An Analysis Model of IEEE 802.11p with Difference Services

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Abstract. Quality of Service (QoS) is a critical issue for the broadcast scheme of IEEE 802.11p systems in Vehicular Ad hoc Networks (VANETs). We present a 3-dimensional (3-D) Markov chain that the extra dimension, which models the deferring period, allows us to accurately solve for the broadcast scheme of 802.11p systems. The 3-D model solutions are validated by key simulations. Our analyses reveal that the lack of retransmission in the 802.11p system results in poor QoS performance during heavy traffic load, particularly for large VANETs.

1. Introduction

Intelligent Transportation System (ITS) is becoming a crucial part in transportation system, because it provides several key advantages compared with the old system. For example, it can detect the real-time vehicle accident problem to the driver and update the information for the related devices to take appropriate measures in time. An important infrastructure part of ITS is VANETs, which focuses on the Vehicular-to-Vehicular (V2V) and Vehicular-to-Roadside (V2R) communications.

The Wireless Access Vehicular Environment (WAVE) \cite{1} standard includes IEEE 802.11p \cite{2} and IEEE 1609 standard families. The IEEE 802.11p includes the physical layer and medium access control (MAC) layer. The EDCA technique prioritizes the transmission channel into four access categories. The biggest category has the highest priority to transmit packets for it has the shortest channel sensing time and the least contention window (CW).

However, EDCA protocol is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The vehicles must contend for transmission opportunities. So, the current multi-channel MAC protocol in WAVE standard is not fully applicable for real-time VANETs. Arbitrary interframe spacing (AIFS) has an important influence on QoS performance. Few works have been done to accurately evaluate the performance and reliability of the IEEE 802.11p EDCA broadcast. We propose a 3-D Markov chain queuing model with finite buffer under finite load in order to characterize the IEEE 802.11p QoS performance. The 3rd dimension represents AIFS character of different priority stream. AIFS on IEEE 802.11p has scarcely been researched by Markov chain and the result is not published in the literature.

The remainder of this paper is organized as follows. In section II briefly describes related proposals to analyze the performance of the WAVE. Section III the proposed analytical model is presented. Section IV provides simulation analysis on delay and queuing length. Research results are shown and discussed in Section IV. Finally, conclusions of this paper are drawn in section V.

2. Related Work

Many researches have been taken to improve the performance of WAVE. Many works only have one backoff stage to reflect and only applicable to systems with a single access category (AC) \cite{4}, \cite{5}. 

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Gallardo et al. [6], [7] proposed a model of the WAVE broadcast on the CCH but assumed an infinite MAC queue length. Meanwhile, their work did not consider the virtual collision so that all Markov chains of different priority ACs are in 1-D modeling. Yao et al. [8] establish two Markov chain models for ACs with different priorities to analyze the performance and reliability of safety-critical data broadcast on the CCH under both nonsaturated and saturated conditions. Tian et al. [9] proposed a 2-D Markov chain model, which includes backoff counter and remaining frozen time in deferral period.

Malone et al. [10] added post-backoff states to Bianchi’s model to analyze the unsaturated traffic networks under a bufferless assumption. Liu et al. [11] proposed a 3-D Markov chain model with finite buffer under unsaturated traffic load. The extra 3rd dimension models the queue length. Baozhu Li et al. [3] propose a 2-D Markov chain queuing model with finite buffer under finite load to characterize the IEEE 802.11p broadcast scheme for VANETs. In [3]'s 2-D model, the one dimension represents the backoff counter and the another dimension embodies the queuing length. All including backoff counter, queuing length and AIFS is few taken considerate into model.

3. Model and Mathematical Analysis

In the model, we assume that there are $n$ stations in a network and each station has four ACs and a frame arrival follows the Poisson process. We model the backoff procedure of each AC as the finite state 3-dimensional Markov chain under the assumption that $p$ (the transmission failure probability of the $i$-th access category AC, here only considering collision failure), is independent of the backoff procedure.

Let $n_i (i = 0, 1, 2, 3)$ denote the number of stations in the priority $i$ class. A transmitted frame collides when one more station also transmits during a slot time. The probability $p_i$, that a station for the priority $i$ class in the backoff stage senses the channel busy, is given as

$$p_i = 1 - \left[ \prod_{k=0}^{3} (1 - \tau_k)^{x_k} \right] \left( 1 - \tau \right)^{n_i - 1} \left[ \prod_{k=1}^{3} (1 - \tau_k)^{x_k} \right]$$

(1)

$q$ and $q_T$ are the probability that a packet arrives while in each backoff state and transmission state respectively. Each state of the Markov chain consists of three parameters, $(h, k, l)$, where $h$ is a queue length, $k$ is a backoff counter, and $l$ is the remaining number of slots in AIFS deferring.

