A Channel Coordination Scheme for High Density Vehicular Ad-Hoc Networks Based on Time Division Multiplexing

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***Abstract*—**IEEE 802.11p Vehicular Ad-Hoc Network (VANET) applies one control channel (CCH) and six service channels (SCHs). CCH is dedicated for broadcasting traffic safety messages, SCHs are dedicated for transmission of varying application messages. In IEEE 802.11p standard, Coordinated Universal Time (UTC) scheme is recommended for coordinating channel access on CCH and multiple SCHs, Enhanced Distributor Channel Access (EDCA) algorithm is used for wireless channel assignment and priority support. However, both the static methods of synchronization interval partition in UTC or priority queue management in EDCA and contention-based channel competition mechanism in EDCA may have great influence on transmission efficiency in high density VANETs. In this paper, we present a time division multiplexing channel coordination (TDMCC) scheme, which can assign synchronization interval and CCH priority queues dynamically according to estimated real-time VANET conditions. Besides, instead of traditional contention-based channel competition mechanism, a contention-free mechanism is provided for service channel assignment. The analysis results show that our scheme can improve performance of VANETs efficiently in high density scenario.

***Index Terms*—**vehicular ad-hoc network, 802.11p protocol, channel coordination, access category, time division multiplexing, saturated throughput, transmission delay

I. Introduction

Vehicular Ad-Hoc Network (VANET) is considered as an essential technology for future Intelligent Transportation System (ITS), it can provide vehicle to vehicle as well as vehicle to roadside unit (RSU) wireless communications. So that on board units (OBUs) located in vehicles can share messages related to road traffic conditions or varying applications not only with other OBUs in the same VANET, but also transportation management centre and remote users depending on RSU's retransmission. IEEE 802.11p is a new VANET communication standard, which is designed for Wireless Access in Vehicular Environments (WAVE) to support ITS. In IEEE 802.11p protocol, 75MHz bandwidth of licensed spectrum at 5.9GHz is divided into one control channel (CCH) and six service channels (SCHs). CCH is dedicated for broadcasting traffic safety messages, SCHs are dedicated for transmission of various application messages. In order to connect with Internet seamlessly, messages in SCHs are transmitted by IPv6 protocol, control messages in CCH can be transmitted using special Wave Short Message Protocol (WSMP). In MAC layer, the Enhanced Distributor Channel Access (EDCA) mechanism is used for wireless channel assignment and priority support. In physical layer, WAVE uses Orthogonal Frequency Division Multiplexing (OFDM) to split the signal into several narrowband channels to provide a data payload communication capability of 3M bps up to 27M bps. However, contention-based channel competition mechanism and static priority queue management in EDCA may result in extra transmission delay in high density VANETs [1]-[4].

The Coordinated Universal Time (UTC) scheme has been proposed for coordinating channel access on the CCH and multiple SCHs efficiently, the channel access time is divided into fixed 100 ms synchronization intervals, consisting of 50 ms CCH interval and 50 ms SCH interval. During CCH interval, all OBUs except source node must monitor the CCH for the broadcast of messages related to road safety or SCH reservation. During SCH interval, OBUs can switch to preconcerted SCH to perform application message's transmitting [5]. However, in high density VANETs, the limited length of CCH may be unable to provide enough channel capacity to deliver a large number of road safety messages. On the other hand, if the node density is sparse, CCH resource will be wasted.

In recent researches, Dedicated Short-range Communication (DSRC) protocol [6] can offer high bandwidth in both SCHs and CCH by multi-channel communications, but each OBU must be equipped with multiple transceivers, so the complexity of ITS increases. In dynamic time interval algorithm [7], the CCH interval is partitioned into three parts based on the type of different data packets. Although this scheme can reduce the transmission delay of safety messages in CCH, SCH

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utilization can not be ensured. The Dedicated Multi-channel MAC (DMMAC) protocol performs variable length in CCH based on adaptive broadcasting mechanism to conduct collision-free and delay-bounded transmission for safety-related messages [8], but the dynamic adjustment of synchronization interval is not considered. Variable CCH Interval (VCI) multi-channel MAC scheme divides CCH interval into safety interval and WAVE service announcement interval, the interval length ratio can be adjusted dynamically between CCH and SCHs according to network conditions. Although VCI scheme is able to provide efficient channel utilization in both CCH and SCHs in some extend, contention-based wireless channel competing mechanism will influence transmitting efficiency, especially in overload SCHs of high density VANET [9].

