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Saturation Delay Performance Analysis by Markov Chain for WAVE

Jin TIAN*
School of Networks and Telecommunications,
Jinling Institute of Technolog,
Nanjing, China

Ren Ping LIU
CSIRO, Australia

Xu ZHANG
College of Internet of Things Engineering, Hohai University
Changzhou, China

***Abstract*—WAVE plays an important role in ITS. Its MAC meets the IEEE 802.11p and IEEE 1609 standards. In this paper we present a new analytical model by Markov chain, from which we can research e saturation delay performance with theoretical analysis and numerical calculation. The analysis based on our proposed model can provide an indepth understanding of the protocol performance so as to improve the protocol specifies.**

Keywords—WAVE, IEEE 802.11p, MAC, Markov chain, saturation delay

I. INTRODUCTION

Intelligent Transportation System (ITS) is becoming a crucial part in transportation system, because compared with the old system, it provides several key advantages. It can report the real time vehicle accidents to the drivers and update the related devices information so that precaution measures will be taken in time. An important part of ITS is Vehicular ad hoc networks (VANETs), which focuses on the Vehicular -to- Vehicular (V2V) and Vehicular -to- Roadside (V2R) communications.

The WAVE [1] standard includes IEEE 802.11p [2] and IEEE 1609 standard families. The IEEE 802.11p includes the physical layer and medium access control (MAC) layer. The MAC layer is based on the Enhanced Distribution Channel Access (EDCA) in IEEE 802.11e and the PHY layer is similar to IEEE 802.11a [3]. The IEEE 1609.4 specifies the multi-channel operation rules for WAVE MAC.

The current standards with MAC protocol on WAVE have a few disadvantages to apply to VANETs. Firstly, the MAC protocol is based on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). The vehicles must contend transmission opportunities. The EDCA technique divides the transmission stream into four access categories. The category with highest priority transmits packets by the shortest channel sensing time and the smallest contention window (CW) size. Although RTS/CTS (request to send/clear to send) adopted by DCF can mitigate hidden terminal problem, IEEE 802.11p could not make use of such mechanism for broadcast procedure. The priority of AC_i (i_{th} access category, i = 0, 1, 2, 3) is showed in the Table 1, from which we can find that the priorities of AC_BK, AC_BE, AC_VI and AC_VO are sequenced from the lowest to the highest. In the paper, AC_0 and AC_3 denote the lowest priority category and highest priority category, respectively. Our research focuses on the delay performance of IEEE 802.11p considering different access category in saturation state. The work has scarcely been published in the literature.

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Asterisk (*) indicates corresponding author

Table 1: The priority of ACs in WAVE system

Priority	*AC*	*AC$_i$*	*Description*
Lowest	AC_BK	AC_0	Background
↓	AC_BE	AC_1	Best Effort
	AC_VI	AC_2	Video
Highest	AC_VO	AC_3	Voice

The remainder of this paper is organized as follows. In section II briefly describes similar proposals to analyze the performance of the WAVE. The proposed analytical model is presented in section III. Section IV provides the numerical calculation on delay performance. Numerical results are discussed in Section V. The conclusions of this paper are drawn in section VI.

II. RELATED WORK

Recently, many researches have been taken to improve the performance of WAVE. At the same time, there are also many ways on delay performance of WLAN. The Qing et al. [4] found the requirements of the DSRC, which provides us the basis of our work. Many researches have been finished in one-sided method. Gukhool *etl*.[5] simulate to periodic broadcast of time-critical packets in a vehicle-to-vehicle situation of a highway scenario. Bilstrup *etl.*[6] researched the systems in mathematical way with a single access category (AC). In [7], they proposed a different model for each of the access categories AC_1 to AC_3 with different discrete-time Markov chains. Because 802.11p MAC protocol is based on the IEEE 802.11e, the works related to 802.11e have been taken into account. Yang's research method [8] on IEEE 802.11e was applied to our proposed model to derive throughputs and n delays in saturation condition assuming that each station only has a data stream belonging to one priority class. Kong [9] presented a developed analytical model, in which they took many new features of EDCA into consideration, and proposed a recursive method capable of calculating the mean access delay. Yuan Yao [10] establishes two Markov chain models on ACs with different priorities to analyze the performance and reliability of safety-critical data broadcast on the CCH under both nonsaturated and saturated conditions.

