An IEEE 802.11p-Based Multichannel MAC Scheme With Channel Coordination for Vehicular Ad Hoc Networks

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***Abstract*—In recent years, governments, standardization bodies, automobile manufacturers, and academia are working together to develop vehicular ad hoc network (VANET)-based communication technologies. VANETs apply multiple channels, i.e., control channel (CCH) and service channels (SCHs), to provide open public road safety services and the improve comfort and efficiency of driving. Based on the latest standard draft IEEE 802.11p and IEEE 1609.4, this paper proposes a variable CCH interval (VCI) multichannel medium access control (MAC) scheme, which can dynamically adjust the length ratio between CCH and SCHs. The scheme also introduces a multichannel coordination mechanism to provide contention-free access of SCHs. Markov modeling is conducted to optimize the intervals based on the traffic condition. Theoretical analysis and simulation results show that the proposed scheme is able to help IEEE 1609.4 MAC significantly enhance the saturated throughput of SCHs and reduce the transmission delay of service packets while maintaining the prioritized transmission of critical safety information on CCH.**

***Index Terms*—Channel coordination, IEEE 1609.4, medium access control (MAC), multichannel, vehicular ad hoc networks (VANETs).**

I. Introduction

Vehicular communications are becoming one of the most important aspects of future vehicle equipment. Vehicular ad hoc networks (VANETs) have been considered to be an important part of the intelligent transportation system (ITS).

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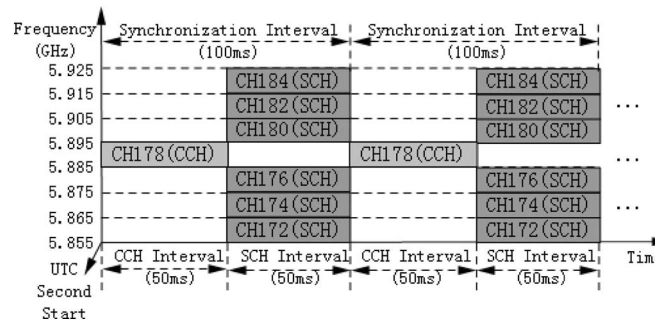

Fig. 1. Frequency channel layout of a 5.9-GHz WAVE system.

Based on the standard draft of IEEE 802.11p [7], VANETs employ the technique of dedicated short-range communication (DSRC) for the enhancement of driving safety, as well as comfort of automotive drivers. The U.S. Federal Communication Commission allocated 75 MHz of the DSRC spectrum at 5.9 GHz to be exclusively used for vehicle-to-vehicle and infrastructure-to-vehicle communications. As shown in Fig. 1, the overall bandwidth is divided into seven frequency channels. CH178 is the control channel (CCH), which is used as a public channel for safety-relevant applications on the road. The other six channels are service channels (SCHs) for nonsafety service applications for the comfort of driving [1].

Wireless access in vehicular environments (WAVE) is designed for an ITS on 5.9-GHz frequency with the IEEE 802.11p and IEEE 1609 standard family. The IEEE 802.11p working group is investigating a new physical layer (PHY)/medium access control (MAC) amendment of the 802.11 standard for VANETs. It employs the orthogonal frequency-division multiplexing technique on the PHY, which can provide up to a 27-Mb/s data rate with 10-MHz bandwidth and a 300–1000-m communication distance.

The overall DSRC communication stack between the link layer and applications is being standardized by the IEEE 1609 working group. The IEEE 1609.4 standard draft [8] is considered to be a default multichannel MAC standard for VANETs, which defines a multichannel wireless radio operation mode, including the interleaving operation of CCH and SCH, priority access parameters, and other characteristics of MAC and PHYs. To efficiently coordinate channel access on the CCH and multiple SCHs, a globally synchronized channel coordination scheme based on the Coordinated Universal Time (UTC) was developed in [8]. As shown in Fig. 1, the channel access time is divided into synchronization intervals with a fixed length of 100 ms, consisting of a CCH interval and an SCH interval. According to the coordination scheme, all devices must monitor the CCH for safety and private service advertisements during CCH intervals. However, devices can optionally switch to SCHs to perform nonsafety applications during SCH intervals. As a consequence, this scheme allows the transmission of safety packets and nonsafety application on different channels, without missing important packets on CCH [2].

Nevertheless, as a contention-based mechanism, the current WAVE MAC is intuitively questioned on its capability of supporting either delay- or throughput-sensitive applications [9]. In a congested vehicular traffic condition, the limited length of CCH is unable to provide sufficient bandwidth to deliver a large amount of safety packets and control packets. On the other hand, if the node density is sparse, the occasional transmission on the CCH channel will waste the channel resource, whereas some large bandwidth consuming applications, such as video download and map update, cannot obtain sufficient bandwidth resources on the SCHs.

The multichannel MAC protocols are essential to not only ensure reliable transmission of safety packets with low latency but provide the maximal throughput for nonsafety applications in a distributed manner [10] as well. This paper proposes a variable CCH interval (VCI) multichannel MAC scheme to enhance the saturation throughput of IEEE 1609.4 in VANETs. The following salient feature of our work makes it different from the existing schemes: 1) The CCH interval is further divided into *safety interval* and *WAVE service announcement (WSA) interval*. 2) Based on the theoretical analysis, the optimal CCH interval is derived to improve the saturation throughput of SCHs while ensuring the transmissions of safety information and private service advertisements on CCH. 3) A multichannel coordination mechanism is proposed to provide contention-free SCHs by channel reservation on CCH.

The rest of this paper is organized as follows: Section II gives a short survey on the current investigation of MAC schemes in VANETs. Section III describes the proposed VCI multichannel MAC scheme in detail. Section IV presents the theoretical analysis on the optimal VCI. Model validation and performance evaluation are presented in Section V. Section VI finally concludes this paper.