The remainder of this paper is organized as follows: In section 2, we present a time division multiplexing channel coordination (TDMCC) scheme for high density VANETs. In section 3, performance of TDMCC scheme is analyzed by theoretical model. Model validation and performance evaluation in different VANET environments are given in section 4. Finally, some useful conclusions are summed up, and our further research work is introduced in section 5.

II. TDMCC SCHEME

In TDMCC scheme, the methods of synchronization interval partition and time-slot assignment during SCH interval are shown in Fig. 1. The process of SCH reservation is shown in Fig. 2. In order to adapt high density VANET environments, our scheme has following salient features:

- The initial length of CCH interval is 50 ms. In order to ensure safety messages transmission during CCH interval, the subsequent length of CCH interval and SCH interval are adjusted dynamically by

$$T_{CCH} = \beta \cdot (\lambda_C \cdot 100ms \cdot E[L_p]) / V \quad (T_{CCH} < 100ms)$$
$$T_{SCH} = 100ms - T_{CCH} \tag{1}$$

In formula (1), $E[L_p]$ denotes the average length of safety packets, V is data transmission rate, λ_C is sending frequency of safety packets, β is a predefined factor. Considering the extra time of channel collision and SCH reservation packet's transmission, the value of β should be more than 1. The length of next CCH interval is calculated by RSU, and is announced to all OBUs in the VANET at the end of CCH interval.

- CCH is classified into three EDCA access categories (ACs). AC [2], AC [1] and AC [0] are for high priority safety-related packets, AC [1] and AC [0] are for low priority SCH reservation packets. Setting AC queue assignment controller in each OBU, it is intended for detecting previous access delay of each AC queue during CCH interval, estimating transmission delay, and then, guiding AC queue dynamic assignment.
- RTS/CTS mechanism of Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) algorithm is used for control channel competition during CCH interval. TDM scheme is performed to provide contention-free SCH assignment during SCH interval.

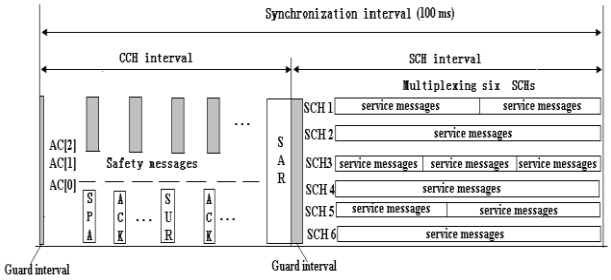


Fig. 1. Synchronization Interval of TDMCC Scheme.

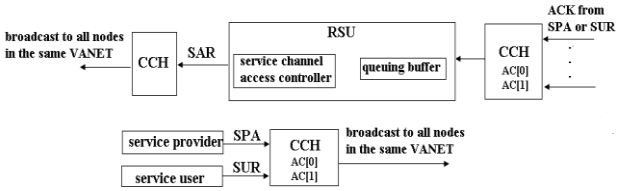


Fig. 2. The process of SCH reservation in TDMCC scheme

The process of TDMCC scheme is as follows:

Algorithm 1: dynamic AC queue assignment during CCH interval.
// *adelayi*: AC[i] access delay.
// *time( )*: function of system time.
// *lenACi*: AC[i] queue length.
// *delayi*: AC[i] transmission delay.
//*packet_type*: packet priority. The value of safety-related packet is 1, SCH reservation packet is 0.