III. ANALYTICAL MODEL

In this section, we present a proposed model for WAVE. Our research is based on the saturation condition. We set the state transition diagram in detail during deferrable and backoff stage. Multiple ACs have packet to transmit. We derive the packet collision probability by the modified Markov chain, and then research on the probability distribution functions. With the result gotten, we investigate the mean access delay.

A. Markov Chain Model for MAC Layer Packet

We model WAVE MAC operation procedure with Markov chain. Saturation condition means that all stations always have packet to transmit. The 2-D Markov chain model is shown as Fig 1.

The 2-D process is a discrete time Markov chain assuming the probability, p_t, that the channel is sensed idle in a time slot during the deferring period, the probability, p_b, that the channel is sensed busy during backoff period and the probability, p_i, that AC_i suffer from collision are independent of the backoff procedure. The probability p_i in this paper means the external collision probability caused by collisions from other stations transmissions. The state of AC is fully determined by (k, l), where k denotes the backoff counter and takes values from $[0,W_i\text{-}1]$;and l indicates the remaining frozen time before the backoff counter is reacted for states(k, l) with $k \geq 1$.

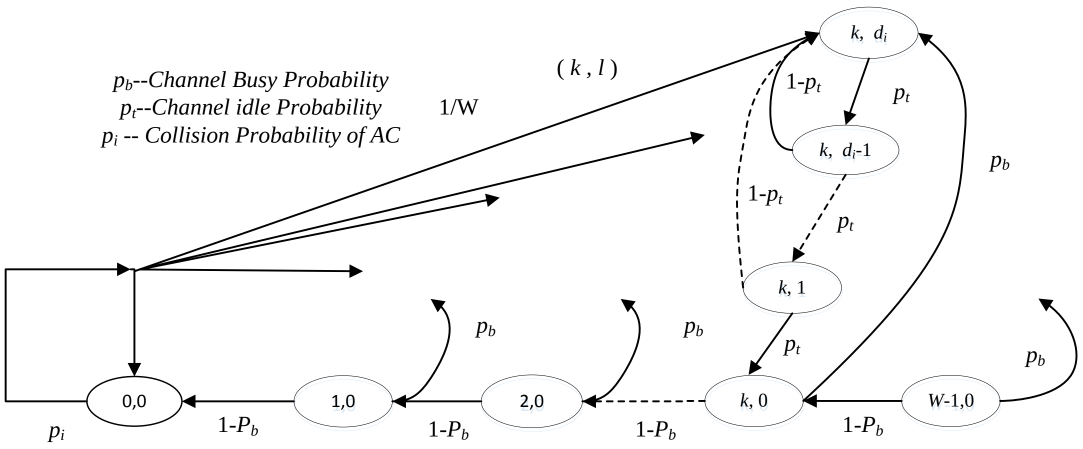

Fig. 1. Discrete time Markov chain model

If a state suffers from channel busy during deferring period, the state will go back to (k, d_i) and again begin AIFS period deferring. The backoff will wait a little time slot to be reactived (the time slot is determined by AIFSs). Ziouva's model [11] assumes that after every successful transmission, a station can transmit if the medium is idle without entering the backoff stage.

B. Transition Probability

For the state (k, l) during deferring period, if there is no other transmission at the same time, the transition is successful.

$P[(k, l\text{-}1)|(k, l)]=p_t,\ 1\leq k\leq W_i\text{-}1,\ 0\leq l\leq d_i$

For all the state (k, l), $1 \leq l \leq d_i\text{-}1$ and $1 \leq k \leq W_i\text{-}1$, if they sense channel busy, the state will transfer back to the initial state during deferring period.

$P[(k, d_i)|(k, l)]=1\text{-}p_t$,

$P[(k, d_i)|(k, 0)]=p_b$,

If the station encounters collision when it transmits, the state will back to the backoff state.

$$P[(k,d_i)|(0,0)]=\frac{p_i}{W_i}$$

Let $b_{k,l}$ be the steady probability of state(k, l), we can derive the following relations through chain regularities. At the state (k, d_i), $1\leq k\leq W_i-1, 1\leq l\leq d_i$, we can get the state balance formula on state (k, d_i):

$$\frac{p_i}{W_i}b_{0,0}+(1-p_t)\sum_{l=1}^{d_i-1}b_{k,l}+p_b b_{k,0}=p_t b_{k,d_i} \quad (1)$$

$$b_{k,l}=p_t^{d_i-l}b_{k,d_i}, \quad (2)$$

From the equation (1) and (2), we can derive the following equations:

$$b_{k,l}=\frac{1}{p_t^l}\left(\frac{p_i}{W_i}b_{0,0}+p_b b_{k.0}\right), \quad (3)$$

$$b_{k,0} = \frac{(W_i - k)p_i}{W_i} b_{0,0}, \quad 1 \le k \le W_i - 1 \tag{4}$$