II. Related Works

Although only a few researchers have discussed the multichannel MAC scheme for VANET, there has been substantial interest on channel assignment and coordination schemes for multihop ad hoc networks. In [17], Mo *et al.* classified multichannel MAC protocols for wireless networks into four categories based on channel coordination principles, i.e., *Dedicated CCH*, *Common Hopping*, *Split Phase*, and *Parallel Rendezvous* protocols. Most VANET researchers prefer the more easily implemented *Split Phase* approach, including the MAC protocol described by IEEE 1609.4. In the *Split Phase* approach, time is divided into an alternating sequence of control and data exchange phases. The authors in [17] observed that the performance of *Split Phase* is very sensitive to parameters such as the duration of the control and data phases.

Menouar *et al.* [5] discussed the feasibility of using MAC protocols for ad hoc networks in a VANET. Considering contention-based access using the Carrier Sense Multiple Access with Collision Avoidance mechanism, the authors concluded that the IEEE 802.11 MAC protocol is not suitable for real-time traffic and quality-of-service provisions. Jiang *et al.* proposed the Peercast model in [3], where the devices regularly switch to CCH and listen for packets from the neighbors. If no safety packet is heard, the devices will switch back to SCHs. Although this scheme can improve the throughput of SCHs, some safety packets may be lost, for the proposed model cannot ensure that all of the devices simultaneously stay on the CCH. The authors of the study in [2] proposed a vehicular MESH network (VMESH) MAC protocol, which applies a distributed beaconing scheme and a reservation-based channel access scheme to improve the channel utilization of SCHs. VMESH outperforms typical WAVE MAC schemes in terms of system throughput. However, CCH still has low channel utilization. The work [12] proposed a DSRC MAC protocol to support multichannel operation. The focus is on offering potentially high bandwidth for nonsafety applications provided by roadside infrastructure, without compromising the safety communication occurring in another channel. Their architecture tries to solve the channel coordination problem in the presence of a road side unit (RSU). This approach also compliments with existing ad hoc schemes when an RSU is unavailable. However, each device must be equipped with different protocols in both ad hoc mode and infrastructure mode in the MAC and network layers. Consequently, the complexity of device implementation largely increases.

The study in [13] proposed a dynamic-changing interval framework for the WAVE system. The CCH interval is partitioned into three parts based on the type of different frames. This scheme can shorten the transmission delay of safety messages. However, the SCHs in this scheme are not fully utilized. The work in [14] presented a dedicated multichannel MAC (DMMAC) protocol for VANETs. DMMAC employed an adaptive broadcasting mechanism to conduct collision-free and delay-bounded transmission for safety-related traffic. By adopting a variable length in CCH, the DMMAC can enhance the delivery ratio of safety packets. However, no analytical model was given, and the dynamic adjustment of the CCH interval was not considered.

III. Variable Control Channel Interval Medium Access Control Scheme

In spite of many ongoing academic and industrial research efforts on VANETs, the proposed MAC solutions allow VANETs to work well only in some limited scenarios with weak channel utilization. This paper proposes the VCI multichannel MAC scheme to help IEEE 1609.4 deliver real-time safety packets and accommodate throughput-sensitive services in VANETs by using a multichannel coordination mechanism and variable intervals of CCH and SCHs.

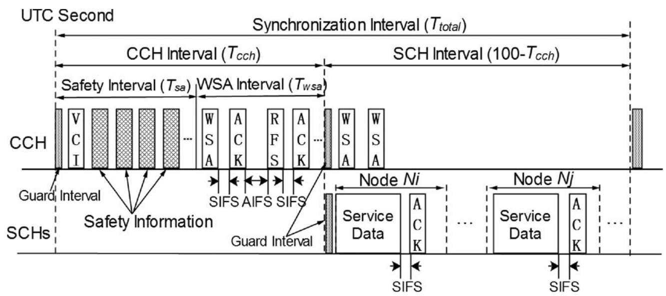

Fig. 2. VCI multichannel MAC scheme.

In our proposed VCI MAC, the timing synchronization UTC [8] mechanism is inherited from IEEE 1609.4. WAVE nodes not only transmit safety information and a WSA packet on CCH but perform measurement and statistics for channel coordination as well. The CCH interval is further divided into the *safety interval* and the *WSA interval*. As shown in Fig. 2, a new CCH interval begins from the *safety interval*, during which WAVE nodes transmit safety information and broadcast the VCI packets. During the *WSA interval*, service providers broadcast WSA packets and piggyback with service information and the identities of SCHs to be used. Nodes that need the service can optionally respond to the WSA packet with an acknowledgement (ACK). Furthermore, a service user can initiatively send a request for service (RFS) packet to make an agreement with a service provider. After the end of the CCH interval, nodes tune to certain SCHs to transmit service packets. More detailed information about channel reservation and service data transmission will be presented in Section III-B.

A. VCI Scheme

Considering the coordinative multichannel access techniques outlined in the IEEE 1609.4, we can find one limitation, i.e., the ratio between CCH interval and SCH interval is a fixed value. However, in a dynamically changing vehicular traffic condition, the restricted CCH and SCH intervals are unable to provide proper bandwidth to deliver both safety/control packets and application streams. To solve this problem, we propose a VCI scheme that can adjust the ratio between the CCH interval and the SCH interval according to the network condition.

As shown in Fig. 2, at the beginning of the CCH interval, the RSU broadcasts a VCI packet containing the length of the CCH interval to the nodes under its radio coverage range. For the sake of reliable delivery, each VCI packet will be broadcast at least twice. Under heavy traffic or congested conditions, the VCI packets may not be heard by some nodes. To tackle this issue, we add a field representing the latest CCH interval information into the WSA/RFS packets. The nodes that obtained the latest CCH interval of the current synchronization cycle will fill this field when they send WSA/RFS packets, whereas other nodes will fill this field with 0. Furthermore, a sufficient length of CCH interval should ensure successful transmission of safety packets, as well as WSA packets under the coverage range of the RSU. To improve the channel utilization of SCHs, the interval of CCH should be optimized to achieve the ideal case, i.e., the number of successful reservations equals the number of packets transmitted on all SCHs within an RSU domain. The optimized CCH interval is calculated by RSUs, which need to collect the current vehicular environment, including the number of nodes within their coverage range. The theoretical derivation of the optimal interval can be found in Section IV.