initialize:
adelayi=0; *delayi=0*; *lenACi*=0; (i=2,1,0)

when acknowledgement (ACK) is received by source nodes
lenACi=lenACi-1;
$adelayi_{new}$*=Time(receive ACK)-Time(packet begins to competechannel)*; (2)
if *adelayi==0*
adelayi=$adelayi_{new}$; (3)
else
*adelayi=(1-α)*adelayi+α**$adelayi_{new}$; (4)

when packet arrives to AC queue assignment controller
*delayi=lenACi*adelayi;* (5)
switch (*packet_type*)
{case 1 *k=2*;
if *delay1<delay2& delay1<delay0 k=1*;
if *delay0<delay2 & delay0<delay1 k=0*;
case 0 *k=1*;
if *delay0<delay1 k=0*;}
data packet ⟶ AC[k] queue ;
lenACk=lenACk+1;}

Algorithm 2: SCH selection and time slot assignment by SCH access controller in RSU.
// *Num*: the amount of SCH assignment request in RSU queue buffer.
// *rt[n]*: remainder time in SCH n (n=1-6).
//*Aij*: SCH assignment matrix. Line number *i* denotes the number of assigned SCH, column number *j* denotes the number of assigned time-slot. The element in *Aij* denotes service provider identity (SPID).

initialize：
k=Num; *rt[n]=*T_{SCH}; *col [s]=1*(s=1-6);

do while (*k>=1*)
{*r=a random number between [1,k]*;
dt=duration time in SCH assignment request r;
sd=SPID in SCH assignment request r;
for *n*=1:6
{if *rt[n]>=dt*
i=n; *j=col[n]*; *col[n]=j+1*; *Aij=sd*; *rt[n]=rt[n]-dt*; break}
k=k-1;
deleting SCH assignment request r from queue buffer;}
Calculate SCH assignment matrix *Aij*.
Broadcasting the content of matrix *A* to all OBUs at the end of CCH interval.

The time complexity of algorithm 1 is O(1). The time complexity of algorithm 2 is O([*Num*]^2), it increases with the amount of SCH assignment request.

Our scheme has two main steps:

Step 1: dynamic AC queue assignment.

AC[i]'s access delay includes time to compete CCH, packet sending delay, propagation delay and time to send back ACK. It is detected dynamically by AC queue assignment controller in OBUs according to formula (2) (3) (4). In formula (4), the value of α is between 0 and 1. If α is bigger, the new collected samples of access delay would make more influence on estimated average access delay. When a packet arrives to CCH controller, transmission delay of AC [2], AC [1] and AC [0] are estimated according to formula (5). And then, safety-related packet would be mapped into the AC queue that estimated transmission delay is the smallest among AC [2], AC [1] and AC [0]. SCH reservation packet would be mapped into the AC queue that estimated transmission delay is the smallest among AC [1] and AC [0]. In order to economize CCH resource, ACK of safety-related packet can only be sent back by RSU.

Step 2 service channels assignment.

SCH reservation packet has two types: Service Provider Announcement (SPA) and Service User Request (SUR). SPA is broadcasted by service providers during CCH interval. It contains information of SPID, service type and duration time. OBUs which need this service must send back ACK containing SPID and duration time. On the other hand, service users can also initiatively broadcast SUR containing information of required SPID or service type, the requested service providers can accept or reject this request based on current service channel conditions. If the service request is accepted, the ACK from service provider would be broadcasted through CCH. RSU records each SCH assignment request has been acknowledged into its queuing buffer. Service channel access controller in RSU reads SCH assignment requests randomly, and then, calculates SCH assignment matrix A. To support varying QOS requirements of different applications on SCHs, priority control strategy by queuing algorithm can also be used to achieve differentiated service. At last, the time slot in appropriate service channel would be assigned according to expected service packet duration time and service channel conditions. If expected duration time of service packet is longer than the remainder time of each SCH (it means there isn't enough time slot in SCHs to transmit this service packet during SCH interval), this SCH assignment request will be discarded. At the end of CCH interval, RSU broadcasts SCH Assignment Result (SAR) packet containing CCH length of next synchronization interval and the content of matrix A to all OBUs. During subsequent SCH interval, permitted service providers send service packets in the assigned time slot of specified SCH, De-multiplexing can be accomplished by service users based on SCH assignment matrix A.

