Modeling CCH switch to SCH in IEEE 802.11p/WAVE vehicular networks

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***Abstract*—Packet collision and packet delay are considered to be critical for safety applications in vehicular networks. This paper designs a new analytical model to evaluate the performance of channel switching for IEEE 802.11p/WAVE in vehicular networks. Under this model, it explicitly expresses the WAVE channel switching, and constructs contention window size and number of vehicles as packet collision probability and packet delay time function of variables. Finally, we evaluate accuracy of the designed model of collision caused by channel switching and transmission delay in vehicular networks. The results show that the model could analyzes perfectly packet collision which is caused by channel switching and packet delay in vehicular networks.**

I. INTRODUCTION

Vehicular networks are a novel class of wireless networks that have emerged thanks to advanced in wireless technologies and automotive industry. Such networks are proposed primarily for vehicle safety applications and have been caused great interests and attentions among researchers during recent years. Study group IEEE 802.11p [1] and standards family IEEE 1609 WAVE [2] are formed to support in vehicular networks with the rapidly changing topology. IEEE 802.11p is an approved amendment to the IEEE 802.11 standard to add wireless access in vehicular environments (WAVE). IEEE 1609 which includes IEEE standards 1609.1 to IEEE 1609.4 is a higher layer standard based on the IEEE 802.11p. The WAVE is more authoritative framework agreement [3] and it works on 5.9GHz bandwidth of 75MHz for Dedicated Short Range Communications (DSRC). Within this range, the safety-related data, such as short status messages (Beacons), WAVE-Basic Service Set (WBSS) establishment and advertisement messages (WAVE Service Advertisements, WSAs), are periodically delivered by control channel (CCH) and service channels (SCHs) mainly transmit the non-safety-related services, such as infotainment based on IPv6.

In this paper, we focus on collision probability model and delay analysis model when each vehicle periodically switches and alternates between CCH and SCH. In order to ensure the correct delivery of safety messages, vehicles must switch regularly between CCH and SCH according to its requirements. However, vehicles that perform synchronously channel switching between CCH and SCH may result in an unexpectedly high collision rate. Packets collision problems also cause the transmission delay and lead to a serious degradation in performance with aspect of applications in vehicular networks. The specifical details will be analyzed in the following. About collision probability of vehicular networks has been studied from an analytical point of view [4]–[8], the related works mainly focus on broadcasting in VANETs and they do not consider WAVE channel switching and verify its effects on the network performance. [7] [9] cannot meet the strict reliability requirements for safety-related services under DSRC environments. Under the constraints characters of vehicular, the primary challenge in designing vehicular communication protocols is to provide good delay performance [10].

The remainder of this paper is structured as follows. In Section II, DCF mechanism is described. The exciting problems about IEEE 1609.4 are pointed out in Section III. Section IV depicts the system model and analyzes on collision probability and delay in vehicular networks. In Section V, the model validation and simulation results are presented. Finally, conclusions and future works are provided in Section VI.

II. DCF MECHANISM OVERVIEW

In summarize, distributed coordination function (DCF) is the core access mechanism of the IEEE 802.11. The following will gives brief introduction of the DCF basic access method. When node attempts to transmit, node needs to monitor channel state until the channel is idle and an idle period equals to a distributed interframe space (DIFS). Suppose node A and node B share the same channel. Before a next new packet attempts to transmit from node B, an idle period equals to DIFS is detected and then node B randomly chooses a back-off timer and its counter decrements as long as the channel is sensed idle. After a DIFS, node A has one packet to transmit.

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Note that node A transmits packet which happens in the process of the packet transmission of node B. As a result, the channel busy is detected. The back-off timer is "frozen" to its currently number value, and the channel is reactivated again only when the channel is sensed idle for a DIFS. The counter decrements from the last "frozen" number value.

More specifically, the DCF mechanism utilizes binary back-off algorithm, with one transmission attempts making at each back-off stage. When packet transmission begins, in the back-off stage i, for $i = 0, 1, \ldots, m$, where m is the maximum back-off stage. The initial value of back-off timer is uniformly chosen from a contention window which is in the range $[W_{min}, W_{max}]$. The specific values about W_{min} and W_{max} are decided by the final version of the standard [11] in PHY-specific. For description convenience, $W_i = 2^{min(i,m)} W_0$ demonstrates the contention window size in the back-off stage i, where W_0 is the initial contention window size and m is the maximum retransmission time. So that $W_{min} = W_0 - 1$ and $W_{max} = 2^m W_0 - 1$.

