A QoS Supported Multi-channel MAC for Vehicular Ad Hoc Networks

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Abstract—**The emerging wireless vehicular communication technology is intended to improve safety and comfort of transportation systems. Different types of traffic information could be delivered through vehicle-to-vehicle and vehicle-to-infrastructure communications. This paper proposes a Quality-of-Service (QoS) supported multi-channel MAC scheme for Vehicular Ad Hoc Networks (VANETs), which can adaptively tune the contention window for different services at each node, and dynamically adjust the intervals of the Control Channel (CCH) and the Service Channels (SCHs) working in multi-rate. Theoretical model is proposed to obtain the contention window and optimize the intervals based on traffic conditions. Analysis and simulation results show that the proposed MAC is able to help IEEE 1690.4 MAC support QoS services, while ensuring the high saturation throughput and the prioritized transmission of critical safety information.**

Keywords-vehicular ad hoc newtworks; medium access control; Quality of Service; multi-rate; multi-channel

I. INTRODUCTION

Vehicular ad hoc networks (VANETs) have been considered as an important communication infrastructure for the Intelligent Transportation Systems (ITS). Mainly based the on IEEE 802.11p [1], VANETs employ Dedicated Short Range Communication (DSRC) for the enhancement of driving safety and comfort of automotive drivers. The U.S. Federal Communication Commission (FCC) has allocated 75 MHz of spectrum at 5.9GHz to be used exclusively for vehicle communications. The overall bandwidth is divided into seven frequency channels. The channel CH178 is defined as the public Control Channel (CCH) for delivering the safety information and exchanging control packets among vehicles. The other six channels are Service Channels (SCHs) which support the transmission of non-safety applications [2].

The overall DSRC communication stack between the physical layer and applications is defined in the IEEE 802.11p and the IEEE 1609 standard family. The IEEE 802.11p working group is investigating a PHY/MAC amendment of the 802.11 standard for VANETs. Due to the complicated DSRC electromagnetic environment, particular in the VANET with heavy vehicle density, the interference caused by DSRC devices and other electronic equipment may result in different quality of the seven DSRC frequency channels. Since the IEEE 802.11p standard draft supports different data rates in each channel, the data transmission rates may be drastically different among distinct channels. Therefore, it is challenging to design the Quality-of-Service (QoS) provision mechanism for multi-rate SCHs.

The current contention based Wireless Access in Vehicular Environments (WAVE) MAC is questioned on its capability of supporting either delay or throughput sensitive applications [3]. Menouar *et al.* [4] discussed the feasibility of using MAC protocols for ad hoc networks in a VANET. Considering the contention-based access using Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism, the authors concluded that the IEEE 802.11 MAC protocol is not suitable for real-time traffic and QoS provision.

In [5], we proposed a Variable CCH Interval (VCI) MAC scheme to help the IEEE 1609.4 MAC deliver real-time safety packets and accommodate throughput-sensitive services in VANETs, by using a multi-channel coordination mechanism and dynamically tuning the duration ratio between CCH and SCHs. The VCI MAC compatible nodes not only transmit safety information and WAVE Service Announcement (WSA) packet on CCH, but also perform measurement and statistics for channel coordination. Based on the network condition, the VCI MAC adjusts the CCH interval and the SCH interval to provide proper bandwidth for the delivery of both safety/control and application information. However, the proposed VCI MAC cannot satisfy various QoS requirements of different applications. Qian et al. [8] proposed a novel secure MAC protocol for VANETs, by assigning different priorities of application message to access the DSRC channel. The protocol mainly focuses on CCH control and the QoS provision in SCHs is not discussed. The existing MAC solutions cannot offer the QoS delivery for different application in SCHs with variable data transmission rate.