However, the CCH intervals announced by different RSUs may be variable. In this case, nodes that receive different values of CCH interval should adopt the longest CCH interval to ensure the transmission of safety information. On the other hand, when a node tends to communicate with another node within a neighbor RSU that has a different CCH interval, this pair of nodes should select the longer CCH interval.

The process that a node selects its proper CCH interval is presented in Algorithm 1.

Algorithm 1. Procedure in selecting CCH interval
// Executed by nodes at the beginning of the CCH interval
// CI_{curr}: *CCH interval of the current-synchronizing cycle*
// CI_{prev}: *CCH interval of the previous synchronizing cycle*
// $CI_{\mathrm{wsa\_f}}$: *CCH interval announced in the WSA/RFS/ frame*
// $CI_{\mathrm{vci\_f}}$: *The CCH interval announced in the VCI frame*

// Set the default CCH interval
if CI_{prev} not equal zero then
    $CI_{\mathrm{curr}} = CI_{\mathrm{prev}}$
else
    $CI_{\mathrm{curr}} = 50$ ms
end if

// Update the CCH interval when receiving the VCI frame
if receive a VCI frame then
    if it is the first time receiving a VCI frame then
        Update the CI_{curr}
    else if $CI_{\mathrm{curr}} < CI_{\mathrm{vci\_f}}$ then
        $CI_{\mathrm{curr}} = CI_{\mathrm{vci\_f}}$
    end if
end if

// Update CCH interval when receiving the WSA/RFS/ACK frame
if receive a WSA/RFS/ACK frame then
    if have not yet received a VCI frame then
        Update the CI_{curr}
    else if the WSA/RFS/ACK frame is from the node will connect to then
        // Under different RSUs
        if $CI_{\mathrm{curr}} < CI_{\mathrm{wsa\_f}}$ then
            $CI_{\mathrm{curr}} = CI_{\mathrm{wsa\_f}}$
        end if
    end if
end if

Moreover, when no RSU can be detected, nodes within one hop will choose a leader to perform the VCI packet broadcast. The smallest ID mechanism is a simple but effective leader selection strategy. Alternatively, only the nodes that act as service providers can broadcast the VCI packet. As the WSA packets broadcasted by service providers during the WSA interval contain the basic service set identity (BSSID) information [8], the service provider with the smallest BSSID will transmit the VCI packet.

In addition, when the RSU or the selected node acting as an RSU calculates the proper CCH interval, it must determine how long the safety interval should be. The safety interval is associated with the number of nodes and current vehicular environment. When the number of nodes increases, the need for a longer safety interval is necessary, whereas when accidents occur or are under other emergence cases, the number of safety messages that need to be transmitted also increases. In this paper, we use the sending frequency of safety messages to denote the level of the number of safety messages to be transmitted due to occurred accidents and other emergency cases. The calculation of safety interval is shown in (18).

B. SCH Access Reservations

Different from the original contention-based IEEE 1609.4 MAC approach, our VCI MAC scheme adopts a new coordination mechanism to provide contention-free SCHs by the channel reservation on CCH. Fig. 2 shows the detail of the channel reservation and service data transmission. At the beginning of the WSA interval, service providers broadcast WSA packets, containing the identities of SCHs to be used, as well as other information [8]. The other nodes that need the service can optionally compete to respond with an ACK. The node that successfully sends the response can make an agreement with the service provider on data transmission resource with a specific SCH ID and transmission duration. Considering that too many service providers may share an SCH in a dense node environment, each service provider can only transmit one service packet for successful contention. All nodes will store the channel reservations for SCHs in the dedicated queues by monitoring the successful reservations. During the WSA interval, nodes that act as service users can initiatively start a reservation. An RFS packet will be sent by a service user with the ID of service provider and the service type. Then, the service provider will accept or reject the service request based on the channel conditions. If the service request is accepted, the ACK packet from the service provider will contain the ID of the SCH to be used in the upcoming SCH interval. Services providers will select an SCH when they require the CCH to broadcast a WSA packet or response to a service request. Based on the SCH usage information, a service provider selects the channel that accommodates the least service data packets in the next SCH interval. If more than one SCH is available, the service provider preferentially selects the same SCH used in the previous service data transmission. Upon the beginning of the SCH interval, nodes that have made reservations will switch to SCHs to perform service transmission according to the reservations records in the relevant queues in an orderly way. Nodes that have not made any reservations can stay on the CCH. Among these nodes, service providers can broadcast WSA packets, and service users record the information contained in the WSA packets so that service users can join the WAVE Basic Service Set (WBSS) or initiatively send RFS in the next WSA interval.

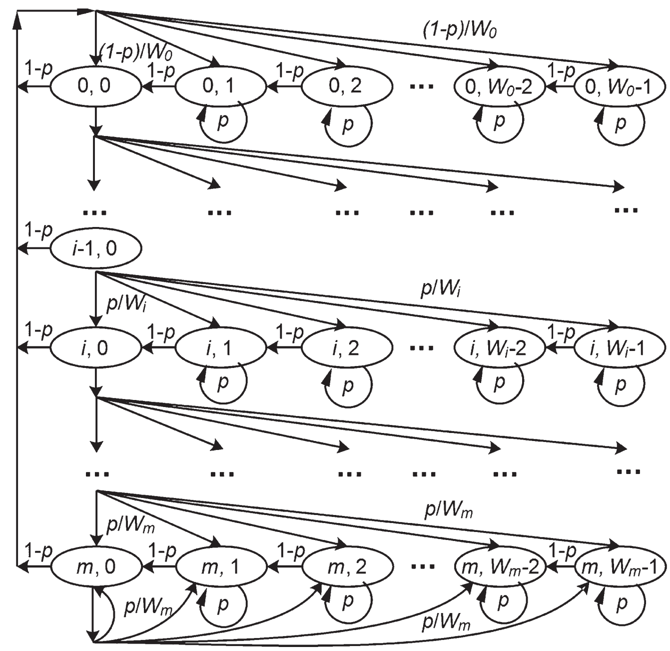

Fig. 3. Markov chain model of WSA transmission.