Let $b_{h,k,l}$ be the stationary distribution of the proposed 3-D Markov chains and be the steady probability of state $(h, k, l)$. Then, based on the chain regularities (Fig. 1) we calculate the following steady state probabilities for the $i_{th}$ AC. The priority $i$ class responds to $n_i$, $p_i$, et al. To simple denote, the signs denote one priority with no subscript, such as $p$ instead of $p_i$. From Fig. 1 and from the normalization condition, for all $i$ we have:

Deferring period equation:

$$b_{h,k,l} = q (1 - p) b_{h-1,k,l+1} + (1 - q) (1 - p) b_{h,k,l+1}$$

$$1 \leq h \leq L, 1 \leq l \leq d - 1$$

(2a)

$$b_{0,k,l} = (1 - q) (1 - p) b_{0,k,l+1}$$

$$1 \leq k \leq W - 1, 1 \leq l \leq d - 1$$

(2b)

Node equilibrium equation:

$$\frac{1}{W} [q b_{h,0,0} + (1 - q_r) b_{h+1,0,0} + q p b_{h+1,1,0}] + (1 - q) p \left[ b_{h,k,0} + \sum_{l=1}^{d-1} b_{h,k,l} \right] = [1 - p (1 - q)] b_{h,k,l}$$

$$2 \leq h \leq L - 1$$

(3a)

$$\frac{1}{W} [q b_{h,0,0} + (1 - q_r) b_{h+1,0,0} + (1 - q) p \left[ b_{h,k,0} + \sum_{l=1}^{d-1} b_{h,k,l} \right]] = [1 - p (1 - q)] b_{h,k,l}$$

(3b)
\[
\frac{1}{W} \left[ p (1 - q) b_{0,0,0} + q b_{1,0,0} + (1 - q) b_{2,0,0} \right] + q p b_{0,1,0} \\
+ (1 - q) p \left[ b_{1,k,0} + \sum_{j=1}^{d-1} b_{1,k,j} \right] = [1 - p (1 - q)] b_{1,k,d} \\
q b_{k,1} = (1 - q) b_{0,0,0}, 1 \leq k \leq W - 1
\]

(3c)

\[
\frac{1}{W} q r q b_{L,0,0} + q p b_{L-1,k,0} + (1 - q) p [b_{L,k,0} + \sum_{j=1}^{d-1} b_{L,k,j}] \\
= [1 - p (1 - q)] b_{k,1,k,d}, 1 \leq k \leq W - 1
\]

(3d)

Backoff period equation:

\[
b_{0,k,0} = q (1 - p) b_{k-1,k+1,0} + (1 - q) (1 - p) (b_{k,k,0} + b_{k,k+1,0}) \\
1 \leq h \leq L, 1 \leq k \leq W - 2
\]

(4a)

\[
b_{0,k,0} = (1 - q) (1 - p) (b_{0,k,0} + b_{0,k+1,0}) \\
1 \leq k \leq W - 2
\]

(4b)

\[
(1 - q) b_{l,k,0} = q (1 - p) b_{l-1,k+1,0} + (1 - q) (1 - p) (b_{l+1,k,0} + b_{l,k+1,0}) \\
1 \leq k \leq W - 2
\]

(4c)

Normalization condition equation:

\[
1 = b_{0,0,0} + \sum_{k=1}^{W-1} b_{0,k,0} + \sum_{k=1}^{L} \sum_{l=1}^{W-1} b_{l,k,0} + \sum_{k=1}^{L} \sum_{l=1}^{d} \sum_{j=1}^{d-1} b_{l,k,j}
\]

(5)

Above equations allow us to calculate \(b_{0,0,0}\).

For a network with \(n\) stations we define the transmission probabilities \(\tau\) for each AC. Since the transmission attempt of AC happens at state \((h, 0, 0)\), \(\tau\) is described as

\[
\tau = q b_{0,0,0} + \sum_{k=1}^{W} b_{0,k,0}
\]

(6)

where \(L\) is the maximum queue size of AC.