For example, suppose SCH assignment matrix A is

$$A = \begin{bmatrix} 1,30,24 \\ 2,9 \\ 10,4,11,12 \\ 20,15,17 \\ 6,3,26 \\ 8,25,31,7,20 \end{bmatrix}$$

According to algorithm 2, time slots in SCH-1 to SCH-6 will be assigned as Fig. 3.

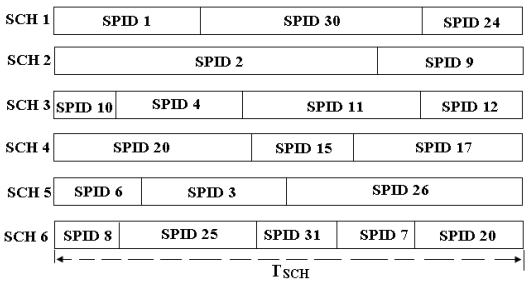


Fig. 3. Time slots assignment of multiple service channels

III. Performance Analysis Model of TDMCC Scheme

A. CCH Interval Performance Analysis

Let *N* be the number of nodes in a VANET, τ_i be packet transmitting probability of AC[i] in a EDCA time-slot, τ be packet transmission probability, p_{ic} be packet

collision probability of AC[i], p_{si} be successful probability of transmitting AC[i] packet in a EDCA time slot, p_{tr} be CCH utilization probability, CW_{min} be EDCA minimum back off window, m_i be EDCA maximum back off stage. Then, we have [10], [11]

$$\tau_i = \frac{2(1-2p_{ic})}{(1-2p_{ic})(CW[i]_{\min}+1)+p_{ic}CW[i]_{\min}(1-(2p_{ic})^{m_i})} \quad (6)$$

$$\tau = 1-\prod_{i=0}^{2}(1-\tau_i) \quad (7)$$

$$p_{si} = \frac{N\tau_i\prod_{j\neq i}(1-\tau_j)(1-\tau)^{N-1}}{1-(1-\tau)^{N-1}} \quad (8)$$

$$p_{ic} = 1-(1-\tau)^{N-1}\prod_{j\neq i}(1-\tau_j) \quad (9)$$

$$p_{tr} = 1-(1-\tau)^{N} \quad (10)$$

Further more, Let T_{si} denote average time to transmit AC[i] packets successfully, T_{ci} be average collision time of AC[i] packets, δ be propagation delay, σ be EDCA time slot length, we can get normalized channel utilization of AC[i] is

$$S_i = \frac{p_{si}p_{tr}T_{packet}}{(1-p_{tr})\sigma + p_{tr}\sum_{k=0}^{2}(p_{sk}T_{sk}) + p_{tr}\sum_{k=0}^{2}(p_{ck}T_{ck})} \quad (11)$$

In formula (11), if RTS/CTS mechanism in EDCA is used, we have [12]

$$\begin{aligned} T_{si} &= T_{packet-head} + T_{packet} + 3SIFS[i] + 4\delta + \\ &\quad T_{ACK} + AIFS[i] + T_{RTS} + T_{CTS} \\ T_{ci} &= T_{RTS} + AIFS[i] + \delta \end{aligned} \quad (12)$$