IV. Model Analysis

In the VCI MAC scheme, the optimal length of the CCH interval is very important for effective collaboration of the channel resource on the CCH and SCHs, particularly under heavy traffic conditions. To derive this optimal interval, we first apply a Markov chain model to examine the behavior of a single node and obtain the stationary probability that the node transmits a WSA or RFS packet in each time slot. Then, a contention model is proposed to analyze the average time consumed on the CCH for the negotiation of service packet transmission. Finally, we derive the optimum ratio between the CCH interval and the SCH interval.

A. WSA or RFS Transmission Probability

A Markov chain model is proposed to obtain the stationary probability τ that a node transmits a WSA or RFS packet in an arbitrary time slot. Considering that a WBSS has n WAVE nodes, which can communicate with each other through single hop. It is assumed that a fixed number of nodes providing service are always under a saturated traffic condition [16], i.e., every node has WSA or RFS packets available after a successful reservation during the *WSA Interval*. Moreover, both CCH and SCHs have the same transmission rate.

Let $b(t)$ and $s(t)$ be the stochastic process representing the backoff window size and backoff state for a given node at slot time t, respectively. Let m be the maximum backoff stage and W_i be the maximal contention window (CW) of the ith backoff stage, where $i \in (0, m)$, and $W_i = 2^i W_0$. The process of a node trying to send WSA or RFS packets at a time slot on state $s(t)$ is supposed to be independent. Let p be the probability of collision that more than one node transmits in a single slot. Then, the bidimensional process $\{s(t), b(t)\}$ can be modeled with a discrete-time Markov chain, as shown in Fig. 3. Note that our proposed Markov model is different from that in [16] due to the following aspects. First, when a node detects that the channel is busy, the counter of the backoff timer in our model will be "frozen" until the channel is detected to be idle again. Second, when the backoff stage of a node exceeds the maximal value m, it holds m until the WSA or RFS packet is successfully retransmitted, rather than being reset to 0.

Let $b_{i,k} = \lim_{t\to\infty}\{s(t) = i, b(t) = k\}$, $0 \le i \le m$, $0 \le k \le W_i - 1$ be the stationary distribution of the Markov chain, then we can get Theorem 1.

Theorem 1: The stationary probability τ that a node sends a WSA or RFS packet in each time slot is $\tau = b_{0,0}/(1-p)$, and the probability of collision is $p = 1-(1-\tau)^{n-1}$.

Proof: In the Markov chain, as shown in Fig. 3, the only nonnull one-step transition probabilities are

$$\begin{cases} P\{0,k|i,0\} = (1-p)/W_0, & 0\le k\le W_0-1, \quad 0\le i\le m \\ P\{i,k|i-1,0\} = p/W_i, & 0\le k\le W_i-1, \quad 1\le i\le m \\ P\{i,k|i,k+1\} = 1-p, & 0\le k\le W_i-2, \quad 0\le i\le m \\ P\{i,k|i,k\} = p, & 0\le k\le W_i-1, \quad 0\le i\le m \\ P\{m,k|m,0\} = p/W_m, & 0\le k\le W_m-1. \end{cases} \tag{1}$$

Equation (1) represents five facts.

1) After successful transmission of the WSA or RFS packet, the backoff stage for a new packet is set to 0.
2) An unsuccessful transmission makes the backoff stage increase.
3) When the channel is free, the backoff timer decreases.
4) When the channel is busy, the backoff timer remains.
5) In the maximal backoff stage m, CW holds if the transmission is unsuccessful, whereas the backoff timer will be reset.

From the Markov chain, it is clear that

$$b_{i-1,0}\cdot p = b_{i,0} \rightarrow b_{i,0} = p^i \cdot b_{0,0}, \qquad 1\le i\le m-1 \tag{2}$$

$$b_{m,0} = (b_{m-1,0} + b_{m,0})\cdot p \rightarrow b_{m,0} = \frac{p}{1-p} b_{m-1,0}. \tag{3}$$

Since the Markov chain is regular and considering the fact that $\sum_{j=0}^{m} b_{j,0} = b_{0,0}/(1-p)$, we have

$$b_{i,k} = \frac{W_i - k}{W_i}\frac{1}{1-p} b_{i,0}, \qquad 0\le i\le m, \quad 1\le k\le W_i-1. \tag{4}$$

Therefore, by using the normalization condition for stationary distribution, then

$$\begin{aligned} 1 &= \sum_{i=0}^{m}\sum_{k=0}^{W_i} b_{i,k} \\ &= \sum_{i=0}^{m-1} b_{0,0}\cdot p^i + b_{m,0} + \sum_{i=0}^{m}\sum_{k=1}^{W_i-1}\frac{W_i-k}{W_i}\frac{1}{1-p} b_{i,0}. \end{aligned} \tag{5}$$

Using (2), (3), and (5), we get

$$b_{0,0} = \frac{2(1-p)^2(1-2p)}{(1-2p)^2 + W_0\left[1-p-p(2p)^m\right]}. \tag{6}$$

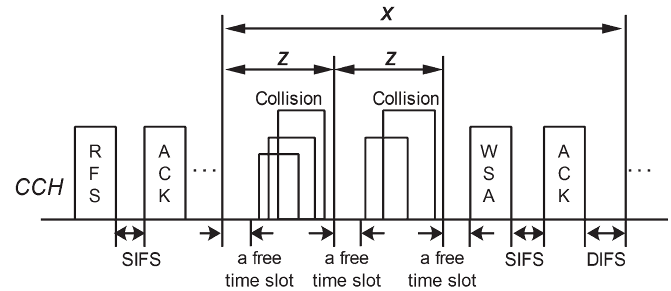

Fig. 4. Contention model of making reservations on CCH.

