A Realistic Analytical Model of IEEE 802.11p for Wireless Access in Vehicular Networks

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Abstract—The IEEE 802.11p is an emerging wireless protocol dedicated for Wireless Access in the Vehicular Environment (WAVE). It employs the Enhanced Distributed Channel Access (EDCA) mechanism to access the channel. Its objective is to provide differentiated services to vehicular networks which are delay-sensitive and requires high communication throughput. In this paper, we carry out comprehensive performance analysis of the IEEE 802.11p standard. We propose a Markov chain-based analytical model that depicts accurate representation of the IEEE 802.11p MAC sub-layer. We take into account the internal collision probability that occur among different Access Categories (ACs) in the same vehicle. We also consider an unsaturated traffic condition and include the probability of finding the medium busy when sensed during the backoff period. We study the performance of the system in terms of average throughput and average time delay.

Index Terms—Markov chain, IEEE 802.11p, Unsaturated traffic, internal collision, Throughput, Delay, Performance analysis, Vehicular networks.

I. INTRODUCTION

The emerging number of applications that can be applied in the Intelligent Transportation System (ITS), the continuing growth of Electrical Vehicles (EVs) that commute on roads and the increasing need to an advanced inter-vehicle communication systems (Vehicle To Vehicle V2V) and Vehicles To Infrastructures (V2I) communication, have led to the development of a new sophisticated communication standard IEEE 802.11p [1]-[4]. In fact, the main goal of the ITS and the Vehicular Ad-hoc Network (VANET) is to provide an effective and safe transportation system, in addition to a reliable and modern traffic management platform. For example, numerous collisions related to excessive speed or to a sudden traffic stop can be avoided if the vehicles could exchange warning or safety messages at the right time, and re-routing information can be disseminated to vehicles to prevent congested routes at peak hours [5][6].

The 75 MHz Dedicated Short Range Communication (DSRC) band was allocated for inter-vehicular communication in the USA. It is composed of seven channels; each of them consists of 10 MHz of bandwidth [7]. DSRC was exploited by IEEE 802.11p to enable the V2V and V2I communication services [8]. The principle role of IEEE 802.11p is to handle the rapidly changing communication topology and to satisfy the basic requirements of the applications. These applications usually are delay-sensitive and necessitate a high reliable service. Moreover, different applications may have different priorities, for example the priority of message sent by a police car or by an ambulance supersedes the priority of any other non-urgent message transmitted by another vehicle.

The IEEE 802.11p protocol was designed and implemented based on both IEEE 802.11a [9] and IEEE 802.11e [10]. Its physical layer is similar to that of IEEE 802.11a with few modifications so it can manage the highly dynamic vehicular environment. The MAC layer of IEEE 802.11p employs an Enhanced Distributed Channel Access (EDCA) mechanism, which was adopted initially by IEEE 802.11e to support differentiated services. However some adjustments had to be applied to deal with the new network requirements. One key difference between IEEE 802.11p and IEEE 802.11e is that the former has four Access Categories (ACs) while the latter can support up to 8 ACs.

One accurate and highly effective way to study the performance of IEEE 802.11p is by developing an analytical model that translates its actual operations and functions, into mathematical equations. In this paper, we establish a complete Markov chain-based analytical model to analyze and evaluate the performance of the IEEE 802.11p. Our model is based on the standard described in [8]. We replicate the behavior of IEEE 802.11p by considering the internal collision probability between the classes that takes place within the node. We also take into account the fact that backoff counter freezes if the channel is sensed busy during the backoff stage. In addition to that, our model covers the non-saturated and the saturated mode of operation.

The remainder of this paper is organized as follows, In Section II, we present the related work. We then present our analytical model in Section III. In Section IV, we present our results and we conduct our analysis. Finally we conclude the paper in Section V.

II. RELATED WORK

In recent years, several papers have been published in the area of discrete Markov chain models of the EDCA in IEEE 802.11p [11]-[14]. We note that most of the analytical model of IEEE 802.11p found in the literature are based on the models of Bianchi [18] and Huang [19].

In [15], the authors have established a two dimensional Markov chain to analyze the performance of the EDCA mechanism in IEEE 802.11p MAC sub-layer. They have calculated the normalized throughput and the time delay of the protocol, taking into account the following factors: different
Contention Window (CW) sizes, the internal collision that occurs inside the node as a result of the internal contention among the classes, and the frozen mechanism that takes place during the backoff stage when the channel is sensed busy. Their model have proven high accuracy, however it is simulated under saturated traffic conditions, which does not actually reflects the real operation of the IEEE 802.11p. Our model assumes that the vehicle may not have packets to transmit at some periods (unsaturated mode) which replicate the actual vehicular communication environment.