For our scheme, let packet arrival rate of AC[i] be λ_i, $p_i(X=k)$ be probability distribution of channel competing times of AC[i] packets, λ_C be sending frequency of safety packets, λ_S be sending frequency of SCH reservation packets, $E[Lr]$ be the length of SCH reservation packet. We can get

$$p_i(X=k) = [1-(p_{tr}p_{si})]^{k-1}(p_{tr}p_{si})(i=0,1,2) \quad (13)$$

$$\begin{aligned} adelayi &= \frac{1}{\mu_i} = \sum_{k=1}^{\infty} p_i(X=k)[(k-1)T_{ci}+T_{si}] \\ &= (\frac{1}{p_{tr}p_{si}}-1)T_{ci}+T_{si} \end{aligned} \quad (14)$$

$$d_i = lenACi \times adelayi \quad (15)$$

$$p_{Hi} = probability\{\min(d_2, d_1, d_0) = d_i\}\ (i=0,1,2) \quad (16)$$

$$p_{Li} = probability\{\min(d_1, d_0) = d_i\}\ (i=0,1) \quad (17)$$

Hence, saturated throughput of safety-related packets is

$$S_C = (\sum_{i=0}^{2} p_{Hi}S_i)\times T_{CCH}\times V \ \text{(bit)} \quad (18)$$

Saturated throughput of SCH reservation packets is

$$S_r = \sum_{i=0}^{1} p_{Li}S_i \times T_{CCH}\times V \ \text{(bit)} \quad (19)$$

According to Markov queuing theory, the average transmission delay of safety packet can be obtained by

$$delay_{safety} = \frac{1}{\mu_C - \lambda_C} \quad (20)$$

The average transmission delay of SCH reservation request packet is

$$delay_{SCH-reservation} = \frac{1}{\mu_S - \lambda_S} \quad (21)$$

In formula (20) (21), μ_C and μ_S can be given by

$$\mu_C = \sum_{i=0}^{2} p_{Hi}\mu_i, \qquad \mu_S = \sum_{i=0}^{1} p_{Li}\mu_i \quad (22)$$

B. Performance Analysis of Service Packets in SCHs

During SCH interval, our scheme conduct contention-free TDM mechanism to perform service packets transmission. Let $E[Ls]$ denote the average length of service packets, nsr denote normalized channel utilization of service reservation packet in CCH, the saturated throughput of service packets can be calculated by

$$\begin{aligned} & nsr = \sum_{i=0}^{1} p_{Li}S_i \\ & if\ \text{int}(nsr\cdot T_{CCH}\cdot V/E[L_r]) < 6\,\text{int}(T_{SCH}\cdot V/E[L_s]) \\ & S_S = \text{int}(nsr\cdot T_{CCH}\cdot V/E[Lr])\cdot E[Ls] \\ & else \\ & S_S = \text{int}(T_{SCH}\cdot V/E[L_s])\cdot E[L_s] \end{aligned} \quad (23)$$

IV. TDMCC Performance Evaluation

TABLE I. IEEE 802.11 EDCA PARAMETERS

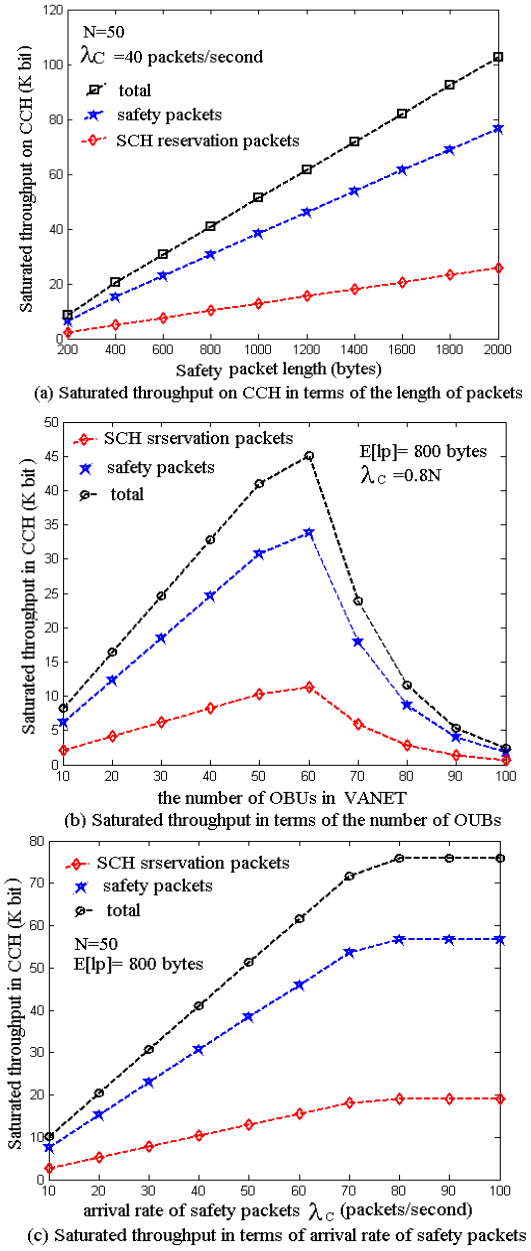
Parameter	Value	Parameter	Value	Parameter	Value
AC[0]-CWmin	31	PHY header	192bit	Slot time	20μs
AC[1]-CWmin	15	RTS length	160bit	Propagation Delay	1μs
AC[2]-CWmin	7	MAC header	272 bit	Transmission Rate	5M bps
AC[0]-AIFS	7	CTS length	112bit	m0	4
AC[1]-AIFS	3	ACK length	112 bit	m1	3
AC[2]-AIFS	2	SIFS	10μs	m2	2