In this paper, we propose a QoS supported Variable CCH Interval (Q-VCI) MAC scheme. By adjusting the minimum contention window for different service classes at each node, the Q-VCI MAC scheme is able to support the QoS delivery in a multi-rate multichannel VANET environment. Furthermore, we present the theoretical model for analyzing the network performance of Q-VCI MAC, and derive the optimal CCH interval and the SCH interval which can maximizing the system throughput of SCHs, while ensuring the transmissions of safety information and private service advertisements on CCH. There are two major differences between the proposed Q-VCI MAC and the existing VCI MAC [5]. Firstly, using the

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Q-VCI MAC, the minimum contention windows of nodes delivering different service during the WSA interval are different when nodes contend the CCH for SCH reservation. In this case, the higher priority service has smaller minimum contention window than the lower priority service. Secondly, upon the existence of multi-rate and multi-channel, the Q-VCI MAC compatible nodes with high priority service will be assigned to the SCHs with high data rate.

The rest of this paper is organized as follows. Section II describes the detail of the proposed Q-VCI MAC, and presents the theoretical analysis on the contention window and the optimization of CCH interval and SCH interval. Performance evaluation is presented in Section III and section IV finally concludes the paper.

II. Q-VCI MAC Scheme and Analysis

It is assumed that all nodes in a VANET can communicate with each other directly. A Road-Side Unit (RSU) acting as a centralized access point provides synchronized channel coordination based on Coordinated Universal Time (UTC) [9]. In the Q-VCI MAC, the CCH interval is further divided into safety interval and WSA interval. As shown in Fig. 1, a new CCH interval begins from the safety interval, during which WAVE nodes transmit safety information and broadcast the Variable CCH Interval (VCI) packets. During the WSA interval, service providers broadcast WSA packets, piggybacked with service information and the identities of SCHs. Nodes can optionally respond to the WSA packet with an acknowledgement (ACK). Furthermore, service users can send Request for Service (RFS) packets to make an agreement with service providers. At the end of the CCH interval, a node tunes to a specific SCH to transmit service packets.

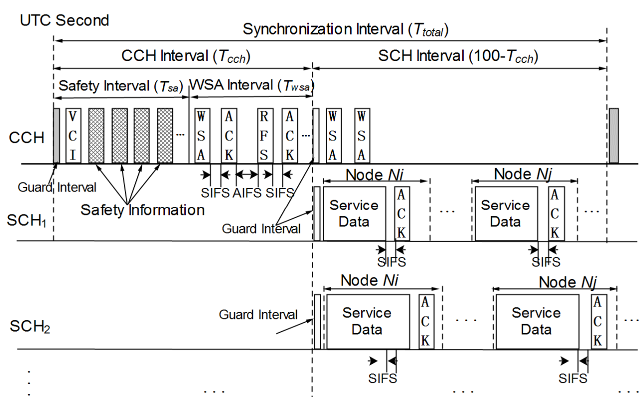

Fig. 1 The Q-VCI Multi-channel MAC Scheme

A. Analysis of Differentiated Minimum Contention Window

In order to derive the proper minimum contention window size for different service classes as well as the consequent optimal CCH intervals, we propose a Markov chain model to obtain the stationary probability τ that a node transmits a WSA or RFS packet in an arbitrary time slot during the WSA interval. We consider a WAVE Basic Service Set (WBSS) that has K classes of services classified by different bandwidth requirement over SCHs. The number of nodes delivering service class k is denoted as N_k and the total number of nodes is N, then $N=\sum_{k=1}^{K} N_k$. It is assumed that nodes are always in a saturated traffic condition. That is, each node has WSA/RFS packets available after a successful reservation. Moreover, the transmission rate on CCH is assumed to be same for all nodes, while nodes have various maximum transmission rates on different SCHs.

Let $b_q(t)$ and $s_q(t)$ be the stochastic process representing the backoff window size and backoff state for a node of class q at slot time t, respectively. Let m be the maximum backoff stage, and W_q^i be the contention window size of the i^{th} backoff stage, where $i\in[0,m]$, $q\in[1,K]$ and $W_q^i=2^i W_q^0$. The process of a node that sends WSA or RFS packets at a time slot on state $s_q(t)$ is supposed to be independent. Then the bi-dimensional process $\{s_q(t),b_q(t)\}$ can be modeled as a discrete-time Markov chain in Fig. 2.

