Performance Analysis of a Hybrid Efficient and Reliable MAC Scheme for Vehicular Ad Hoc Networks in Safety Applications

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Abstract. Safety applications are the highest priority services in the Vehicular Ad Hoc NETworks (VANETs). To support the highest priority service, the Medium Access Control (MAC) protocol is designed to provide efficient broadcast. Compared to IEEE 1609.4, a new multi-channel MAC for VANET (HER-MAC) is proposed which is more reliable in safety applications. In this paper, we propose an analytical model to evaluate the performance of HER-MAC protocol under non-saturation condition through the packet delivery ratio. We also describe two MAC access schemes for HER-MAC protocol: safety application packets using TDMA access scheme and safety application packets using Distributed Coordination Function (DCF). Simulation results show that safety application packets using TDMA access scheme has higher packet delivery ratio and more reliability than safety application packets using distributed coordination function.

Keywords: VANET, MAC , HER-MAC, a multi-channel MAC

1 INTRODUCTION AND RELATED WORKS

One of the major goals of the Intelligent Transportation System (ITS) is to improve the quality, effectiveness and safety the future transportation systems. Vehicular Ad Hoc Networks (VANETs) are an important component ITS. VANETs are designed to enable communication between vehicles and vehicles or vehicles and infrastructures. Each vehicle is equipped with a radio interface, called onboard unit (OBU). Beside, along the road, to connect to the Internet, the roadside units (RSUs) are distributed. Based on RSUs and OBUs, VANETs consist of two communication types: vehicle-to-vehicle (V2V) and vehicle-to-RSU (V2R). They aim to increase a variety of safety applications and non-safety applications, and provide comfort to drivers and passengers. Safety applications are the most

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This research was one of KOREN projects supported by National Information Society Agency (15-951-00-001). Dr. CS Hong is the corresponding author.

important message [1]. They have the very strict delay demand and high priority. Non-safety applications are more throughput-sensitive instead of delay-sensitive.

In year 1999, to support vehicular communications, the Federal Communication Commission (FCC) of the U.S gas approved 75 MHz bandwidth at 5.850-5.925 GHz frequency band for ITS wireless communications. It is divided into seven channels, as shown in Fig. 1 . One of the seven channels is assigned the Control Channel (CCH), i.e CH 178, which can only provide safety relevant applications and system control and management with high priority. Service Channels (SCHs) use other six channels, mainly supporting the non-safety relevant applications.

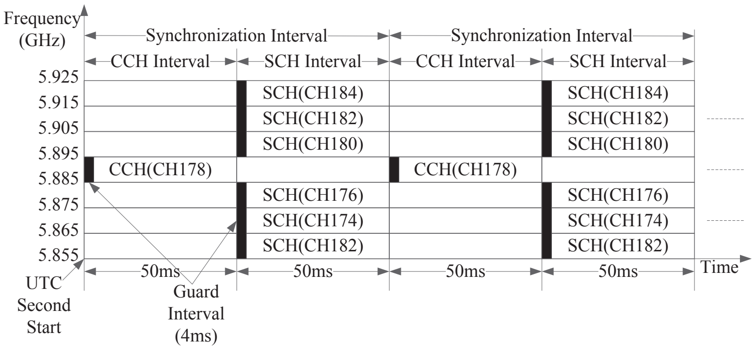


Fig. 1: Frequency channel layout of a 5.9GHz WAVE system.

Due to characteristic of the VANET, such as high speed, unstable communication link, and network partitioning, information transfer becomes inevitably challenging. Compared to other wireless networks, VANETs suffer from some unique feature, such as high node mobility, topology dynamics and frequent link breakage. The effectiveness of traffic safety applications using VANETs depends upon the performance of Medium Access Control (MAC) protocol. The main challenge for design of MAC protocol for VANETs is to achieve reliable delivery of messages within the time limit even when the density of vehicles varies rapidly in the network.

Recently, IEEE 802.11p [2] and IEEE 1609.4 [3] have been proposed for VANETs. Based on the standard draft of IEEE 802.11p, VANETs employ the technique of dedicated short-range communication (DSRC) for enhancement of the driving safety, as well as, comfort of automotive drivers. In IEEE 802.11p, the broadcast service suffers from hidden terminal problem. This reason is that no request to send/clear to send (RTS/CTS) packets are exchanged before transmission of broadcast messages and no acknowledge message is sent back to the source node. The IEEE 1609.4 standard draft is considered to be a default multichannel MAC standard for VANETs, which defines a multichannel wireless radio operation mode, including the interleaving operation of the CCH and SCH, priority access parameters, and other characteristic of MAC and PHYs. In IEEE 1609.4, nodes broadcast safety messages or negotiate the SCHs on the CCH during the Control Channel Interval (CCHI). In the Service Channel Interval (SCHI), nodes switch to the negotiated SCHs for their non-safety messages transmissions. This scheme has a high contention during the CCHI and the SCHI resources cannot be utilized during this interval.