In [16], the authors have tackled the communication among vehicles that handle safety and non-safety messages with priority. To achieve their goal, they have proposed a Markov chain-based model and a queuing model to evaluate the performance. Their model is quite accurate but it lacks the non-saturation assumption which is essential to duplicate the behavior of IEEE 802.11p.

In [17], an analytical model has been suggested to describe the performance of the IEEE 802.11p MAC sub-layer in V2V safety applications. A Markov chain has been created to show the performance in terms of the mean, deviation and probability distribution of the access delay. Their model have taken into account the non-saturation mode, the internal probability of collision and the probability of finding the channel busy when sensed during the backoff stage. However the study is limited to only two ACs, AC0 and AC1, while IEEE 802.11p standard defines four ACs. Our model follows the IEEE 802.11p standard, it shows the performance of all ACs described in IEEE 802.11p MAC sub-layer.

III. THE ANALYTICAL MODEL

IEEE 802.11p employs the EDCA based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) to support different priority applications through four ACs defined at the MAC sub-layer. Each AC operates as an independent Distributed Coordination Function (DCF) mechanism, and it is characterized by its specific EDCA parameters like the minimum and maximum CW size and the Arbitration Interframe Space (AIFS). These four ACs have to contend first for a Transmission Opportunity (TXOP) inside the vehicle, and the winner will then contend with ACs from different vehicles to grant the access to the medium.

To model the complete process through which the IEEE 802.11p MAC sub-layer is executed, from the point where a packet is available for transmission to the point where the packet is successfully transmitted or dropped, we use the discrete 2-D Markov chain presented in Fig. 1. In brief each AC in the IEEE 802.11p functions as the following:

1. It first waits for a packet dedicated to it.
2. It contends with other ACs for a TXOP.
3. If it succeeds, it proceeds to the backoff stage after finding the medium busy for AIFS period of time.
4. In the backoff stage, at every state the AC checks the availability of the medium. If the medium is idle for AIFS period of time, the backoff counter decrements by one. However if the medium was found busy, the backoff counter freezes and it remains in the same state.
5. Once the backoff counter reaches zero, the AC grants access to the medium and transmits its packet.
6. If the transmission is successful, the AC receives an Acknowledgment packet (ACK) and it returns back to its initial state. However if the packet experiences a collision, it returns back to the backoff stage after increasing its size, and the AC repeats the steps 4 and 5.

Before we proceed, it is very important to mention that the AIFS value decreases if the priority of the AC increases, and that the CW size of high priority AC is smaller than the one of low priority AC. This allows higher priority ACs to wait less before sensing the medium and remains in the backoff stage for shorter periods, which give them the preference in accessing the medium.

Our aim is to duplicate the exact operation described above. We incorporate the following state and probabilities in our Markov chain model:

- We use an unsaturated traffic condition, which is presented by the idle state IDLE. The probability of packet arrival from the application layer is given as θ.
- We take into account the internal collision probability which results from the ACs contention for a TXOP.
- We consider the probability of finding the channel busy when sensed during the backoff stage, which is presented by σ.

![Fig. 1 Markov chain representation of one AC.](image)

Each state in the Markov chain, except the IDLE state, is described by the couple \((s(t), b(t))\). \(b(t)\) and \(s(t)\) are stochastic processes that characterize the backoff counter and the backoff stage at time \(t\) respectively. \(b(t)\) values range from 0 to \(W_{s,i}\), and \(s(t)\) values range from 0 to \(M+f\). \(W_i\) is the backoff window size at stage \(i\), \(M\) is the maximum number of times the CW may be increased, and \(M+f\) is maximum number of times the packet transmission is retried.

The IDLE state is the starting point of the operation. Upon packet arrival from upper layers with \(θ\) probability, the corresponding AC passes to a random state in the first backoff stage after sensing the channel idle for AIFS period of time. The AC then may remain in the same state with \(σ\) probability if the channel is found busy and the backoff counter remains unchanged, or it proceeds to the next state with \((1-σ)\).
probability if the channel is sensed free for AIFS period of time and the backoff counter is decremented by 1. Once the vehicle arrives at state \((0,0)\), it transmits the packet. The next state of the AC depends on whether the packet is successfully transmitted (with probability \(1 - p_c\)) or is collided (with probability \(p_c\)). In the former, the AC returns to its initial state (IDLE), in the latter it passes to another level of backoff stage. This sequence of operation is repeated until the packet is sent with success or dropped after \(M+f\) retries, in both cases the AC goes back to IDLE state.