The value of IEEE 802.11 EDCA parameters is as shown as Table I, and let $\beta = 1.2/(\sum_{i=0}^{2} p_{Hi}S_i)$, $E[Lr]$=400 bit. We analyze performance of our TDMCC scheme in varying VANET environments by theoretical analysis model. Table II shows the length of CCH interval in different conditions calculated by formula (1). Obviously, with the increase of sending frequency or average length of safety packets, the CCH interval increases dynamically, so the required transmission time of safety packets can be ensured commendably. Besides, the CCH interval increases with the number of OBUs. This is because that more packet collision make OBUs have only little chance to transmit safety packet when the number of OBUs is

large. In this case, CCH interval has to increase to make up for low control channel utilization.

TABLE II. THE LENGTH OF CCH INTERVAL (UNIT: MS)

E[Lp] (bytes)	N=30			N=50		
	λ_C=40	λ_C=60	λ_C=80	λC=40	λC=60	λC=80
200	15.1654	22.7408	30.3308	40.0170	60.0254	80.0340
400	19.8004	29.7006	39.6008	44.7796	67.1693	89.5592
600	24.4207	36.6311	48.8414	49.4624	74.1935	98.9248
800	29.0302	43.5453	58.0604	54.1075	81.1613	100
1000	33.6352	50.4528	67.2704	58.7345	88.1018	100
1200	38.2383	57.3575	76.4766	63.3534	95.0301	100
1400	42.8396	64.2595	85.6792	67.9664	100	100
1600	47.4399	71.1599	94.8798	72.5769	100	100



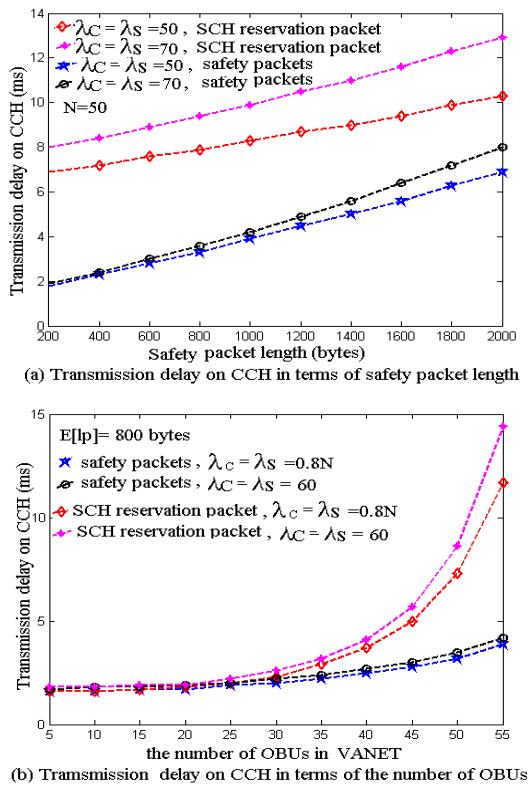
(a) Saturated throughput on CCH in terms of the length of packets