The HER-MAC protocol [4] allows vehicle nodes to broadcast their safety messages in the reserved time slot to improve the reliability. Compared to IEEE 1609.4, HER-MAC protocol is more reliable in the safety message broadcast, efficient in the service channel utilization. In this paper, we propose an analytical model to evaluate the performance of HER-MAC protocol under non-saturation condition through the packet delivery ratio. We also describe two MAC access schemes for HER-MAC protocol: safety application packets using TDMA access scheme and safety application packets using Distributed Coordination Function (DCF).

The rest of this paper is organized as follows: Section II gives the analytical model of HER-MAC protocol in safety applications. Performance evaluations are drawn in Section III. Section IV finally concludes this paper.

2 ANALYTICAL MODEL OF HER-MAC PROTOCOL IN SAFETY APPLICATIONS

In our analytical model, we consider the CCH is divided into two parts: reservation period (T_{re}) and contention period (T_{con}), as shown in Fig. 2. In this paper, we use two access schemes to transmit safety application packets in HER-MAC. In the first scheme, we use TDMA access scheme and re-transmission mechanism for safety message broadcast, as shown in Fig. 2. Safety application packets using distributed coordination function is considered in the second scheme. DCF is a carrier sense multiple access with collision avoidance scheme with binary slotted exponential backoff, as shown in Fig. 5. Since safety application packets are sent by broadcast mechanism, the vehicle nodes will not send any acknowledgement for the received safety messages. The sender does not detect the failure of the safety transmission and there is no re-transmission. The Markov chain model is proposed to obtain the stationary probability τ_e that a node transmits a safety application in an arbitrary time slot. We divide packet transmissions into 2 types: safety application and WSA/RES packet transmissions on the CCH. There are N vehicle nodes in the network, the packet arrival rate of safety application and service packet in Poisson manner at each node are λ_e and λ_s. The packet arrival rate of safety application and WSA/RES packet at each node are $2\lambda_e$ and $2\lambda_s$ because there are two queues with the same arrival rate during the CCHI: SCCHI and SCHI queues, referred detail in [5].

2.1 Case 1: Safety application packet uses TDMA access scheme

In this case, HER-MAC protocol uses TDMA access scheme and retransmission mechanism to transmit a safety application. Each node will broadcast a SAFE packet to reserve an Emgslot on reservation period. If a node reserved an EmgSlot successfully, it can broadcast its safety application packet during its reserved EmgSlot without any any collision. Each node must transmit a SAFE packet in its time slot on the reservation period. Each SAFE packet is divided into five main fields: a ID, a serviced slot, the IDs of neighbor nodes, the time slot of each neighbor node, safe applications, as shown in Fig. 3. Based on each SAFE packet is transmitted on the reservation period, if all neighbor nodes confirm a ID and serviced EmgSlot of contended node, this node will occupy successfully an EmgSlot. Otherwise, a node occupied unsuccessfully EmgSlot. If nodes do not reserve EmgSlots successfully, nodes will broadcast HELLO packets to reserve Emgslots in the next sync interval, as shown in Fig. 2. In this scheme, we consider each node has only a safety application packet to broadcast in the CCHI.

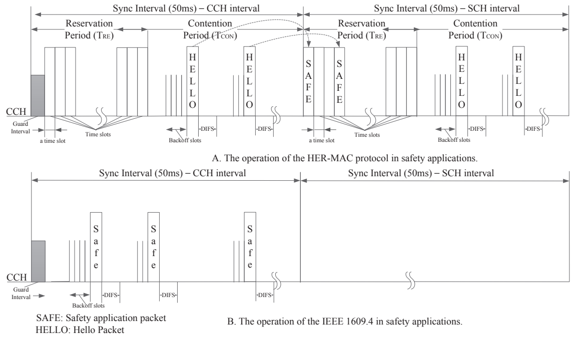


Fig. 2: The analytical model of safety application broadcast in case 1.

Because HELLO packet broadcast and safety application broadcast use the same mechanism, we use the same Markov chain for both safety application and HELLO packet broadcast depicted in Fig. 4. We assume the payload of HELLO packet and safety application packet both have the same length.