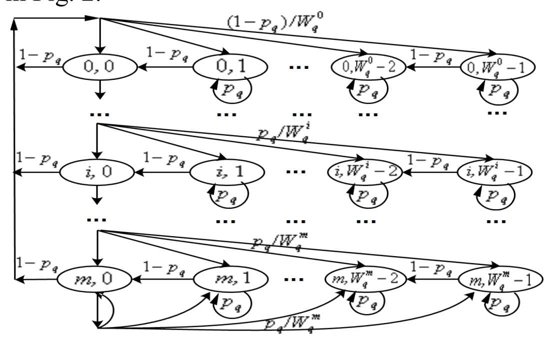

Fig. 2 Markov chain model of WSA transmission

Let $b_q^{i,k}=\lim_{t\to\infty}\{s_q(t)=i,\, b_q(t)=k\}$, $(0\le i\le m_q,\, 0\le k\le W_q^i-1)$ be the stationary distribution of the Markov chain for a node in class q, the one-step transition probabilities are

$$\begin{cases} P\{0,k\mid i,0\}=(1-p_q)/W_q^0 & 0\le k\le W_q^0-1,\, 0\le i\le m \\ P\{i,k\mid i-1,0\}=p_q/W_q^i & 0\le k\le W_q^i-1,\ 1\le i\le m \\ P\{i,k\mid i,k+1\}=1-p_q & 0\le k\le W_q^i-2,\, 0\le i\le m \\ P\{i,k\mid i,k\}=p_q & 0\le k\le W_q^i-1,\, 0\le i\le m \\ P\{m,k\mid m,0\}=p_q/W_q^m & 0\le k\le W_q^m-1 \end{cases}, \quad (1)$$

where p_q represents the probability that the node delivering the service of class q detects the channel collision.

After solving (1), we have

$$b_q^{0,0}=\frac{2(1-p_q)^2(1-2p_q)}{(1-2p_q)^2+W_q^0\left[1-p_q-p_q(2p_q)^m\right]} \quad (2)$$

$$p_q=1-(1-\tau_q)^{N_q-1}\prod_{k=1,k\neq q}^{K}(1-\tau_k)^{N_k} \quad (3)$$

$$\tau_q=\sum_{i=0}^{m} b_q^{i,0}=\sum_{i=0}^{m-1} b_q^{0,0}\cdot p_q^i+\frac{p_q^m}{1-p_q}b_q^{0,0}=\frac{1}{1-p_q}b_q^{0,0} \quad (4)$$

where τ_q represents the probability that the node delivering the service of class q sends a WSA/RFS packet in each time slot.

Let p_q^{suc} denote the probability that a node deliver the service of class q makes a successful reservation on the CCH during the WSA interval, which occurs when only this particular node tries to access the CCH. Then, p_q^{suc} is given by

$$p_q^{suc} = \tau_q \left(1-\tau_q\right)^{N_q-1} \prod_{k=1,k\neq q}^{K} \left(1-\tau_k\right)^{N_k} \quad (5)$$

In order to offer QoS supported delivery in SCHs, different service classes have different minimum contention windows. Let S_q and S_j be the throughput obtained on SCH of nodes delivering service class q and j, respectively. Then, we have

$$\begin{aligned}\frac{S_q}{S_j} &= \frac{N_q}{N_j}\cdot\frac{p_q^{suc}}{p_j^{suc}} = \frac{N_q}{N_j}\cdot\frac{\tau_q\left(1-\tau_q\right)^{N_q-1}\prod_{k=1,k\neq q}^{K}\left(1-\tau_k\right)^{N_k}}{\tau_j\left(1-\tau_j\right)^{N_j-1}\prod_{k=1,k\neq j}^{K}\left(1-\tau_k\right)^{N_k}} \\ &= \frac{N_q}{N_j}\cdot\frac{\tau_q\left(1-\tau_j\right)}{\tau_j\left(1-\tau_q\right)}\end{aligned} \quad (6)$$

Therefore, if the predefined throughput ratio between different service classes and the minimum contention window for any certain service class is given, we can obtain the minimum contention windows for other service classes.