Then, the probability τ that a node transmits a WSA or RFS packet in an arbitrary time slot can be expressed as

$$\tau = \sum_{i=0}^{m} b_{i,0} = \sum_{i=0}^{m-1} b_{0,0}\cdot p^i + \frac{p^m}{1-p} b_{0,0} = \frac{1}{1-p} b_{0,0} \tag{7}$$

where $b_{0,0}$ is shown in (6).

Let p be the collision probability when more than one node transmits at the same time slot; we have

$$p = 1-(1-\tau)^{n-1}. \tag{8}$$

Consequently, based on (6)–(8), variables τ and p can be solved by the numerical methods as in [16]. Note that $0 < p < 1$ and that $0 < \tau < 1$.

B. Time Analysis for WSA or RFS Transmission

A contention model is proposed in this paper to analyze the average single reservation time on CCH, as shown in Fig. 4. Let X represent the time interval from CCH access contention to the time when a reservation is successfully made. It is also assumed that the n nodes providing service always have available WSA packets. Moreover, the following notations are used in the transmission time analysis.

1) In every time slot during the WSA interval, an agreement will be successfully made with probability $p_{\rm suc}$, a channel collision occurs with probability $p_{\rm col}$, or the channel is idle with probability $p_{\rm idle}$; then, we have

$$\begin{cases} p_{\rm idle} = (1-\tau)^n \\ p_{\rm busy} = 1 - p_{\rm idle} = 1-(1-\tau)^n \\ p_{\rm suc} = n\tau(1-\tau)^{n-1} \\ p_{\rm col} = p_{\rm busy} - p_{\rm suc} = 1-(1-\tau)^n - n\tau(1-\tau)^{n-1}. \end{cases} \tag{9}$$

2) Let $T_{\rm wsa}$, $T_{\rm rfs}$, and $T_{\rm ack}$ denote the time for transmitting a WSA, RFS, and ACK packet, and suppose that $T_{\rm wsa} = T_{\rm rfs}$. Let $T_{\rm sifs}$ and $T_{\rm difs}$ be the SIFS time and the DIFS time, respectively.
3) Let $T_{\rm idle}$, $T_{\rm col}$, and $T_{\rm suc}$ denote the duration of a free time slot, the duration for a transmission collision, and the duration for a successful reservation, respectively. Then, we have

$$\begin{cases} T_{\rm idle} = aSlotTime \\ T_{\rm col} = T_{\rm wsa} + T_{\rm difs} \\ T_{\rm suc} = T_{\rm wsa} + T_{\rm sifs} + T_{\rm ack} + T_{\rm difs}. \end{cases} \tag{10}$$

Theorem 2: Under the condition of saturated traffic load, the mean of time interval X is given by

$$E[X] = T_{\text{idle}}/p_{\text{suc}} + p_{\text{col}} \cdot T_{\text{col}}/p_{\text{suc}} + T_{\text{suc}}.$$

Proof: Let Z be the interval between two continuous free time slots before a reservation is successfully made. Because of the backoff mechanism, the probability of continuous packet collisions or continuous successful reservations is too low to be considered [18]. Hence, Z can be expressed by

$$Z = T_{\text{idle}} + Y \tag{11}$$

where the random variable Y is given by

$$Y = \begin{cases} 0, & p_{\text{idle}}/(p_{\text{idle}} + p_{\text{col}}) \\ T_{\text{col}}, & p_{\text{col}}/(p_{\text{idle}} + p_{\text{col}}). \end{cases} \tag{12}$$

With (11) and (12), the mean value of Z can be written as

$$E[Z] = T_{\text{idle}} + \frac{p_{\text{col}}}{p_{\text{idle}} + p_{\text{col}}} T_{\text{col}}. \tag{13}$$

Furthermore, the probability that k free time slots exist during interval X follows a general distribution, i.e.,

$$P\{K=k\} = (1-p_{\text{suc}})^{k-1} \cdot p_{\text{suc}}, \qquad k=1,2,3,\ldots. \tag{14}$$

There is a successful reservation after k free time slots. Based on Fig. 4 and using (13) and (14), the mean value of X can be given by

$$\begin{aligned} E[X] &= (1/p_{\text{suc}})E[Z] + T_{\text{idle}} + T_{\text{suc}} \\ &= T_{\text{idle}}/p_{\text{suc}} + p_{\text{col}} \cdot T_{\text{col}}/p_{\text{suc}} + T_{\text{suc}}. \end{aligned} \tag{15}$$

C. CCH Interval Optimization

To analysis the optimal CCH interval, we define the following notations.

1) Let N_{sch} denote the number of available SCHs in a VANET.
2) Let T_{cch}, T_{sch}, T_{wsa}, and T_{sa} denote the CCH interval, SCH interval, WSA interval, and safety interval, respectively. The synchronization interval [8], i.e., the whole CCH and SCH period, is denoted as T_{total}; then

$$\begin{cases} T_{\text{cch}} = T_{\text{wsa}} + T_{\text{sa}} \\ T_{\text{total}} = T_{\text{wsa}} + T_{\text{sa}} + T_{\text{sch}}. \end{cases} \tag{16}$$

3) Let β be the ratio between T_{wsa} and T_{sch}; then

$$\begin{cases} T_{\text{wsa}} = \beta T_{\text{sch}} \\ T_{\text{sch}} = (T_{\text{total}} - T_{\text{sa}})/(\beta + 1). \end{cases} \tag{17}$$

4) Let G_1 represent the number of reservations made on CCH during the WSA interval and G_2 be the number of service packets transmitted on all N_{sch} SCHs during the SCH interval.