(b) Saturated throughput in terms of the number of OUBs

(c) Saturated throughput in terms of arrival rate of safety packets

Fig. 4. Saturated throughput of TDMCC scheme on CCH

Fig. 4(a) shows saturated throughput of safety packet and SCH reservation packet during CCH interval in terms of safety packet length with 50 nodes and λ_C=40 packets/second. It can be found that saturated throughput increases with safety packet length significantly, especially for saturated throughput of safety packets. The reason is as follows: according to formula (1) and (11), when the safety packet length increases, the CCH interval and channel utilization increase, it means that nodes have more efficient time to transmit safety packets or SCH reservation packets. Fig. 4(b) shows saturated throughput in terms of the number of OBUs with E[Lp]=800 bytes and λ_C=0.8N. It can be observed that, at the beginning, the saturated throughput increases with the number of OBUs, this is because the increase of safety packet sending frequency makes CCH interval longer. When N is larger than 50, the uptrend of saturated throughput becomes slower due to more packet collision. When N is larger than 60, CCH interval reaches to maximum value 100 ms, the saturated throughput begins to decrease rapidly. Fig. 4(c) shows saturated throughput in terms of safety packet sending frequency with 50 nodes and *E[Lp]*=800 bytes. The saturated throughput also increases with the safety packet sending frequency. When λ_C is larger than 80, CCH interval reaches to maximum value, after that the saturated throughput of safety packet is stabilized at 55 K bit, the saturated throughput of SCH reservation packet is stabilized at 15 K bit. Meanwhile, the analysis results in Fig. 1 show that safety packets have an approximately 60%-70% improvement on saturated throughput with respect to SCH reservation packets.



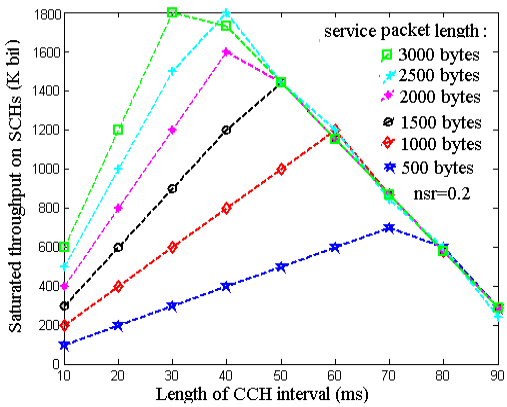
(a) Transmission delay on CCH in terms of safety packet length

(b) Tramsmission delay on CCH in terms of the number of OBUs

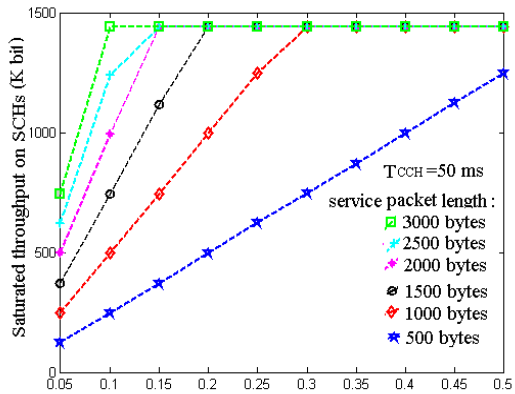
Fig. 5. Transmission delay of TDMCC scheme on CCH

Fig. 5 shows the transmission delay of TDMCC scheme on CCH. It is clear that:

- Transmission delay of safety packets or SCH reservation packets increases with safety packet length. This is because the increase of safety packet length makes packet sending time becoming longer. In general, the length of safety packets is much smaller than service packets, so the QOS requirements of safety packets can usually be meet.
- If network load is light (i.e. packet arrival rate is low, or the number of OBUs is small), transmission delay is small. Transmission delay increases with the network load, especially in heavy load conditions. This is because packet collision probability and queuing time are larger in heavy load conditions, these would lead to the time that packets compete channel becomes longer. In order to ensure transmission performance, network scale must be restricted according to different network conditions.
- Dynamic CCH interval adjustment mechanism in TDMCC scheme can meet QOS requirements of safety packets adequately. Transmission delay of safety packets is smaller than SCH reservation packets obviously. Besides, network load or packet length has less influence on transmission delay of safety packets than SCH reservation packets.