B. CCH and SCH Interval Optimization

The optimization of the CCH interval and the SCH interval is able to maximize the system throughput of SCHs. Considering the stationary probability that a node transmits a WSA or RFS packet in each time slot, we propose a contention model to analyze the average time consumed on CCH for the negotiation of service packet transmission. Table I lists the notations in the analysis.

Based on the derivations in Section II.A, we have

$$\begin{cases} p_{idle} = \prod_{k=1}^{K}\left(1-\tau_k\right)^{N_k} \\ p_{busy} = 1 - p_{idle} = 1 - \prod_{k=1}^{K}\left(1-\tau_k\right)^{N_k} \\ p_{suc} = \sum_{j=1}^{K} N_j \tau_j \left(1-\tau_j\right)^{N_j-1} \prod_{k=1,k\neq j}^{K}\left(1-\tau_k\right)^{N_k} \\ p_{col} = p_{busy} - p_{suc} = 1 - \prod_{k=1}^{K}\left(1-\tau_k\right)^{N_k} \\ \qquad - \sum_{j=1}^{K} N_j \tau_j \left(1-\tau_j\right)^{N_j-1} \prod_{k=1,k\neq j}^{K}\left(1-\tau_k\right)^{N_k} \end{cases} \quad (7)$$

Also, T_{col} and T_{suc} can be expressed as

$$\begin{cases} T_{col} = T_{wsa\_pkt} + T_{sifs} + T_{ack\_pkt} + T_{difs} \\ T_{suc} = T_{wsa\_pkt} + T_{sifs} + T_{ack\_pkt} + T_{difs} \end{cases} \quad (8)$$

Let X represent the interval from CCH access contention to the time when a reservation is successfully made. The probability that k free time slots exist during X can be given by

$$P\{K=k\} = \left(1-p_{suc}\right)^{k-1}\cdot p_{suc}, \; k = 1,2,3\ldots \quad (9)$$

Then, the mean of X can be expressed as

$$\begin{aligned} E[X] &= \left(1/p_{suc}-1\right)\left(T_{idle} + \frac{p_{col}}{p_{idle}+p_{col}} T_{col}\right) + T_{idle} + T_{suc} \\ &= T_{idle}/p_{suc} + p_{col}\cdot T_{col}/p_{suc} + T_{suc} \end{aligned} \quad (10)$$

According to Fig. 1, the relationship among T_{cch}, T_{sch}, T_{wsa} and T_{sa} is given by

$$\begin{cases} T_{cch} = T_{wsa} + T_{sa} \\ T_{total} = T_{wsa} + T_{sa} + T_{sch} \end{cases} \quad (11)$$

The time arranged for safety packets transmission is given by

$$T_{sa} = \alpha\cdot\sum_{k=1}^{K} N_k \times 10^3 \big/ R_{cch}\,, \quad (12)$$

where α is a factor representing the ratio of the safety interval to the CCH interval, and α is proportional to the total number of nodes in current network. If the length of the service packet is supposed to be constant, T_j is given by

$$T_j = \left(L_h + V\right)\big/R_j + T_{sifs} + T_{ack\_pkt} + T_{difs} \quad (13)$$

where L_h is the cost of MAC and PHY header introduced by the service data packet, V represents the payload of the service packet, and R_j is the data rate of j th SCH, $j = 1,2,\ldots N_{sch}$.