ID	SerSlot	IDs of neighbor nodes	The time slot used by each neighbor node	Safety applications

Fig. 3: Frame format of SAFE packet.

Let $b_e(t)$ be the stochastic process representing the backoff window size for a given node at slot time t, respectively, p_e be the probability collision, W_e be the contend window (CW), I_e be the idle state with an empty buffer and q_e be the probability of at least one HELLO or safety application packets in the buffer. This statistical model of q_e will be discussed later.

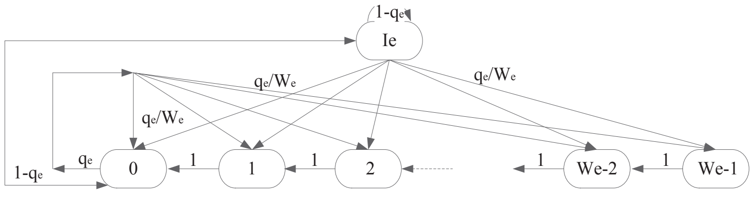


Fig. 4: Markov chain of safety application or HELLO packet broadcast.

Let $b_{e,k} = \lim_{t\to\infty}\{b_e(t) = k\}, 0 \le k \le W_e - 1$ be the stationary distribution of the Markov chain. From the Markov chain, it is clear that the probability τ_e

that a node transmits a HELLO or safety application packet in an arbitrary time slot can be expressed as

$$\tau_e = b_{0.0} = \left[\frac{1-q_e}{q_e} + \frac{W_e+1}{2}\right]^{-1} \tag{1}$$

Let p_e be the collision probability when more than node transmit at the same time slot, we have

$$p_e = 1-(1-\tau_e)^{N-1} \tag{2}$$

The packet delivery radio (PDR) of the safety application packet in IEEE 1609.4 is

$$PDR_{1609} = \frac{P_{ssuc}}{N\tau_e} = (1-\tau_e)^{N-1} \tag{3}$$

Consequently, based on (1) -(2), variables τ_e and p_e can be solved by the numerical methods as in [6]. Note that $0 \leq \tau_e \leq 1$ and $0 \leq p_e \leq 1$. In every time slot during the safety application or HELLO packet interval, let P_{esuc}, P_{ecol}, P_{eidle} and P_{ebusy} be the probability of successful transmission, collision transmission, a idle channel, a busy channel, respectively.

$$\begin{cases} P_{ebusy} = 1-(1-\tau_e)^N \\ P_{eidle} = (1-\tau_e)^N \\ P_{esuc} = N\tau_e(1-\tau_e)^{N-1} \\ P_{ecol} = P_{ebusy} - P_{esuc} \end{cases} \tag{4}$$

Let T_{esuc}, T_{ecol} and σ be the time the channel is busy because of the successful transmission of HELLO or safety application packet, the channel is idle, and a slot time.

$$T_e = T_{esuc} = T_{ecol} = T_{HELLO} + \delta + T_{DIFS} = T_{safe} + \delta + T_{DIFS} \tag{5}$$

where δ is a propagation time. Each state maybe a successful transmission, a collision or the medium is idle. The expected time spent per state E_S.

$$\begin{aligned} E_s = (1-P_{ebusy})\sigma + P_{ebusy}.(1-P_{esuc}).T_e + \\ +P_{ebusy}.P_{esuc}.P_{ecol}.T_e + P_{ebusy}.P_{esuc}.(1-P_{ecol}).T_e \end{aligned} \tag{6}$$

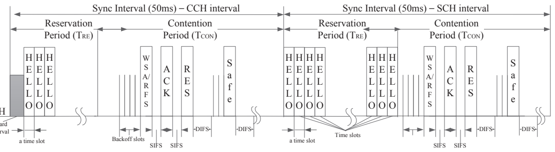
From the average slot time E_S, the probability q_e can be approximated as