The transition probabilities of the backoff process are given in the following relations:

\[
P(\text{IDLE} | \text{IDLE}) = 1 - \theta
\]  
\[
P(0, k | \text{IDLE}) = \frac{\theta}{W_0} 0 \leq k \leq W_0 - 1
\]  
\[
P(i, k | \text{IDLE}) = 1 - \sigma \text{ for } 1 \leq k \leq W_i - 2, 0 \leq i \leq M + f
\]  
\[
P(i + 1, k | \text{IDLE}) = \frac{p_c}{W_i} \text{ for } 0 \leq k \leq W_i - 1, 0 \leq i \leq M + f - 1
\]  
\[
P(0, 0 | \text{IDLE}) = \frac{1 - p_c}{W_0} 0 \leq W_0 - 1, 0 \leq i \leq M + f - 1
\]  
\[
P(\text{IDLE} | M + f, 0) = 1 - \theta
\]  
\[
P(i, j | \text{IDLE}) \text{ is in fact } P(s(t+1) = i, b(t+1) = k | s(t) = k, b(t) = i) . \text{ It is the transition probability from the state } (k, l) \text{ at time } t \text{ to the state } (i, j) \text{ at time } t+1. \text{ We assume in this model that the probability of collision } p_c \text{ and the probability } \theta \text{ are the same in all backoff stages.}
\]

The first term in the set of equations (1) represents the probability of remaining in the IDLE state if no packet has been received from upper layers. The probability of switching to a random state in the first backoff stage (stage 0) from the IDLE state upon the receipt of a packet is given by the second term. The backoff counter randomly chooses a value between 0 and \(W_i - 1\). The third term depicts the situation when the vehicle detects the medium free for an AIFS time unit, the backoff counter decrements by one with a probability equal to \(1 - \sigma\). The fourth term corresponds to the condition when the vehicle finds the medium busy when sensing it. The vehicle in this case remains in the same state with probability equal to \(\sigma\). The fifth term describes the case of an unsuccessful transmission at backoff stage \(i\), and the system selects a state in the backoff stage \((i+1)\) randomly. The sixth term presents the transition probability of a successful transmission. In this case, the packet returns to the backoff stage 0 if there is a new packet ready to be transmitted. The last term means that the packet is discarded if unsuccessfully transmission happen for \(M+f\) times and the vehicle returns to the IDLE state.

Let \(b_{ij} = \lim_{t \to \infty} P(s(t) = i, b(t) = j), i \in (0, M + f), j \in (0, \max(W_i - 1))\) be the stationary probability of the state \((s(t)=i, b(t)=j)\) in the Markov chain, and let \(b_{IDLE}\) be the stationary probability of the idle state IDLE.

According to equation (1), the steady states probabilities of the first backoff stage can be derived as follows:

\[
b_{0, i} = (\sigma \times b_{0,j}) + (1 - \sigma) \times b_{0,i+1}
\]  
\[
+ \frac{1}{W_0} \left( (1 - p_c) \times \sum_{i=0}^{M+f-1} b_{i,0} + b_{M+f,0} \right) f \text{ for } 1 \leq i \leq W_0 - 2
\]  
\[
b_{0,W_0-1} = (\sigma \times b_{0,W_0-1})
\]  
\[
+ \frac{1}{W_0} \left( (1 - p_c) \times \sum_{i=0}^{M+f-1} b_{i,0} + b_{M+f,0} \right)
\]  

From equation (2) we can determine \(b_{0,i}\) as a function of \(b_{0,0}\)

\[
b_{0,i} = \frac{W_0-1}{\sigma} \times \frac{1 - p_c}{W_0} \times b_{0,0} \text{ for } 1 \leq i \leq W_0 - 1
\]  

The steady states probabilities of the other backoff stages are given by:

\[
b_{i,j} = (\sigma \times b_{i,j+1}) + (1 - \sigma) \times b_{i,j+1} + b_{i-1,0} \times \frac{p_c}{W_i}
\]  

Where \(i\) represents the backoff stage level.