TABLE I NOTATIONS USED IN ANALYSIS OF CCH INTERVAL OPTIMIZATION

NOTATION	DESCRIPTION
p_{suc}	The probability an agreement is successfully made
p_{col}	The probability that a channel collision occurs
p_{idle}	The probability that the channel is idle
T_{wsa_pkt}, T_{rfs_pkt}	Time used to transmit a WSA and RFS packet
T_{ack_pkt}	Time used to transmit an ACK packet
T_{data}	Time used to transmit an service packet on SCH
T_{sifs}, T_{difs}	Duration of SIFS and DIFS, respectively
T_{idle}, T_{col}	Duration of a free slot and a collision transmission
T_{suc}	Duration of a successful reservation
T_{cch}, T_{sch}	CCH interval and SCH interval, respectively
T_{sa}, T_{wsa}	Safety interval and WSA interval, respectively
N_{sch}	Number of SCHs
R_{cch}	Data rate of CCH

The optimal CCH interval and SCH interval can be obtained only if 1) the number of reservations made on CCH equals the number of service packets transmitted on all SCHs, and 2) there are not enough time slot left either in WSA interval for making more reservations or in SCH interval for more service packet delivery. Thus we have

$$T_{wsa}\big/E[X] = \sum_{j=1}^{N_{sch}}\left(T_{sch}\big/T_j\right) \quad (14)$$

Based on (11), (12), (13) and (14), the optimal CCH interval and SCH interval can be expressed as

$$T_{cch} = T_{sa} + \left(T_{total} - T_{sa}\right)\frac{E(X)\cdot\sum_{j=1}^{N_{sch}}\left(T_j\right)^{-1}}{1+E(X)\cdot\sum_{j=1}^{N_{sch}}\left(T_j\right)^{-1}} \tag{15}$$

$$T_{sch} = \left(T_{total} - T_{sa}\right)\Big/\left[1+E(X)\cdot\sum_{j=1}^{N_{sch}}\left(T_j\right)^{-1}\right] \tag{16}$$

Let G represent the number of reservations made on CCH during the WSA interval. Without loss of generality, we consider the case of two classes, i.e., $K = 2$. Let G_1 and G_2 be the number of packets with service class 1 and class 2, transmitted on all SCHs, respectively. The maximum data rates over SCHs are R_1 and R_2, and the number of SCHs on which the nodes can obtain these data rates are denoted as N_{R1} and N_{R2}.

Let T_{delay_1} and T_{delay_2} represent the transmission delay of a packet of service class 1 and class 2, respectively. The transmission delay consists of the delay during the CCH interval $T_{d\_cch\_1}$ and $T_{d\_cch\_2}$, as well as the delay during SCH interval $T_{d\_sch\_1}$ and $T_{d\_sch\_2}$, then

$$\begin{cases} E\left[T_{delay\_1}\right] = E\left[T_{d\_cch\_1}\right] + E\left[T_{d\_sch\_1}\right] \\ E\left[T_{delay\_2}\right] = E\left[T_{d\_cch\_2}\right] + E\left[T_{d\_sch\_2}\right] \end{cases} \tag{17}$$

The average values of $T_{d\_cch\_1}$, $T_{d\_cch\_2}$ and $T_{d\_sch\_1}$ can be expressed by

$$E\left[T_{d\_cch\_1}\right] = E\left[T_{d\_cch\_2}\right] = \frac{1}{2}(G+1)\cdot E[X] \tag{18}$$

$$E\left[T_{d\_1\_sch}\right] = \left\{\frac{T_1}{2}\left\lfloor\frac{T_{sch}}{T_1}\right\rfloor\left(1+\left\lfloor\frac{T_{sch}}{T_1}\right\rfloor\right)\cdot N_{R1} + H_{d\_1\_sch'}\right\}\Big/ G_1 \tag{19}$$

where

$$H_{d\_1\_sch'} = \frac{T_2}{4}\left[\left(N_{R2}-1\right)\left\lfloor\frac{G_{1left}}{N_{R2}}\right\rfloor\left(1+\left\lfloor\frac{G_{1left}}{N_{R2}}\right\rfloor\right)\right] \cdot\left(\left\lfloor\frac{T_{sch}}{T_2}\right\rfloor + \left(G_{1left} \bmod N_{R2}\right)\right)\left(1+\left\lfloor\frac{T_{sch}}{T_2}\right\rfloor + \left(G_{1left} \bmod N_{R2}\right)\right) \tag{20}$$

$$G_{1left} = G_1 - N_{R1}\cdot\left\lfloor\frac{T_{sch}}{T_1}\right\rfloor \tag{21}$$