During the CCH interval, we must arrange enough time for safety packet transmission, i.e.,

$$T_{\text{sa}} = \frac{\alpha \cdot f \cdot N}{B_{\text{cch}}} \times 10^3 \tag{18}$$

where N represents the total nodes sending safety packets, B_{cch} is the data rate of CCH, α is a predefined factor according to current vehicular environment, and f is the sending frequency of safety messages.

If the length of the service packet is constant, the duration transmitting a service packet on SCH is given by

$$T_{\text{data}} = T_h + T_e + T_{\text{sifs}} + T_{\text{ack}} + T_{\text{difs}} \tag{19}$$

where T_h is the cost of MAC and PHY header introduced by the service data packet, $T_e = V/B_{\text{sch}}$, and V represents the payload of the service packet.

The ratio between the CCH interval and the SCH interval is optimum only when the number of reservations made on CCH equals with the number of service packets transmitted on all SCHs, i.e., $G_1 = G_2$, and there are not enough idle time slots left in either the *WSA interval* for making more reservations or the SCH interval for transmitting more service packets. Thus, based on (15), (17), and (19), we have

$$\begin{aligned} \beta &= \frac{T_{\text{wsa}}}{T_{\text{sch}}} = \frac{E[X] \cdot G_1}{E[T_{\text{data}}] \cdot G_2/N_{\text{sch}}} = \frac{E[X] \cdot N_{\text{sch}}}{E[T_{\text{data}}]} \\ &= \frac{(T_{\text{idle}}/p_{\text{suc}} + T_{\text{col}} \cdot p_{\text{col}}/p_{\text{suc}} + T_{\text{suc}}) \cdot N_{\text{sch}}}{T_h + T_e + T_{\text{sifs}} + T_{\text{ack}} + T_{\text{difs}}}. \end{aligned} \tag{20}$$

Then, using (16) and (20), T_{wsa} and T_{sch} can be expressed as

$$T_{\text{wsa}} = \frac{\left(\frac{1}{p_{\text{suc}}} T_{\text{idle}} + \frac{p_{\text{col}}}{p_{\text{suc}}} T_{\text{col}} + T_{\text{suc}}\right) \cdot N_{\text{sch}} \cdot (T_{\text{total}} - T_{\text{sa}})}{\left(\frac{1}{p_{\text{suc}}} T_{\text{idle}} + \frac{p_{\text{col}}}{p_{\text{suc}}} T_{\text{col}} + T_{\text{suc}}\right) \cdot N_{\text{sch}} + T_{\text{data}}}. \tag{21}$$

Finally, based on (16), (18), and (21), the optimum CCH interval can be easily calculated.

Moreover, since T_{wsa} has be obtained by (21), we have

$$G_1 = T_{\text{wsa}}/E[X]. \tag{22}$$

Let T_{delay} represent the total delay for transmitting a service packet, which consists of the delay during the CCH interval $T_{\text{cch\_delay}}$ and the delay during the SCH interval $T_{\text{sch\_delay}}$. The two parts can be expressed by (23) and (24), respectively, shown at the bottom of the page. Consequently, the

$$E[T_{\text{cch\_delay}}] = \frac{1}{2}(G_1 + 1) \cdot E[X] \tag{23}$$

$$E[T_{\text{sch\_delay}}] = \frac{\left[\frac{1}{2}\left\lfloor\frac{G_1}{N_{\text{sch}}}\right\rfloor \cdot N_{\text{sch}} + (G_1 \bmod N_{\text{sch}})\right] \cdot \left[\left\lfloor\frac{G_1}{N_{\text{sch}}}\right\rfloor + 1\right] \cdot E[T_{\text{data}}]}{G_1} \tag{24}$$

TABLE I
SYSTEM PARAMETERS FOR SIMULATIONS

Parameter	VALUE
Data rate of each channel	3Mbps
Number of CCH	1
Number of SCHs	4
W_0	32
W_m	1024
MAC header	256bits
PHY header	192bits
WSA/RFS	160bits + PHY header
ACK	112bits + PHY header
Slot time	20 µs
SIFS	10 µs
DIFS	50 µs
Service packet length	2000 bytes
Sending frequency of safety messages	2
Number of nodes	60

average transmission delay of a service packet can be easily obtained.

Moreover, as nodes need not to compete the SCHs for the transmission of service packets, the saturated throughput is given by

$$S_{\text{sch}} = \frac{T_{\text{sch}}}{E[T_{\text{data}}]} \cdot N_{\text{sch}} \cdot V. \tag{25}$$

V. MODEL VALIDATION AND PERFORMANCE EVALUATION

In this section, we validate the proposed analytical model for the VCI MAC scheme by simulation experiments. The CCH interval defined in [8] is variable to evaluate its effect on the saturated throughput on SCHs. Then, we obtain the optimum CCH intervals in the VANET environment with different system parameters, in terms of the number of nodes and the average length of service packets.

It is assumed that the CCH and four SCHs have the same transmission data rate. All nodes are under the transmission range of each other. Half of the nodes act as service providers, and the other acts as service users. Simulation experiments are conducted in a network environment by using NS-2 [15]. Table I summarizes the parameters used in both theoretical analysis and simulations.

Fig. 5 shows the transmission probability of safety messages in terms of the duration of safety interval. It can be observed that, with higher safety interval, the transmission of safety messages is ensured. When the duration of the safety interval equals 20 ms, all safety messages can be successfully transmitted. In this case, α is 1 from (18).