Hence, \(b_{0,0} = b_{0,0} \times p_c \text{ for } 0 \leq i \leq M + f\)

And

\[
b_{i,j} = \frac{W_i-1}{\sigma} \times \frac{1 - p_c}{W_i} \times b_{i,0} \text{ for } 1 \leq i \leq M + f, 1 \leq j \leq W_i - 1
\]

As illustrated in Fig. 1, the IDLE state symbolizes the unsaturated traffic condition. We calculate \(b_{IDLE}\) by taking into account all the possible circumstances that make the system remain or return to its initial state: no packet arrival from the upper layers, successful transmission, and unsuccessful transmission for \(M+f\) times

\[
b_{IDLE} = (1 - \theta) \times b_{IDLE} + (1 - \theta) \times \sum_{i=0}^{M+f-1} (1 - p_c) \times b_{i,0} + (1 - \theta) \times b_{M+f,0}
\]

From equations (5 and 7) we calculate \(b_{IDLE}\):

\[
b_{IDLE} = \frac{1 - \theta}{\theta} \times b_{0,0}
\]

The probability conservation relation affirms that the sum of all steady state probabilities in the Markov chain is equal to one.

\[
\sum_{i=0}^{M+f} \sum_{k=0}^{W_i-1} b_{i,k} + b_{IDLE} = 1
\]

Taking into consideration equations (5, 6, 8 and 9) we calculate \(b_{0,0}\) of our model:

\[
b_{0,0} = 2 \times \frac{2 \times 1 - \theta + 1 - p_c \times M_f + 1}{1 - p_c} + W_0 \times \frac{(1 - 2 p_c M_f) - 1}{1 - 2 p_c} + W_0 \times \frac{(1 - 2 p_c M_f)}{1 - 2 p_c}
\]

Equation (10) represents the relation that determines \(b_{0,0}\) for one AC. The same computation process can be used to find \(b_{0,0}\) for all other ACs. We calculate the probability of transmission \((\tau_i)\) of each access class. \(\tau_i\) can be calculated as a function of the external collision probability \(P_{cl}\) of the same class AC. The external collision probability differ from the internal collision probability by the fact that the former takes place among vehicles as they compete for the channel access, while the latter occur among classes inside the vehicle node as they contend for TXOP.

The transmission probability of any access class is

\[
\tau_i = \sum_{i=0}^{M+f-1} b_{i,0} = b_{0,0} \times \frac{1 - p_{cl} M_f}{1 - p_{cl}} ..., i = 0, 1, 2, 3
\]
Equation (11) can be extended to form a system of four nonlinear equations; each equation corresponds to an AC. As we can see from equation (10 and 11), the transmission probability depends on the values of $\theta$, $p_{ci}$, $W_0$, and $W_M$. These variables are not the same in all classes; each AC has its own specific parameters. Our next step is to find the mathematical expressions of $\sigma_i$ and $p_{cl}$ in terms of $\tau_i$. equation (12) and Table I. show the description of AIFS and CW parameters for each AC; as described in [8].

$$AIFS[i] = T_{SIFS} + AIFS[i] \times T_{Mslots}$$  \hspace{1cm} (12)$$

### Table I. DEFAULT PARAMETERS IN IEEE 802.11P

<table>
<thead>
<tr>
<th>AC</th>
<th>CW_{min}/l</th>
<th>CW_{max}/l</th>
<th>AIFS[l]</th>
<th>CW_{min}/l</th>
<th>CW_{max}/l</th>
<th>AIFS[l]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC0</td>
<td>(CW_{min}+1)/4 - 1</td>
<td>(CW_{min}+1)/2 - 1</td>
<td>2</td>
<td>(CW_{min}+1)/4 - 1</td>
<td>CW_{min}</td>
<td>3</td>
</tr>
<tr>
<td>AC1</td>
<td>(CW_{min}+1)/4 - 1</td>
<td>CW_{min}</td>
<td>6</td>
<td>(CW_{min}+1)/2 - 1</td>
<td>CW_{min}</td>
<td>9</td>
</tr>
</tbody>
</table>

Fig. 2. EDCA Operation.