$$q_e = 1 - e^{-2\lambda_e.E_s} \tag{7}$$

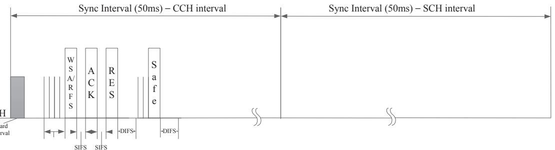
In HER-MAC protocol, if nodes did not reserve EmgSlots successfully, nodes will broadcast HELLO packets to reserve Emgslots in the next sync interval. The HER-MAC uses a frame (*100ms*) to transmit concurrently HELLO and safety applications. However, the IEEE 1609.4 only uses one sync interval (*50ms*) to transmit safety applications. After one sync interval (*50ms*), in HER-MAC protocol, the average number of node transmitted unsuccessfully HELLO packet is $N_2 = N.p_e$. By replacing N_2 for N in (2), we can solve variables τ_{e2} and p_{e2}. The PDR of the safety application packet in the second sync interval is $PDR_2 = (1 - \tau_{e2})^{N_2 - 1}$. The PDR of HELLO packet of HER-MAC protocol through a frame is

$$PDR_{HER-MAC} = 1 - (1 - PDR_{1609})(1 - PDR_2) \tag{8}$$

2.2 Case 2: Safety application packet uses distributed coordination function



A. The operation of the HER-MAC protocol in safety applications.



Safe: Safety Application packet
WSA/ACK/RES: WAVE Service Announcement
RFS/ACK/RES: Request For Service

B. The operation of the IEEE 1609.4 in safety applications.

Fig. 5: The analytical model of safety application broadcast in case 2.

For analyze transmission of safety application packet, we use Markov chain of safety application packet in case 1 because the transmission of safety application packets are independent of transmission of WSA/RES packets. Now, we analyze transmission of WSA/RES packets. Let $b_s(t)$ and $s_s(t)$ be the stochastic process representing the backoff window size and backoff state for a given node at slot time t, respectively. Following [7], let m be the maximum backoff state, be the value such that $W_{max}=2^m W$. W_i is maximal contention window (CW) of the ith backoff state, where $i \in (0, m)$, and $W_i=2^i W$. Let p_s be the probability of collision that more than one node transmits in a single slot and q_s be the probability at least one new WSA/RES packet in the buffer. Then, the bidimensional process $s_s(t)$,$b_s(t)$ can be modeled with a discrete-time Markov chain, as shown in Fig. 6.

Let $b^s_{i,k} = \lim_{t\to\infty} \{s_s(t) = i, b_s(t) = k\}, 0 \le i \le m, 0 \le k \le W_i - 1$ be the stationary distribution of the Markov chain. From the Markov chain and [8], it is clear that

$$\begin{aligned} b_{0.0} &= \frac{2(1-p_s)(1-2p_s)q_s}{q_s[(W_s+1)(1-2p_s)+W_s p_s(1-(2p_s)^m)]+2(1-q_s)(1-p_s)(1-2p_s)} \\ \tau_s &= \frac{b_{0,0}}{(1-p_s)} = \frac{2(1-2p_s)q_s}{q_s[(W_s+1)(1-2p_s)+W_s p_s(1-(2p_s)^m)]+2(1-q_s)(1-p_s)(1-2p_s)} \end{aligned} \tag{9}$$

So p_e and p_s is the collision probability when more than one node transmits at the same time slot, based on (2) and (6) we have

$$\begin{aligned} p_e &= 1 - (1 - \tau_e)^{N-1}(1 - \tau_s)^N \\ p_s &= 1 - (1 - \tau_s)^{N-1}(1 - \tau_e)^N \end{aligned} \tag{10}$$

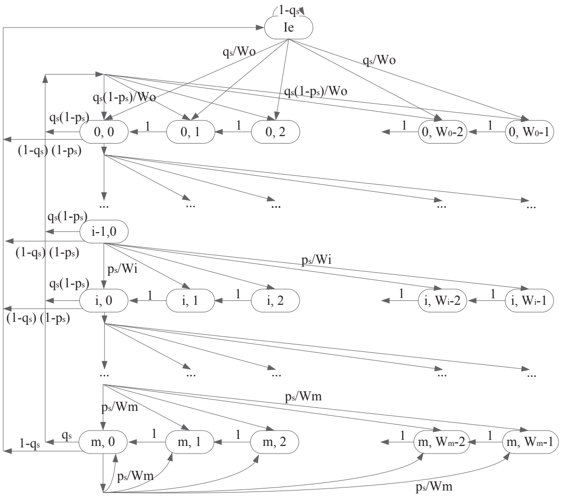


Fig. 6: Markov chain of the WSA or RES transmission.

Consequently, based on (1) - (9) - (10), variables τ_e, p_e, $\tau_s$and p_s can be solved by the numerical methods as in [6]. Note that $0 \leq \tau_e \leq 1$, $0 \leq p_e \leq 1$ $0, \leq \tau_s \leq 1$ and $0 \leq p_s \leq 1$.