The mean of $T_{d\_sch\_2}$ can be expressed by

$$E\left[T_{d\_2\_sch}\right] = \left(H_{d\_1\_sch'} + H_{d\_2\_sch'}\right)\Big/ G_2 \tag{22}$$

where

$$H_{d\_2\_sch'} = T_2\cdot\left[\frac{\left(N_{R2}-1\right)}{2}\left\lfloor\frac{G_2}{N_{R2}}\right\rfloor\left(1+\left\lfloor\frac{G_2}{N_{R2}}\right\rfloor\right)\right] + \frac{T_2}{2} \cdot\left[\left(\left\lfloor\frac{G_2}{N_{R2}}\right\rfloor + \left(G_2 \bmod N_{R2}\right)\right)\left(1+\left\lfloor\frac{G_2}{N_{R2}}\right\rfloor + \left(G_2 \bmod N_{R2}\right)\right)\right] \tag{23}$$

III. PERFORMANCE EVALUATION

In this section, we validate the proposed analytical model for the Q-VCI MAC by simulations. It is assumed that all nodes have the same highest data rates on a certain channel. However, nodes on different channels may have the different highest data rate. In each simulation, half of the nodes act as service providers and the other act as service users. Simulation experiments are conducted in a network environment NS-2 [6]. Based on the simulation results in [7], the factor α is optimally set to 3 in the following theoretical analysis and simulations. Moreover, we consider two classes of service, namely $K = 2$, and let S_1 and S_2 denote the saturated throughput obtained on SCHs for service of class 1 and 2, respectively. Table II lists the other parameters used in both theoretical analysis and simulations.

Fig. 3 shows the minimum contention window for service class 2 under different S_1/S_2. It is clear that the minimum contention window for service class 2 becomes larger when fewer nodes deliver high priority services If $S_1/S_2 = 3$, the minimum contention window for service class 2 is 134 when N_1=10 and N_2=15, while the contention window is 62 when N_1=15 and N_2=10. If the number of nodes delivering each service class is fixed, the minimum contention window for service class 2 decreases with higher S_1/S_2. Thus, the proposed Q-VCI MAC can differentiate the transmission opportunities for the packets with different service classes.

TABLE II SYSTEM PARAMETERS FOR SIMULATIONS

PARAMETER	VALUE
Data rate of CCH	6Mbps
Data rate of SCHs	Two 6Mbps, two 9Mbps
Number of CCH and SCHs	1, 4
m	5
PHY header, MAC header	192bits, 256bits
WSA/RFS	160bits + PHY header
ACK	112bits + PHY header
Slot time	20us
SIFS	10us
DIFS	50us
Service packet length	2000 bytes

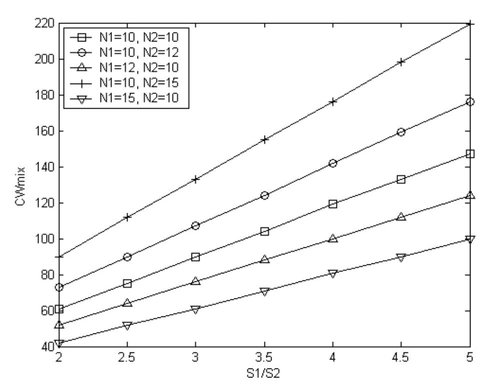

Fig. 3 Minimum contention window for service class 2 (the minimum contention window for service class 1 is set to 31)

Fig. 4 shows the optimum CCH and SCH intervals in terms of the number of nodes delivering two service classes. It is observed that our proposed Q-VCI MAC scheme can guarantee the reliable transmission of safety packets by providing longer safety intervals in dense circumstances. The WSA interval and SCH interval decrease with the increasing number of nodes. Moreover, the WSA interval increases with higher S_1/S_2 . This is because the minimum contention window for service class 2 increases in order to ensure the reservation of higher priority service, which prolongs the interval of WSA.