According to normalization theory of all probabilities,

$$1 = \sum_{k=0}^{W_i-1} \sum_{l=0}^{d_i} b_{k,l} \tag{5}$$

From (1) to (5), we can get

$$b^{-1}{}_{0,0} = 1 + p_i \frac{W_i - 1}{2} + \frac{1 - p_t^{-d_i}}{p_t - 1} \bullet \left(1 + p_i + \frac{W_i - 1}{2} p_i p_b\right) \tag{6}$$

Let the τ_i be the probability an AC accesses the medium in the randomly chosen time slot. In the Zhen's model, it is the sum of all the steady-state probability $b_{i,0}$, but it is only (0, 0) for WAVE. So

$$\tau_i = b_{0,0} \tag{7}$$

Let n_i denote the number of stations in the priority i class. A transmitted frame collides when other station transmits during a slot time. The probability p_i that a station in backoff stage for the priority i class senses the channel busy is given as

$$p_i = 1 - \left[\prod_{h=0}^{i-1} (1 - \tau_h)^{n_h}\right] \bullet (1 - \tau_i)^{n_i - 1} \left[\prod_{h=i+1}^{3} (1 - \tau_h)^{n_h}\right] \tag{8}$$

Substituting (1) and (8) to (6), we can solve unknown parameters numerically. Then, we can calculate p_i from (8). Let p_b denote the probability that the channel is busy. It happens when at least one station transmits during a slot time. Let p_t denote the probability channel is idle during deferring period. It happens when all stations in higher priorities ($>i$) during deferring period doesn't transmit. Therefore, we have

$$p_b = 1 - \prod_{h=0}^{3} (1 - \tau_h)^{n_h} \tag{9}$$

$$p_t = \prod_{x>i} (1 - \tau_x)^{n_x} \tag{10}$$

IV. Saturation Delay

Let $p_{s,i}$ denote the probability in a slot time for the priority i class, and p_s the probability that a successful transmission occurs in a slot time.

$$p_{s,i} = n_i \tau_i (1 - \tau_i)^{n_i - 1} \prod_{h=0, h \ne i}^{3} (1 - \tau_h)^{n_h} \tag{11}$$

$$p_s = \sum_{i=0}^{3} p_{s,i} = \sum_{i=0}^{3} \frac{n_i \tau_i}{1 - \tau_i} (1 - p_b) = (1 - p_b) \sum_{h=0}^{3} \frac{n_h \tau_h}{1 - \tau_h} \tag{12}$$

Saturation delay is the average delay under the saturation condition and includes the medium access delay (due to backoff, collisions, etc.), the transmission delay, and the interframe spaces (such as SIFS). The average backoff delay depends on the value of a station's backoff counter and the duration when the counter freezes due to other transmissions. Let X_i denote the variable representing the total number of backoff slots, which a frame encounters without considering the case when the counter freezes. The average number of backoff slot a station needs to transmit a frame successfully is

$$E(X_i) = \frac{W_i - 1}{2} + E(Y_i) \tag{13}$$

$$E(Y_i) = \sum_{u=1}^{\infty} p_t^{d_i} (1 - p_t^{d_i})^u u E(L_i) \tag{14}$$

$$E(L_i) = \sum_{l=1}^{d_i} p_{ti}^{d_i - l} (d_i - l) \tag{15}$$

Y_i denote the random variable representing the total number of slots when the station again and again attempts during the deferring period. L_i denote the random variable representing the number of slots the station goes through each attempt during the deferring period.