In each time slot, let P_{suc}^e and P_{suc}^s be the probabilities of successful transmission for emergency and service packet. A channel is collision with probabilities P_{col}^e and P_{col}^s and channel is idle with P_{idle}^e and P_{idle}^s. We have

$$\begin{cases} P_b = 1 - (1-\tau_e)^N (1-\tau_s)^N \\ P_{idle} = (1-\tau_e)^N (1-\tau_s)^N \\ P_{suc}^e = N\tau_e (1-\tau_s)^N (1-\tau_e)^{N-1} \\ P_{suc}^s = N\tau_s (1-\tau_e)^N (1-\tau_s)^{N-1} \\ P_{col}^e = (1-\tau_s)^N (1-(1-\tau_e)^N - N\tau_e(1-\tau_e)^{N-1}) \\ P_{col}^s = (1-\tau_e)^N (1-(1-\tau_s)^N - N\tau_s(1-\tau_s)^{N-1}) \\ P_{col}^{es} = P_b - P_{suc}^e - P_{suc}^s - P_{col}^e - P_{col}^s \end{cases} \tag{11}$$

Let T_{WSA}, T_{RES}, T_{ACK} and T_{safe} denoted the time for transmitting a WSA, RES, ACK , safety application packet, and we assume that T_{WSA}=T_{RES} and T_{Safe}=T_{WSA}. T_{SIFS} and T_{DIFS} are the SIFS time and DIFS time, respectively.

The duration of a free time slot, the duration of a transmission collision and the duration for a successful reservation are T_{idle}, T_{col} and T_{suc}, respectively. Then from Fig. 5, we have

$$\begin{cases} T_{idle} = aSlotTime \\ T_{col}^s = T_{WSA} + \delta + T_{DIFS} \\ T_{suc}^s = T_{WSA} + +T_{RES} + 2 * T_{SIFS} + T_{ACK} + 3 * \delta + T_{DIFS} \\ T_{suc}^e = T_{col}^e = T_{SWT} + \delta + T_{DIFS} \end{cases} \tag{12}$$

The expect time spent per state E_S is given

$$E_S = (1-P_b)\sigma + P_{suc}^e T_{suc}^e + P_{suc}^s T_{suc}^s + P_{col}^e T_{col}^e + P_{col}^s T_{col}^s + P_{col}^{e,s} \max(T_{col}^e, T_{col}^s) \tag{13}$$

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

$$q_e = 1 - e^{-2\lambda_e . E_s} \tag{14}$$

$$q_s = 1 - e^{-2\lambda_s . E_s} \tag{15}$$

The packet delivery ratio (PDR) of the safety application packet in IEEE 1609.4 can be calculated as

$$PDR_{1609} = \frac{P^e_{suc}}{N\tau_e} = (1-\tau_e)^{N-1}(1-\tau_s)^N \tag{16}$$

The safety application packets in the HER-MAC protocol are transmitted twice and the successful transmission in the CCHI is the same with the IEEE 1609.4 (Eq. 16). During the SCHI, HER-MAC protocol, the safety application and SWA/RES packets are transmitted on the CCH. The PDR of the safety application packet also is the same with the IEEE 1609.4. Then, we have the PDR of the safety application packet in the HER-MAC protocol through a frame is

$$PDR_{HER-MAC} = 1 - (1 - PDR_{1609})^2 \tag{17}$$

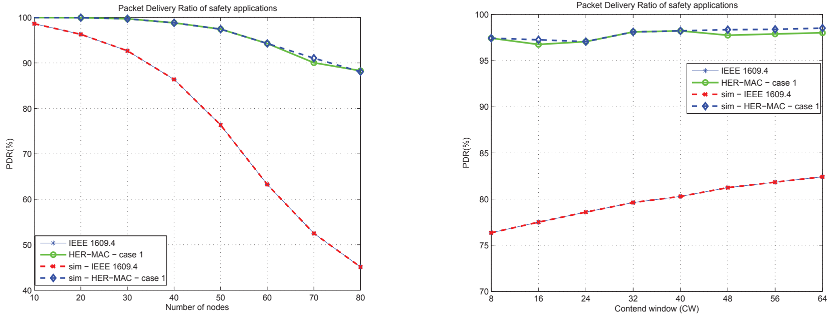
3 PERFORMANCE EVALUATION

In this section, we validate our model using the event-driven simulation program written in Matlab. We consider a segment of a two-way vehicle traffic highway (20m x 1000m). The values of the parameters used to obtain the numerical results for both the analytical model and simulation runs, are summarized in Table. 1. We fix the safety application and HELLO packets arrival rate λ_e at 50 pks/sec, service arrival rate λ_s at 200 pks/sec and vary the number of nodes N or the content windows W_s to evaluate the PDR of safety applications.