(a) Saturated throughput on SCHs in terms of the length of CCH interval



(b) Normalized channel utilization of service reservation packet in CCH

Fig. 6. Saturated throughput of TDMCC scheme on SCHs

Fig. 6(a) shows the saturated throughput of service packet in terms of CCH interval with different service packet length. It can be observed that when the CCH interval is small, saturated throughput of service packet increases with the CCH interval. However, when the CCH interval is larger than the threshold which relates to average length of service packet, the saturated throughput of service packets decreases. The reason is that the OBUs have only little chance to reserve SCHs when CCH interval is small. But when the CCH interval is large, too small SCH interval brings about the shortage of service packet transmitting time. Fig. 6(b) shows the saturated throughput of service packet in terms of normalized channel utilization of service reservation packet in CCH with 50 ms CCH interval. It is clear that saturated throughput on SCHs increases with channel utilization of service reservation packet, until it reaches the maximum capacity of services channels. The service channel capacity is related to the length of SCH interval, service packet average length and data rate.

We validate the theoretical analysis of TDMCC scheme by simulation experiment. Table III shows the simulation scenario built in Network Simulator 2 (NS2). It is assumed that all nodes in one VANET can communications with each other through single hop, and wireless channel is ideal. The value of other EDCA parameters is as same as theoretical analysis in Table I. From the simulation results shown in Table IV, it is observed the analysis results match simulation results better. The slight error may be caused by stochastic characteristics of data flow and node location in simulation experiment.

TABLE III. PARAMETERS OF SIMULATION

Simulation Parameter	Value
The number of nodes	50
The number of service providers	20
The number of service users	30
Safety packets length	800 bytes
SCH reservation packets length	50 bytes
Service packets length	3000 bytes
Safety packet sending frequency	40 packets /second
SCH reservation packets sending frequency	60 packets /second
simulation time of CCH interval	54ms

TABLE IV. SIMULATION RESULTS COMPARE WITH THEORETICAL ANALYSIS

Analysis indicator	Theoretical Value	Simulation Value
Throughput of safety packet in CCH interval	30.72K bit	33.64K bit
Throughput of SCH reservation packets in CCH interval	10.30K bit	11.38K bit
Total throughput in CCH interval	41.02K bit	45.02K bit
Throughput of service packets in SCH interval	600 K bit	672K bit

V. Conclusions.

In this paper, we propose a TDMCC scheme to improve transmission efficiency in high density VANET. It is difficult to keep high throughput capacity both in CCH and SCHs. Our strategy in TDMCC scheme is to ensure high CCH throughput capacity by dynamic CCH interval adjustment, meanwhile, contention-free TDM scheme is resorted to improve SCH throughput capacity. CCH is classified into three ACs to support requirements of two priority services: high priority road safety-related messages and low priority SCH reservation messages. Access delay of each AC queue is detected dynamically by AC queue assignment controller in OBUs, data packet is mapped into appropriate AC queue according to estimated transmission delay. Besides, instead of traditional contention-based channel competition mechanism in IEEE 802.11 wireless LAN, our scheme gives a contention-free TDM scheme to achieve high efficiency in SCHs. Saturated throughput and transmission delay are analyzed in different network conditions based on Markov random model, Analysis results shows that our TDMCC scheme is an efficient way to improve performance both in CCH and SCHs under high density environment.

Our further work includes researching on network performance analysis based on more accurate simulation model under varying urban transportation environments, secret communication technology used in intelligent transportation system, and efficient routing algorithm in VANET.

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