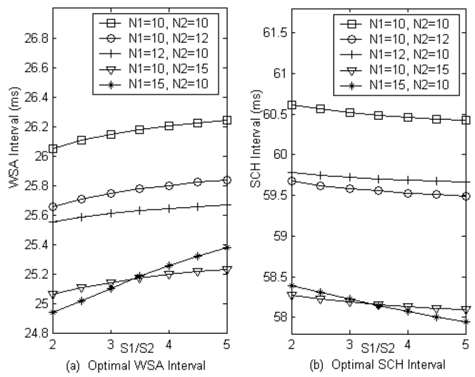

Fig. 4 Optimum intervals under different numbers of nodes: (a) Optimum WSA intervals; (b) Optimum SCH intervals

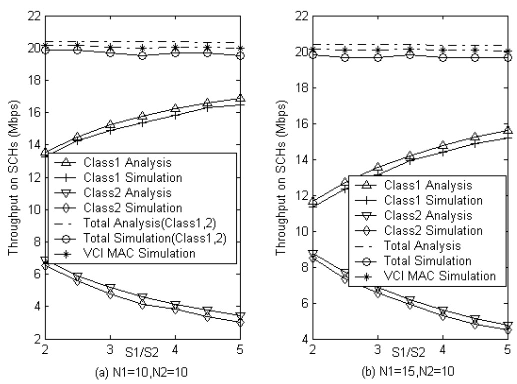

Fig. 5 Throughput on SCHs: (a) N_1=10, N_2=10; (b) N_1=15, N_2=10

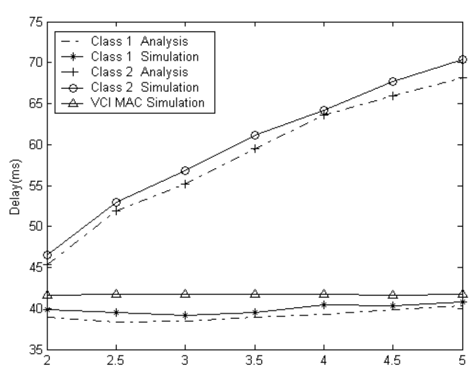

Fig. 6 Average service packet delay (N_1=15, N_2=10)

Fig. 5 shows the saturation throughput over SCHs in terms of S_1/S_2 . The minimum contention window for service class 2, the optimum CCH interval and SCH interval are set based on the results in Fig. 3 and Fig. 4. It is clear that the analytical results match the simulation curves very well. The throughput of service class 1 increases while that of service class 2 decreases with higher S_1/S_2 . The throughput in Q-VCI MAC is slightly smaller than that in VCI MAC. This is because in Q-VCI MAC, the minimum contention window for service class 1 is 31 and that for service class 2 is even larger, while in VCI MAC, the minimum contention window for both service classes is always 31.

Fig. 6 illustrates the average packet delay in terms of S_1/S_2 . Again, the simulation result and the analytical result match with each other very well. The packets of service class 1 have less delay than those of service class 2, which demonstrates the QoS differentiation in the Q-VCI MAC. Furthermore, the packet delay in the VCI MAC is between those of service class 1 and service class 2 using the Q-VCI MAC since all service classes in the VCI MAC have the same minimum contention window.

IV. CONCLUSION

This paper proposes a QoS supported multi-channel MAC scheme to enhance the transmission performance of the IEEE 1609.4 based WAVE systems. An analytical model by using Markov Chains and stochastic process is proposed to obtain the proper minimum contention windows for different service classes and the optimal CCH and SCH intervals. Both analytical results and simulation experiments indicate that the proposed Q-VCI MAC scheme can provide QoS supported delivery on SCHs in terms of differentiated throughput and delay, by using variable CCH interval under multi-rate multichannel, while improving the channel utilization with higher saturation throughput.

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