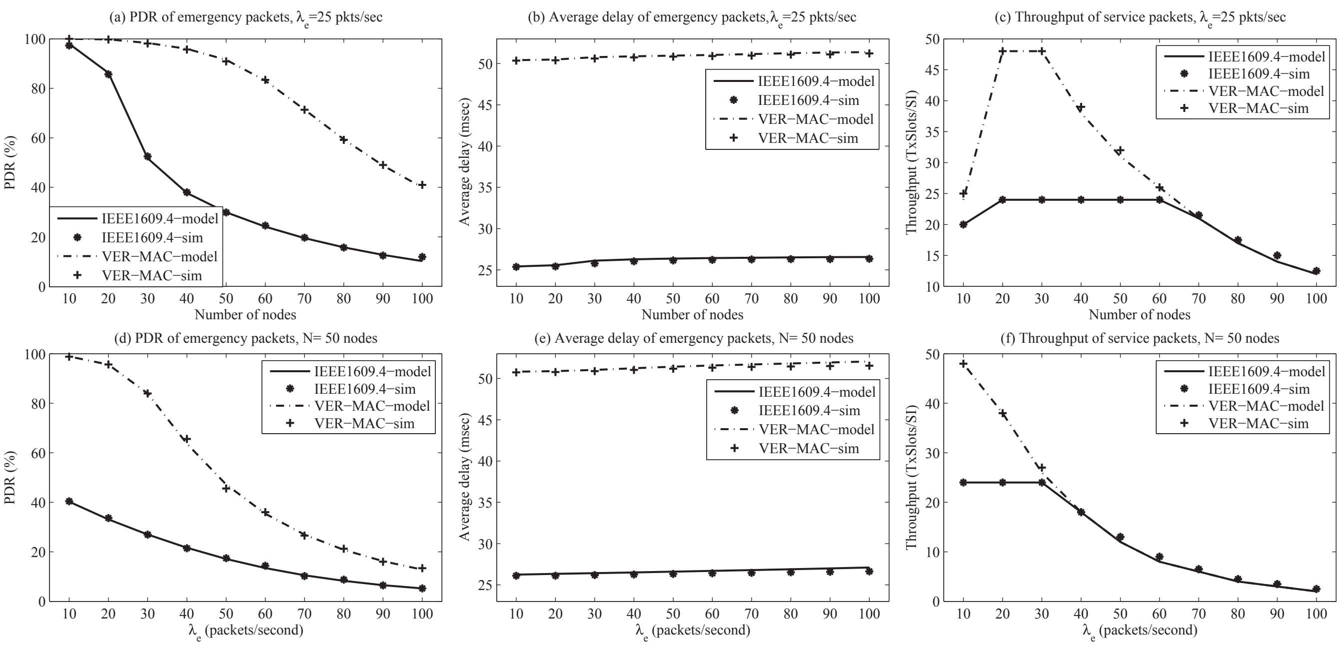


Fig. 4: Performance comparison of the IEEE 1609.4 and the proposed VER-MAC.

Fig. 4 shows the performance comparison between the IEEE 1609.4 and the proposed VER-MAC. The analytical results (lines) closely match the simulation results (symbols). As the number of nodes increases or the emergency packet arrival rate increases, the collision probability increases; that results in the lower PDR and the higher average delay of emergency packets. However, the PDR of the proposed VER-MAC is higher than that of the IEEE 1609.4 (Figs. 4(a, d)) by utilizing the CCH during the SCHI for the EMG broadcast and employing the EMG retransmission. Due to the broadcast transmission, the average delay increases slowly. Only an EMG which arrives during the SCHI will be delayed 50ms before being broadcast during the CCHI in the IEEE 1609.4 while a copy of every EMG is delayed 50ms for the retransmission in the upcoming CCHI/SCHI in the VER-MAC (Eqs. 13 and 14). Moreover, the average delay is calculated until the retransmission completed in the VER-MAC. That is why the average delay of the VER-MAC is higher than that of the IEEE 1609.4 (Figs. 4(b, e)). The service throughput decreases when the number of nodes is too large due to the high collision probability and when the emergency packet arrival rate increases because of the high priority of emergency packet. Obviously, the maximum service throughput of VER-MAC is double compared to the IEEE 1609.4 as shown in Figs. 4(c, f) since the VER-MAC utilizes the SCH resources for the service traffics during the CCHI.

## V. Conclusion

In this paper, we propose the VER-MAC which allows nodes to broadcast the emergency packets during the SCHI and to exchange the service packets during the CCHI. The analytical and simulation results prove that the VER-MAC outperforms the IEEE 1609.4 in terms of the PDR of emergency packets and the throughput of service packets. However, the VER-MAC requires the additional complex data structures and suffers from a more delay of the emergency packets.

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