III. Exciting problems

IEEE 1609.4 standard describes multi-channel operation as channel switching between CCH and SCH on the basis of IEEE 802.11p. IEEE 1609.4 standard rules a DSRC spectrum for vehicular usage, divided into one CCH and six SCH. The spectrum bandwidth of each channel is 10MHz. In IEEE 1609.4, the channel time is divided into synchronization intervals with a fixed length of 100ms. The synchronization interval is constituted by the CCH Interval (CCHI) and SCH Interval (SCHI). They have equal-length 50ms (including the Guard Interval (GI) starts), as shown in Fig.1. In this paper, synchronization is needed, and CCHI and SCHI are synchronized to the Coordinated Universal Time (UTC), which is provided by the Global Positioning System (GPS).

If the vehicle detects channel idle during the Arbitrary InterFrame Space (AIFS) interval time, it is allowed to transmit messages according to the IEEE 802.11p MAC [1]. If channel is busying, the vehicle randomly selects back-off timer from the Contention Window (CW). The back-off timer will decrements to zero at the end of each idle slot. Then the vehicle will accesses idle channel.

Suppose WAVE devices, which install a single radio and transmit some critical information, such as safety messages etc.. Generally, with regard to single radio vehicle, when transmission startup, vehicle device needs to switch constantly between CCH and SCH. When one vehicle receives a WAVE service advertisement (WSA) during CCHI, it announces a service will occupy one SCH. It must note that vehicle needs to switch at between CCH and SCH in the CCHI and SCHI.

When multiple single radio vehicles monitor synchronously the same high-priority message in CCHI, they need to switch synchronously to the same SCH and bound to cause the high collision as illustrated in Fig.2. When small amount of part of the vehicles occur collision in the initial time, other vehicles will still wait and all of their back-off timers already reduced by 1. So another round of collision will almost certainly happen, then another round, and so on and so forth. Eventually, all critical messages of vehicles will be lost. Fig.2 shows that high collision caused by channel switching in vehicular networks. That's to say channel congestion phenomenon follows a channel switch. And it caused by packet collision happen in channel or dropped and this eventually results in packet delay. IEEE 1609.4-2010 standard [12] also elaborates this issues on its Annex B but not gives out any analysis. To the best of my knowledge, it hasn't related studies consider comprehensively the WAVE channel switching in the case of contention back-off mechanism and analyze the performance of the vehicular networks. This is the focus of this article.

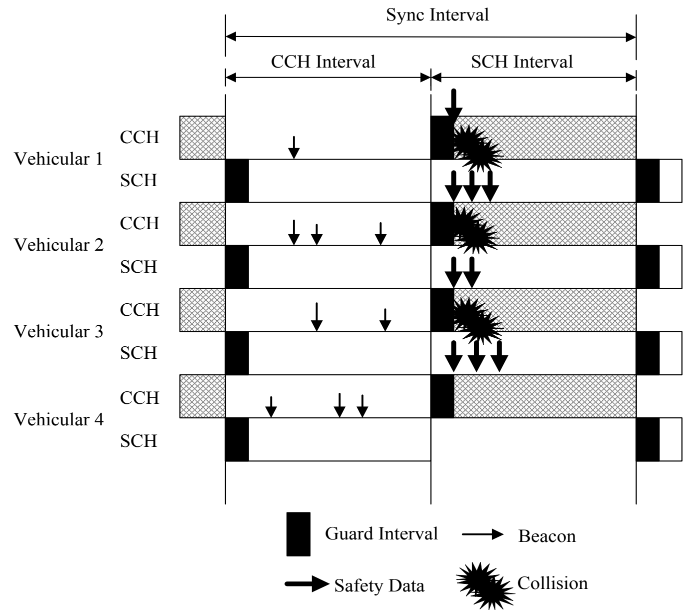

Fig. 1: Diagram of channel switching model in vehicular networks.