Packet arrival and transmitting probability in the transmitting state onto ‘fan-out’ backoff count selectors with Queue length \(h\) is

\[
q r b_{0,0,0} + (1 - q r) b_{h+1,0,0}
\]

for \(h = 1, 2, \ldots, L - 1\)

Packet arrival probability in the deferring state is

\[
p_{d, l, f} = \sum_{r=1}^{d-1} \left( \frac{r + f}{f} \right) (1 - q)^{r^2} (1 - p)^{r^2} q f
\]

(8)

Packet arrival probability in the back-off state is

\[
p_{(h, l, f)} = \frac{1}{W} \sum_{k=1}^{W-1} \sum_{r=1}^{d} \left( \frac{r + f}{f} \right) (1 - q)^{r^2} (1 - p)^{r^2} q f
\]
\begin{align}
\begin{cases}
  h = 0, \ldots, L - 1, \\
  f = 0, \ldots, f^*.
\end{cases}
\end{align}

\begin{align}
  f^* &= \min(L - 1 - h, W - 1) \\
  P_{\mu j} &= 0, \ j = h + f + 1, \text{ otherwise, for } j \neq L + 1; \\
  p_{(L-1)k} &= \frac{W + 1}{2} - \sum_{f=1}^{L} P_{\mu j}, \text{ for } k = 1, \ldots, L + 1.
\end{align}

We define $P[Q=h]$ as the probability of the interface queue length, $Q$, being $h$ at any given time, for $h = 0, \ldots, L$. Noting that state transitions are not equally spaced, we use $P_{S}[Q = h]$, which we define as the probability of the interface queue length, $Q$, being $h$ during each $n$-station state transition, for $h = 0, \ldots, L$, to calculate $P[Q=h]$. To determine $P_{S}[Q = h]$, we also have to account for non-backoff contributions to $P_{S}[Q = h]$. 

Figure 1 Markov chain state transfer of 802.11p dealing with deferring period.

Then, including non-backoff contributions to $P_{S}[Q = h]$, which comprise being in (idle) and transmitting in (1, 0) directly after a packet arrives in (idle) and the channel is sensed ‘free’, we have progressing probability product, which is denotes
\[ P_r[Q = 0] = q b_{0,0,0} + (1 - q_s) b_{1,0,0} \quad (10a) \]

\[ h = 1,2,3,...,L - 1 \]

\[ P_r[Q = h] = \frac{1}{r_q} \left[ \sum_{i=1}^{L} P_i \left[ q b_{i-1,0,0} + (1 - q_s) b_{i,0,0} \right] \right] \quad (10b) \]

\[ P_r[Q = L] = \frac{1}{r_q} \left[ \sum_{i=1}^{L} P_i \left[ q b_{i-1,0,0} + (1 - q_s) b_{i,0,0} \right] \right] \quad (10c) \]

\[ P_s[Q = h \cap T_s] = q b_{h,0,0}, h = 0 \quad (11a) \]

\[ P_s[Q = h \cap T_s] = b_{h,0,0}, h = 1,2,...,L \quad (11b) \]

We seek solutions to the \( n \)-station system as a function of the normalised offered load, denoted \( \lambda \), which is the expected number of packets delivered to all \( n \) stations per “time for a successful transmission”. Thus:

\[ \lambda = n r_q T_s \quad (12) \]

where is the packet arrival rate per second and \( r_q \) defines \( q_T \) and \( q \) as:

\[ q_T = r_q T_s \quad ; \text{and} \]

\[ q = r_q E s|n-1 \]

To determine time-based system properties, it is necessary to convert the state probabilities into time-based probabilities. The durations are: \( \sigma \) when no station is transmitting; \( T_s \) when a successful (single) transmission occurs (from any station); and \( T_c \) when there is a collision due to two or more simultaneous transmissions. We will also need the expected time spent per Markov state for states in which the station is not transmitting.

We denote this \( E_{s|n-1} \), since, due to station independence, \( E_{s|n} \) is equivalent to \( E_s \) for an \((n - 1)\)-station system. Thus:

\[ E_{e|n-1} = P_{e|n-1} \sigma + P_{e|n-1} T_s + P_{e|n-1} T_c \quad (13) \]

where \( P_{e|n-1} = (1 - \tau)^{n-1}; P_{e|n-1} = (n - 1) \tau (1 - \tau)^{n-2}; \text{and} P_{e|n-1} = 1 - P_{e|n-1} - P_{e|n-1} \)

Weighting transmitting states by \( T_b \) and non-transmitting states by \( E_{s|n}, \) and normalizing by \( E_s \), gives \( P[Q = h] \) as:

\[ P[Q = h] \rightarrow \frac{[P_r[Q = h] - P_r[Q = h \cap T_s]] E_s + P_r[Q = h \cap T_s] P_s]}{E_s} \quad (14) \]

Then, finally, \( \overline{Q} \) is:

\[ \overline{Q} = \sum_{h=0}^{L} h P[Q = h] \quad (15) \]

The MAC delay, \( \Delta \), is the average time from a packet first reaching the head-of-the-line till successful transmission. \( \Delta_s \) denotes the average packet service time from a packet first reaching the head-of-the-
line till it leaves the system, either by successful transmission or retransmission failure. According to no retransmission and acknowledge in IEEE 802.11p, we have:

$$\Delta l = \Delta$$

To obtain $\Delta$, we first calculate the average time per state, given a positive queue length, $E_{\frac{1}{2}}$, as:

$$E_{\frac{1}{2}} = \tau (1 - p) T_s + \tau p T_c + P_{e|Q > 1} E_{\frac{1}{2} - 1}$$

where $P_{e|Q > 1}$ is the state probability of being in a backoff state with positive queue length, such that:

$$P_{e|Q > 1} = \sum_{k=1}^{L} \sum_{i=1}^{W-1} b_{k,i,0} + \sum_{k=0}^{L} \sum_{i=1}^{W-1} d_{i,k,j}$$

where $b_{0,k,0}$ is the state probability of being in state $(0, k, 0)$.