According to Fig. 2, equation (12) and Table I, an ACi experiences an internal collision only if another AC with higher probability is transmitting at the same time. It is impossible to occur with a lower priority class because it has higher probability of collision than that lower class. Based on this interpretation, it is impossible to have an internal collision for the highest priority class AC0. Because in Zone 0 (Fig. 2) no other AC will be contending with AC0 for TXOP. An internal collision of the class AC1 happens only if the class AC0 starts to transmit in zone 1 (Fig. 2), AC2 and AC3 would still be in the waiting period stage. AC2 and AC3 experiences internal collision if AC1 and AC0 transmit in zone 2, and if AC0, AC1 and AC3 transmit in zone 3 respectively. Thus the mathematical expressions of the internal collision probability are given as:

$$\begin{align*}
I_{c0} &= 0 \\
I_{c1} &= \tau_0 \\
I_{c2} &= 1 - (1 - \tau_0)(1 - \tau_1) \\
I_{c3} &= 1 - (1 - \tau_0)(1 - \tau_1)(1 - \tau_2)
\end{align*}$$  \hspace{1cm} (13)$$

The transmission probability of each class in a single station is:

$$\begin{align*}
T_{r0} &= \tau_0 \\
T_{r1} &= \tau_1(1 - \tau_0) \\
T_{r2} &= \tau_2(1 - \tau_0)(1 - \tau_1) \\
T_{r3} &= \tau_3(1 - \tau_0)(1 - \tau_1)(1 - \tau_2)
\end{align*}$$  \hspace{1cm} (14)$$

The total transmission probability of a station is then given by:

$$T_{tot} = \sum_{i=0}^{3} T_{ri}$$  \hspace{1cm} (15)$$

To calculate $\sigma_i$, we apply the following interpretation. A medium is found busy by ACi when at least one station in the same zone is transmitting or one of the ACs in the same station experiences internal collision if AC1 and AC0 transmit in Zone 0 (Fig. 2). AC0 is the only class that transmits in Zone 0, however it contends with AC1 in Zone1, and both contend in Zone3. All ACs contend in Zone 3. The general equation of $p_{cl}$ is given as: $p_{cl} = \sum_{j=1}^{4} Z_{ij} \times p_{clij}$. Where, $Z_{ij}$ is the probability to be in the zone $j$ and $p_{clij}$ is the probability of collision of ACi in zone $j$.

To determine the throughput of each access class, let $(Th_i)$ denote the average throughput of ACi in the network. $Th_i$ is calculated as the ratio of the average value of a successful transmission time of ACi to the average value of total time spent in idle state, successful transmission and failed transmission due to a collision.

$$Th_i = \frac{E_i[Succ]}{E_i[Idle]} + E_i[Col]$$  \hspace{1cm} (17)$$

$$E_i[Succ] = P_i[Succ] \times E_i[L/T] \times E_i[Idle] = P_i[Idle] \times TS$$

$$E_i[Col] = \sum_{j=1}^{4} P_i[Succ] \times T_{sj} \times E_i[Col] = P_i[Fail] \times T_{ci}$$  \hspace{1cm} (18)$$

Where $E_i[Succ]$ is the successful transmission probability of ACi, $L$ and $R$ are the packet Length and the transmission rate respectively. $P_i[Idle]$ is the channel idle probability, $TS$ denotes the duration of a timeslot. $P_i[Fail]$ is the failure probability due to a collision, $T_{sj}$ and $T_{ci}$ are the durations of the successful and unsuccessful transmission time. Every successful transmission is acknowledged by the destination. These variables are given by the following equations:

$$P_i[Succ] = \frac{N \times T_{ri} \times (1 - T_{tot})^{N-1}}{P_i[Idle]} = (1 - T_{tot})^{N-1}$$

$$P_i[Fail] = 1 - P_i[Idle] - N \times T_{tot} \times (1 - T_{tot})^{N-1}$$  \hspace{1cm} (19)$$

$$T_{si} = T_{AIFS[i]} + T_H + T_L + Delta + T_{SIFS} + T_{ACK} + Delta$$

$$T_{ci} = T_{AIFS[i]} + T_H + T_L + Delta$$

$T_{th}$, $T_{ci}$ and $Delta$ are the transmission time of the packet header, the packet payload and propagation delay respectively.
The average time delay of each class is identified as the duration between the moment when the AC starts sensing the medium once a packet arrives at head of the queue to the instant when the packet is received by the destination. Let $D_i$ denotes the time delay of $AC_i$, the average time delay is defined as the sum of the average time spent during a successful transmission and the average time spent during multiple unsuccessful transmission due to a collision. Its mathematical expression is given as:

$$E[D_i] = (E_i[\text{boff}] \times T_{\text{a}}) + (E_i[\text{Retr}] \times (E_i[\text{boff}] + T_{\text{c}}))$$

where $E_i[\text{boff}]$ and $E_i[\text{Retr}]$ are the average time spent in the backoff period and the average number of packet retransmission of the class $AC_i$ respectively.