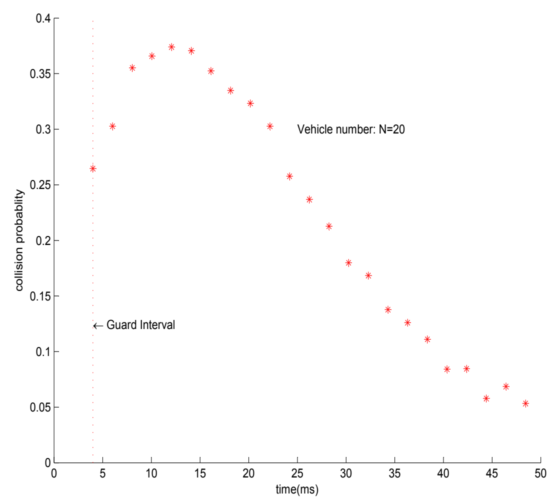

Fig. 2: Simulation results of high collision caused by channel congestion phenomenon following a channel switch

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IV. SYSTEM MODEL AND ANALYSIS

A. collision probability

With respect to IEEE 802.11, similar to the contention behavior of APSD within a beacon period, potentially multiple stations wake up simultaneously and compete to retrieve their packets [13], [14]. Assuming that packet transmission failure, then all $m+1$ transmission attempt and select the longest initial back-off timer in each back-off stage. This will reserve maximum of back-off timers $W_R = \sum_{i=0}^{m} W_i$.

Let us create $(1+m) \times W_R$ matrix $T_{i,k}$ of transmission probability for a particular vehicle, where $T_{i,k}$ is the i^{th} row and the k^{th} column. The transmission probability when the access channel starting is given by

$$T_{1,k} = \frac{1}{W_0}, \, for \; i = 0, k = 1, \ldots, W_0. \tag{1}$$

where $1/W_0$ is the probability of an initial back-off timer selected uniformly by a vehicle. Specifically, the initial back-off timer selected uniformly between 0 and W_0.

After a collision in back-off stage $i = 0$, the back-off stage i will goes into next time repeatedly, till to the maximum back-off stage m. In this case, the transmission probability is given by

$$\begin{aligned} T_{i+1,k} = & \sum_{j \in \psi(i,k)} \frac{1}{W_i} C_{i,j}, \\ & for \; i = 1, \ldots, m, \psi(i,k) \neq \phi. \end{aligned} \tag{2}$$

where $T_{i+1,k}$ equals the probability that the vehicle transmits in back-off stage $(i-1)$ at network timer k, the network timer increments from 1. $\psi(i,k) = \{j : max(k - W_i, i) \leqslant j \leqslant min(k-1, \sum_{R=0}^{i-1} W_R)\}$, ϕ is the empty set. $1/W_i$ is the probability of an initial back-off timer selected uniformly between 0 and W_i. The process is caused by collision happened in back-off stage i at network timer k which leads to the vehicle's next transmission attempts being made between network timers $k+1$ and $k+W_i$ inclusively, each with probability $1/W_i$. The element subscript which couldn't denote this process in transmission matrix $T_{i+1,k}$ value is 0. $C_{i,k}$ is the collision matrix for a particular vehicle. The specific contents will be explained in the following. But this case is not considered: all vehicles has the different back-off stage i in the current transmission situation.

Similarly, let us create $(1+m) \times W_R$ matrix $C_{i,k}$ of collision probability for a particular vehicle, where $C_{i,k}$ is the i^{th} row and the k^{th} column. We assume the transmission processes of vehicles are independent each other. Hence, the collision probability $C_{i+1,k}$, which follows the transmission probability $T_{i+1,k}$, is given by

$$C_{i+1,k} = T_{i+1,k}(1 - [1 - \sum_{j=0}^{m} T_{j+1,k}]^{N-1}). \tag{3}$$

where N is the number of vehicles in vehicular networks.

The collision probability $p(N)$ experienced by N vehicles which switch channel simultaneously between CCH and SCH is given by

$$p(N) = \frac{\sum_{i=0}^{m} \sum_{k=1}^{W_{sum}} C_{i+1,k}}{\sum_{i=0}^{m} \sum_{k=1}^{W_{sum}} T_{i+1,k}}. \tag{4}$$

B. delay

For a particular vehicle, the transmission probability at network timer k could be attempted to get and denote by

$$P_t(k) = \sum_{i=0}^{m} T_{i+1,k}. \tag{5}$$

Return to the front of this section about the transmission matrix $T_{i+1,k}$. Let us consider Eq.(1), Eq.(2) and Eq.(3) again. For each network timer, there are different possible combinations of vehicles transmitting or not. Take one vehicle as example, the other similar, we divide the combinations into five categories by defining the corresponding probability at time k of:

- no vehicle transmitting as $P_{No}(k)$;
- the vehicle transmitting successfully as $P_{Su}(k)$;
- some other vehicles transmitting successfully as $P_{Os}(k)$;
- a collision occurring that involves the vehicle as $P_{Co}(k)$;
- a collision occurring that involves only the other vehicles as $P_{Oc}(k)$.

where,

$$P_{No}(k) = (1 - P_t(k))^N, \tag{6}$$

$$P_{Su}(k) = P_t(k)(1 - P_t(k))^{N-1}, \tag{7}$$

$$P_{Os}(k) = (N-1)(P_{Su}(k)), \tag{8}$$

$$P_{Co}(k) = P_t(k) - P_{Su}(k), \tag{9}$$

$$P_{Oc}(k) = 1 - ((p_{No}(k)) + P_t(k) + P_{Os}(k)). \tag{10}$$

When no vehicle is transmitting, the duration is a slot time, denoted by σ; when a collision occurs, the duration is T_{Co}; and when a successful transmission is made, the duration is T_{Su}. The T_{Su} and T_{Co} based on the IEEE 802.11p/WAVE.

To calculate the delay for a packet that is successful transmission at timer k, we add to the time for the successful transmission made at timer k the average time spent in each network timer up to timer $k-1$, given that all transmission attempts made by the vehicle before timer k is unsuccessful. Denotes by $Av_s(k)$ the average duration of network timer k, the probability of the vehicle does not make a successful transmission during this network timer, such that

$$Av(k) = \frac{P_{No}(k)\sigma + P_{Os}(k)T_{Su} + (P_{Co}(k) + P_{Oc}(k))T_{Co}}{1 - P_{Su}(k)}. \tag{11}$$

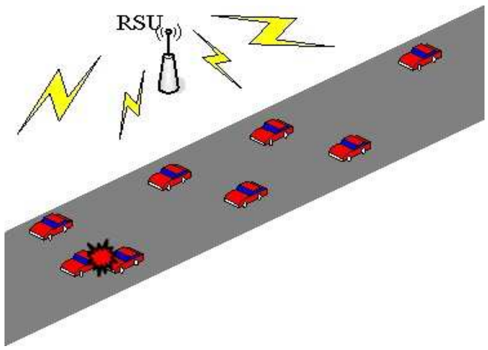

Fig. 3: Simulation scenario.

When N vehicles switch simultaneously their channel from CCH to SCH in one beacon period, we define the average delay time $De(N)$ is that the start of back-off till just after vehicles successfully retrieves their messages. So

$$De(N) = P_{Su}(1)T_{Su} + \sum_{k=2}^{W_R} P_{Su}(k)(T_{Su} + \sum_{j=1}^{k-1} Av(j)). \tag{12}$$

V. SIMULATION RESULTS

In this section, to validate and analyze our model by comparing its predictions with vehicular environment in the first place. There is one more point the performance of model which be applied in vehicular networks will be analyzed.

A. Scenario setup

We consider a scenario that one RSU is placed at the middle of the related communication area. One severity of vehicle accident happened at the head of the following vehicles, see Fig. 3. We suppose the simulation allows the system to achieve steady performance. All vehicles which has only one radio to monitor CCH or SCH. A specification simulation program has been developed in the simulation tool MATLAB.

To validate our model, we setup the simulated vehicular networks which closely follows the IEEE 802.11p basic specifications and contains one RSU and N vehicles with aligned Sync Interval. During each Sync Interval, we assume there is exactly one packet stored for each vehicle at the RSU. Additionally, all N vehicles share the same medium and channel switching is a synchronous operation. The basic vehicular networks system parameters are listed in Table I.

B. Collision probability model validation

Fig. 4 plots the collision probability which calculates from our theoretical analysis model Eq.(4) for different number of vehicles N in the system. On the other hand, it can be seen that analytical model results (lines-asterisk) closely match with simulation results (circles) concerning the collision probability. In process of channel switching between CCH and SCH, we can note that the collision probability rapidly increases with the number of vehicles increasing. In this case, when the number of vehicles is 15, the collision probability reaches 30%. This model could help us to predict the performance of vehicular networks.