We then find the state probability of a packet leaving the system, by successful transmission, given a positive queue length:

$$P_{e|Q > 1} = \tau (1 - p) / (\tau + P_{e|Q > 1})$$

Dividing (16) by (18) gives:

$$\Delta = \Delta l = E_{\frac{1}{2}} / P_{e|Q > 1}$$

For the basic channel access, we have service time $T_s$(successful transmission) and $T_c$(collision):

$$T_s = H + L_p + \epsilon$$

$$T_c = H + L_p + \epsilon$$

where $H$ is the time occupied by the PHY and MAC headers, $L_p$ is the average time to send a DATA frame, and $\epsilon$ is the propagation delay.

$D$ is the average time from a packet first joining the input interface queue till its successful transmission.

$$D = \Delta / \sum_{h=0}^{L} h P[Q = h] + \Delta$$

The states $(L, 0, 0), \ldots (L, W-1, 0)$ represent that the queue is full. In these states, if a new packet arrives, they are blocked except for $(L, 0, 0)$; for $(L, 0, 0)$, the packet being transmitted is removed from the queue so as to allow a new arrival. Thus, the queue blocking probability,

$$P_{b} = P[Q = L] - \sum_{h=1}^{L} P_{Q = h} T_s / E_s$$

4. Simulation and Performance evaluating

Simulations were conducted in NS2 to validate the accuracy of our 3-D Markov chain deferring model. All nodes are within communication range of each other, and each node independently generates Poisson traffic with specified rate. Each simulation experiment for a particular network configuration was run for 80 seconds after a 10 second initialization. The values of interest were calculated for each
The average of the eight 10-second blocks was taken as one simulation value. The network parameters used in the simulations are given in Table I.

The simulation result is very matched to the proposed theoretical analysis because AIFS is considered. Fig. 2 shows the average queue length varying with normalized offered load for different network sizes. The queue length exhibits an almost bimodal behavior. It is close to zero before saturation, and is almost full to the buffer size when the network is saturated. The switching point from empty to full queue corresponds to the level of offered load where the network reaches saturation. The Fig. 2 shows that when the level of offered loads is contrast, the fewer node, the longer the queue.

In theory, the system delay is small if we don’t consider AIFS. The simulation result is very matched to the proposed theoretical analysis because AIFS is considered. Fig. 3 shows the average packet delay varying with normalized offered load for different network sizes. Not surprisingly, similar to the queue length in Fig. 2, the packet delay also exhibits an almost bimodal behavior. However, it is interesting that packet delay reaches different saturation levels for different network sizes: large network incur high packet delay. The reason is that there are more nodes to transmit in a large network. In such case, a node in a large network will encounter more freezes in its backoff count down than the node in a small network. Such frequent freezes prolong the packet backoff count and increase the packet media access delay. As a result, the packet delay becomes long for a large network.

| Parameter  | Value | Parameter  | Value |
|------------|-------|------------|-------|
| Slot time, δ | 20 μs | Buffer size, L | 50 |
| CW, W      | 32    | Node numbers, n | 5, 10, 20 |
| AIFS, d    | 9     | Data payload Lp | 64 bytes |
| Basic rate | 1 Mbit/s | Propagation delay, ε | 1 μs |
| Transmission rate | 1 Mbit/s | Heads, H | (144+48) bits, (30+4) bytes |

Table 1 Simulation Setting

5. Conclusion
In this paper, we proposed a 3-D Markov chain deferring model for analysing the QoS performance of the IEEE 802.11p broadcast scheme in VANETs. Our 3-D model characterizes the unsaturated traffic condition by including an idle state and post-backoff states, and integrates the queueing process with the EDCA deferring procedure. Important QoS measures were obtained and validated by key simulations. Our analytical results revealed the QoS performance degradation due to the lack of binary exponential backoff and retransmission in VANETs. Such performance deterioration can be avoided.
by proper traffic control, and our 3-D Markov chain model pointed to a traffic load threshold from which the network QoS starts to degrade. To maintain good QoS performance for VANETs, traffic control guidelines can be regulated by this threshold.

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