Equation (13) just considers the successful transmissions without considering counter k freezing situation. Let B_i denote the random variable representing the total number of slots when the counter freezes, which a frame encounters.

$$E(B_i) = \frac{E(X_i)}{1 - p_i} p_i \tag{16}$$

Let D_i denote the random variable representing the frame delay for the priority i class. The average slot lengths are δ, (p_s/p_b) T_s and T_s for an idle slot at state (k, l) $(k>0)$, a busy slot at states (k, l) $(k>0)$ and a successful transmission at states (0, 0). We have

$$E(D_i) = E(X_i)\delta + E(B_i)\frac{p_s}{p_b}T_s + T_s \quad (17)$$

V. NUMERICAL ANALYSIS

The paper used parameters can be found in the [7]. The physical layer parameters are used to calculate T_s and the EDCA parameters are used in the CCH of WAVE. The physical layer parameters are shown in the Table 2. The table 3 provides the EDCA parameters used in the CCH of WAVE. With these parameters, we can calculate the unknown parameters in the delay functions.

Table 2: Physical layer parameters in WAVE

Parameter	*Value*
PHY header	
PLCP Preamble	32 μs
PLCP Signal	8 μs
PLCP Service	16 bits
PLCP Tail	6 bits
MAC header	288 bits
Frame payload E[P]	4096 bits
Channel bit rate	6 Mbps
Propagation delay (δ)	1 μs
Slot(σ)	13 μs
SIFS	32 μs

Table 3: the EDCA parameters used in the CCH of WAVE

Access category	*CWmin*	*AIFSN*
AC_0	15	9
AC_1	7	6
AC_2	3	3
AC_3	3	2

We can get the AIFS [AC_i] from the following expression:

$$AIFS[AC_i]=AIFSN[AC_i]\bullet\sigma + SIFS \quad (18)$$

With the parameters shown in the Table 2 and the formula (18), we can calculate the T_s:

$$T_s=PHY_{header}+MAC_{header}+E[P] + AIFS[AC_i]+\delta \quad (19)$$

We use the MATLAB software tool to analyze the saturation delay relating to AC category and node number. Assuming that different AC category has same number of nodes, the numerical result on delay performance shows as figure 2.

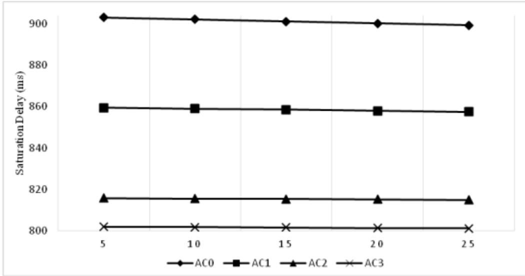

Fig. 2: The delay changes with AC category and node number

The vertical axis and horizontal axis denotes delay parameter and node number in the fig.2, respectively. From the figure, we can know that the saturation delay is changed with access priority. The saturation delay is decreasing as the AC priority increases. AC_3 responds to 800 ms delay; AC_0 responds to 900 ms delay. The numerical value can not fully meet vehicle communication requirement. AC_2's delay is 20 ms more than AC_3's; AC_1's delay is 40 ms more than AC_2's; similarly, AC_0's delay is 40 ms more than AC_1's. The number of the nodes can slightly also influence the delay performance. The saturation delay of an AC is decreased as the number of nodes is increasing, as nodes have more chance to transmit when node number increases.

VI. CONCLUSION

This paper presents a new model to analyze the delay performance of WAVE by Markov chain. We take the AIFS and CW into consideration according to IEEE 802.11p without retrying. With the new analytical model, we analyze the saturation delay by theoretic derivation and numerical calculating. The result shows that the saturation delay is decreasing slightly with the nodes increasing. The higher priority the AC has, less the saturation delay is.

The research model will provide a helpful and important method for the further research. The results of saturation delay from the paper are very good at QoS, especially in virtual vehicular environment. We will simulate the model with NS2 software tool to validate the proposal model availability during the following research.

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AUTHORS PROFILE

Jin TIAN was born in Jiang’an Count, Sichuan Province, the People’s Republic of China, on December 1963. He graduated and received science bachelor degree of physics from physics department, Xuzhou Normal College (now Jiangsu Normal University) on June, 1988. He studied in electronic engineering department, Southeast University from September 1993 to March 1996 and received Master degree on fiber telecommunication. He was a candidate for PhD in National Mobile Communications Research Laboratory, Southeast University from September 2003 to June 2009 and received PhD degree on mobile communications.

He worked 14 years in Nanjing Technology Center, China Potevio Co. Ltd., leading communications equipment manufacture in China. Now he is a professor, school of networks and telecommunications engineering, Jinling Institute of Technology, Nanjing, China. His papers about 40 have been published since 1995. His recent research area is MAC, cognitive radio, and WAVE.