Fig. 6 shows both the analytical results and simulation results of the saturated throughput on SCHs. It is clear that the saturated throughput increases with the CCH interval. However, when the CCH interval is larger than 32.3 ms, the saturated throughput decreases, whereas the CCH interval further increases. This is because the WAVE nodes have only little

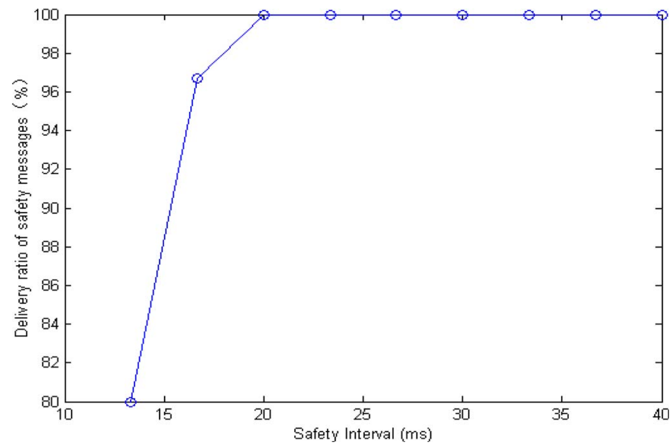

Fig. 5. Ensure the transmission of safety messages.

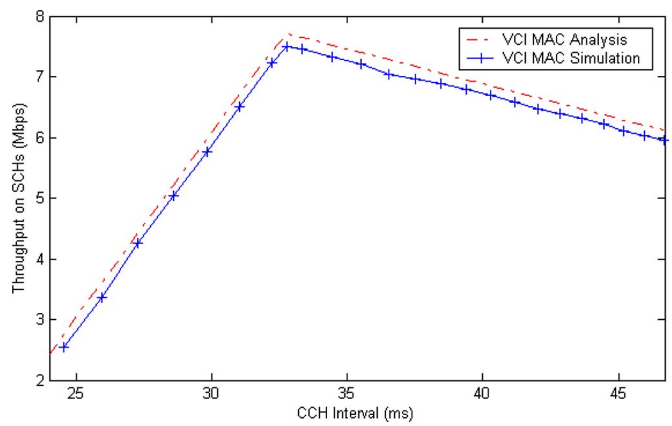

Fig. 6. Saturated throughput on SCHs: analytical results versus simulation results.

chance to make reservations when the CCH interval is small. On the other hand, when the CCH interval is large, too many reservations made during WSA intervals are infeasible, owing to the shortage of the SCH interval.

From Fig. 6, it is clear that the analytical results match the simulation curve well. Thus, the proposed analytical model for the VCI scheme can be validated. Nevertheless, the saturated throughput obtained by analysis is slightly larger than that obtained by simulation, which is caused by the following fact. In the simulation experiment, the remaining time that is insufficient to send a service packet before the end of the SCH interval is wasted. While in the analytical model, it is assumed that the CCH and SCH intervals are both infinite, and therefore, all service packets have adequate time to be transmitted.

Next, we discuss the optimum CCH intervals obtained from model analysis under different network conditions. Fig. 7(a) shows the optimum CCH intervals and the corresponding *WSA intervals* in terms of the service packet length. According to (21), when the length of service packets increases, the *WSA interval* decreases. Therefore, it can be observed in Fig. 6(a) that, when the service packet length increases, the interval of SCH significantly increases, and the CCH interval and *WSA Interval* decreases; on the other hand, according to (18),

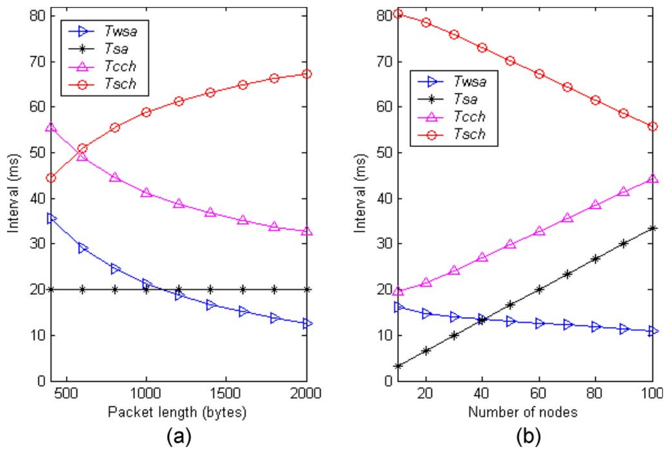

Fig. 7. Optimum CCH intervals. (a) In terms of the length of packets. (b) In terms of the number of nodes.

the *safety interval* remains constant. When the service packet length is about 600 bytes, the intervals of CCH and SCH are approximately equal to 50 ms, which equals with the value defined in [8].

Fig. 7(b) shows the optimum intervals in terms of the number of nodes. From this figure, we can conclude that our proposed VCI MAC scheme can guarantee reliable transmission of safety packets by providing longer CCH intervals in dense circumstances and versus improve the channel utilization by performing more nonsafety applications. According to (18), the more the nodes that exist, the longer the *safety interval* required for safety packet delivery. Consequently, as shown in Fig. 7(b), intervals for service reservations on CCH and service packet transmission on SCHs decrease with the increase in the number of nodes; therefore, the sufficient transmission time for safety information can be ensured. In Fig. 7(b), the *WSA interval* more slowly descends than the SCH interval. This is because the time for service reservations on CCH is much shorter than that for service packet transmission on SCH. Another reason is that the probability of channel collision increases with the number of nodes. As a consequence, the time for service reservations will be prolonged.

We can compare the network performance between the proposed VCI scheme and the original WAVE MAC scheme that has constant intervals of CCH and SCHs, in terms of the saturated throughput on SCHs and service packet delay. The variable intervals of CCH and SCH in the VCI scheme apply the optimal values obtained in Fig. 7.

Fig. 8 shows the saturated throughput in terms of the number of nodes when the service packet length is 2000 bytes. It is clear that the proposed VCI MAC always significantly outperforms the original WAVE MAC scheme. Owing to the variable SCH interval, the VCI scheme compatible nodes have more time to transmit service packets. The contention-free SCH access also helps the VCI scheme to enhance the saturated throughput. Moreover, the throughput on SCHs rapidly decreases with the increase in the number of nodes since more time should be kept for safety packet delivery in a dense network, and the transmission opportunity for service packets will be reduced.