Table 1: SYSTEM PARAMETER FOR SIMULATIONS

Parameter	VALUE	Parameter	VALUE
Data rate of each channel	6 Mbps	λ_s	50 pkts/sec
WSA	100 bytes	λ_e	200 pkts/sec
Safety application	100 bytes	ACK	14 bytes
HELLO	100 bytes	RES	14 bytes
Slot time σ	13 μ_s	SIFS	32 μ_s
Propagation time δ	1 μ_s	DIFS	58 μ_s
Number of SerSlots M	5	W_e	8
W_s	16		

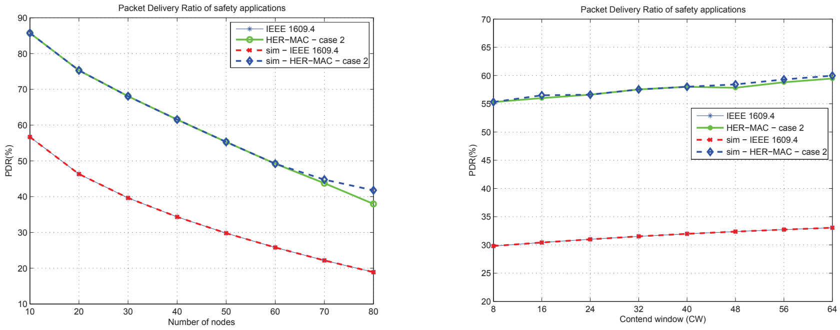
In case 1, all nodes have to reserve the EmgSlots in order to broadcast a safety application packet. If a node did not reserve the EmgSlot successfully and it has some safety application packets to broadcast, a node will attempt to reserve the EmgSlot in next sync interval. In Fig. 7a, when a number of nodes increases, the collision probability at the same time slot also increase, and thus, it takes a long time to finish the EmgSlot reservation for all nodes. In IEEE 1609.4, it uses one sync interval to exchange safety application packets. However, the HER-MAC uses two sync interval to exchange them. As variable W_e increase, the packet delivery ratio also increases respectively. PDR with 50 nodes in the HER-MAC keeps interval between 96% and 98%, but in the IEEE 1609.4 it keeps interval 76% and 83%. Because the probability τ_e decreases when the W_e increases, the collision probability at the same time slot also increases.



(a) Packet delivery with variable nodes. (b) Packet delivery ratio with variable W_es.

Fig. 7: Safety application packets use TDMA access scheme.

In case 2, the safety application and WSA/RES packets transmit concurrently on the same sync interval. The collision probability when more than one node transmits at the same time increases if the number of nodes increases. The number of node affects to collision probability p_e and PDR. The PDR in HER-MAC is greater about 1.86 times than in IEEE 1609.4, as shown in Fig. 8a. In other case, the content window W_e affects to the probability τ_e. Consequently, the collision probability p_e and PDR will increase when the W_e increases, as shown in Fig. 8b.



(a) Packet delivery with variable nodes. (b) Packet delivery ratio with variable W_es.

Fig. 8: Safety application packets use distributed coordination function.

In case 2, if a node has a safety application packet, it will attempt to transmit on the contention period. Because both safety application and WSA/RES packets concurrently transmit on the contention period, the probability of successful safety transmission will be decreased. Unlike case 2, a safety application will be transmitted separately from WSA/RES packet in case 1. Due to safety application is transmitted in a node's time slot on the reservation period, safety application packets using TDMA access scheme more reliability and efficient than safety application packets using distributed coordination function.

4 CONCLUSION

In this paper, we describe an analytical model to evaluate the performance of HER-MAC protocol compared to IEEE 1609.4 in safety application. The safety application packet can transmit by using two MAC access schemes. In the first scheme, if a node has a safety application packet, it will send a HELLO packet to reserve an EmgSlot on reservation period. After a node reserved successfully an EmgSlot, it will transmit a safety application packet through its reserved EmgSot in next sync interval. In the second scheme, the safety application and WSA/RES packets transmit concurrently and both of them use distributed coordination function. In both of two schemes, the PDR in HER-MAC protocol is greater than in IEEE 1609.4. The performance results show that the safety application packets using TDMA access scheme more reliability and efficient than safety application packets using distributed coordination function.

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