### IV. RESULTS AND ANALYSIS

In this section, we validate our analytical model using MATLAB. We conduct a performance study in terms of throughput and average time delay for each class. We used a star topology network, where $N$ vehicles pass by the region covered by a Road Side Unit (RSU) which is the base station. We set the simulation parameters according to the IEEE 802.11p standard [8].

The evaluation of the throughput and the average time delay is carried out as a function of different packet arrival probabilities (from 0.1 to 1). In addition to that, we study the impact of changing the packet length ($L$) (from 512 B to 1024 B) on the performance. Throughout our simulations, we assume that the network is composed of 50 vehicles.

Fig. 3 shows the changes of the average throughput of the network for all ACs versus the probability of packet arrival. Two cases are studied: $L = 512$ B and $L = 1024$ B. We notice that the numerical value of the throughput of the higher priority classes is always higher than those of the lower priority classes. In addition to that, with a fixed $L$ the throughput of all classes decreases with the increasing probability of packet arrival. This is true, because with more packets arriving from higher layers, the contention increases which may cause packet collisions and thus decreases the throughput. We also notice that the throughput of the lower classes reach almost the zero value when $L = 512$ B, that is because higher classes have the preference in accessing the channel before the lower classes as we already have described in the analytical model. Fig. 3 shows that the throughput of all ACs is enhanced with larger packet size. In fact equation (17) shows that the throughput is directly proportion to the average value of $L/R$. Therefore, with bigger packet payload, the throughput is improved.

Fig. 3(a) shows that the numerical value of the throughput of the highest priority class $AC_0$ drops much slower than those of other classes (illustrated in Fig. 3(b), (c) and (d)). This is due to the fact that no other class compete with $AC_0$ for TXOP while $AC_0$ contend with all other classes for TXOP. Fig. 3(c) and Fig. 3(d) show the throughput performance of $AC_2$ and $AC_3$. These results are anticipated because as we have presented in our mathematical model, the AIFS and the CW of $AC_2$ and $AC_3$ are bigger than those of $AC_0$ and $AC_1$ which means they wait much longer before launching the backoff procedure, their backoff window is much bigger.

Fig. 4 presents the average time delay versus the packet arrival probabilities for two different values of $L$. It shows that the average delay experienced by the high priority classes is much lower than the one experienced by the lower priority classes. This takes place because $AC_2$ and $AC_3$ have higher internal collision rate compared to $AC_0$ and $AC_1$, their AIFS value is bigger and their CW is larger. That means they stay longer to have a TXOP, they wait more before the backoff stage and their backoff windowe is larger. Fig. 4 demonstrates that all ACs experienced higher delays with higher packet arrival probability. In fact additional packet means extra competetions, more collisions and higher packet retransmission rates which lead to further delay. By doubling the packet payload size, the delay across all classes increases proportionally. This results is expected, because increasing the packet size will increase the packet transmission time, raise the external probability of collision in the medium and the vehicle then returns back to the backoff stage which has a larger size.

### V. CONCLUSIONS

The MAC sub-layer of IEEE 802.11p protocol is optimized to increase the performance of wireless vehicular communications. It offers four levels of access priority that can be assigned to different applications with different Quality of Service (QoS) requirements.

In this paper, we proposed a realistic analytical model that duplicates the operation of IEEE 802.11p EDCA; we took into account the unsaturated traffic condition, the internal collision probability among different classes in a single vehicle and the probability of finding the channel busy when sensed during the backoff stage. We conducted performance analysis for the four ACs, in terms of the average throughput and the average time delay. Our results show that the throughput is greatly dependent on the size of the packet size across all the classes. However, with higher rate packet arrival rate from the upper layers, the throughput decreases due to the additional contention and to the high packet collision probability. Our findings also show that the higher priority classes experience lower average delay compared to the lower priority classes. In addition to that the delay increases with the increase of packet arrival rate due to the collision and the time spent in retransmission. Based on that, the network designer can optimize the network performance depending on the application type and the delay requirements.

As a future work, we intend to introduce the effect of the hidden nodes and the non-ideal channel which cause the drop of the packet due to channel error in the mathematical model.
REFERENCES


Fig. 3. Average throughput of each AC
(a) Average Throughput of AC0, (b) Average Throughput of AC1
(c) Average Throughput of AC2, (d) Average Throughput of AC3

Fig. 4. Average time delay of each AC
(a) Average time delay AC0, (b) Average time delay AC1
(c) Average time delay AC2, (d) Average time delay AC3

Fig. 5. Average packet delay of each AC
(a) Average packet delay AC0, (b) Average packet delay AC1
(c) Average packet delay AC2, (d) Average packet delay AC3