TABLE I: PHY & MAC PARAMETERS DEFINITION

Parameter	Value
$Data\ Rate(Mbps)$	3
$Packetsize(Bytes)$	58
$PLCP\ Header\ length(\mu s)$	8
$Preamble\ length(\mu s)$	32
$Propagation\ delay\ \delta(\mu s)$	1
$ACK(Bytes)$	38
$Slot\ time\ \sigma(\mu s)$	16
$SIFS(\mu s)$	32
$DIFS(\mu s)$	64
CW_{min}	32
CW_{max}	1024

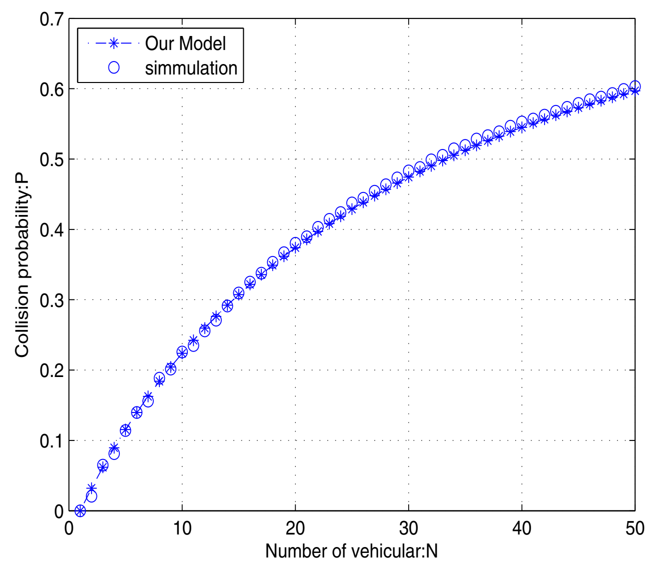

Fig. 4: Collision probability when N vehicles switch channel simultaneously from CCH to the same SCH.

C. Delay model validation

Fig. 5 shows that the packet delay is calculated from our analytical model Eq. (12) for different number of vehicles N in system. Similarly, it can be seen that analytical model results (lines-asterisk) match well with the delay obtained from the simulation results (circles). We can observe that each vehicle experiences delay about $4ms$ in the case where the number of vehicles 15 are at the same situation. Accordingly, the proposed packet delay model in this paper could be better applied to analyze delay performance of vehicular networks.

VI. CONCLUSION

In this paper, from IEEE 1609.4 standard, we know that WAVE devices which perform channel switching in process of communication may undergo a period of packet collision, and possibly result in an unexpectedly high collision

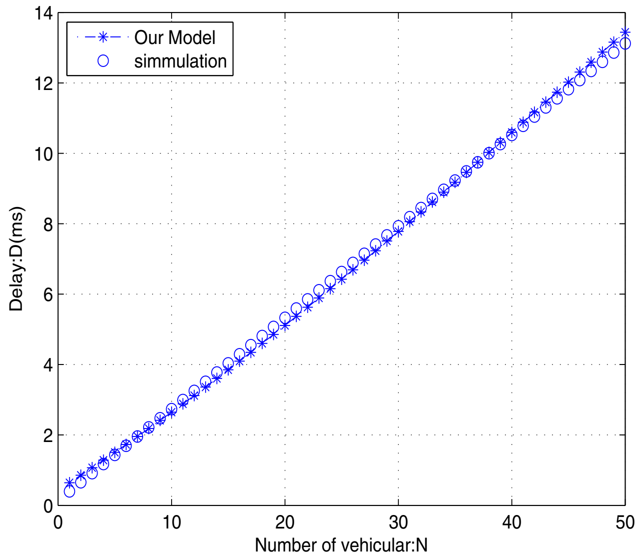

Fig. 5: Packet delay when N vehicles switch channel simultaneously from CCH to the same SCH.

probability. At present, the IEEE 1609.4 standard doesn't give out solutions to this case. A novel analytical model about collision caused by channel switching is proposed for vehicular networks based on IEEE 802.11p/WAVE. Delay model is also proposed and got exactly prediction. Experiments show that the proposed new analytical model could be easily and accurately analyze the performance of vehicular networks. Accordingly, researchers can analyze and improve the performance of vehicular networks with a large number of vehicles and RSU by this proposed model.

In the future, the algorithm or protocol that enhances communication mechanism and ameliorates the performance of vehicular networks, such as high collision probability and long packet transmission delay et.al, will be designed. As well, multi-antenna vehicle about the contention access and packet delay will also be discussed.

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