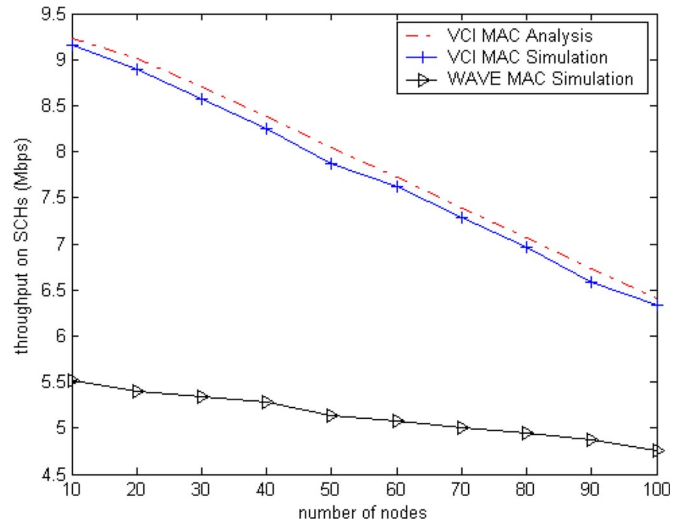

Fig. 8. Throughput results in terms of the number of nodes.

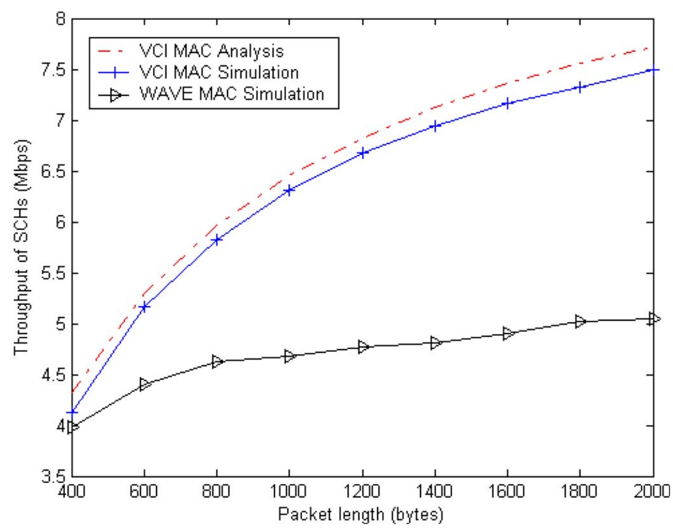

Fig. 9. Throughput results in terms of the length of packets.

Fig. 9 shows the saturated throughput in terms of the service packet length with 60 nodes. It can be found that our proposed VCI MAC greatly outperforms the original WAVE MAC scheme. The performance gain in the VCI scheme increases with the packet size. Even when the packet size equals 600 bytes (i.e., the optimal SCH interval is approximate 50 ms), compared with the original WAVE MAC scheme, the VCI MAC scheme can improve the throughput on the SCHs by 17%. This is because the nodes using the VCI MAC scheme are able to transmit service packets without contentions. When the packet size becomes 2000 bytes, the VCI MAC scheme has an approximately 46% improvement on throughput with respect to the original WAVE MAC scheme.

The average service packet delay in terms of packet length is shown in Fig. 10. Again, the simulation results and the analytical results of VCI MAC match each other very well. When the packet size is less than 960 bytes, the WAVE MAC has shorter service packet delay than the VCI MAC. When the packet size becomes longer, the VCI MAC shows better

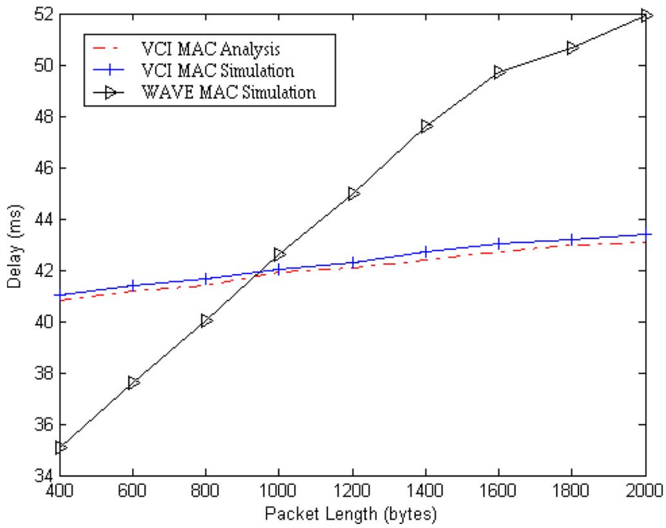

Fig. 10. Average service packet delay under different packet lengths.

performance on reducing the service packet delay than the WAVE MAC. The superiority of VCI increases with the packet size. This is because, unlike the WAVE MAC, the VCI scheme can offer the chance for a more contention-free transmission for service packets.

VI. Conclusion and Future Works

This paper has proposed a VCI multichannel MAC scheme to improve the performance of IEEE 802.11p- and IEEE 1609.4-based WAVE systems. An analytical model by using Markov Chains and stochastic process has been conducted to obtain the optimum CCH interval. Both analytical results and simulation experiments have indicated that the proposed VCI MAC scheme is able to provide efficient channel utilization with higher saturation throughput and low service packet delay when transmitting large service packets. As future work, we will extend the research to a multihop wireless environment with potential hidden terminals.

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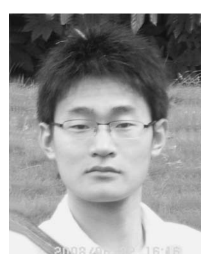

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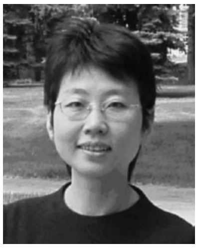

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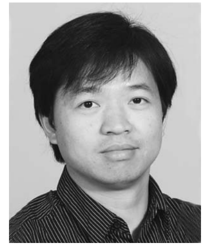

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