Abstract — Since IEEE 802.11p has been adopted as Vehicular Ad hoc Networks (VANET) main technology, the research and development of vehicular safety applications has gained momentum. Because broadcasting is the predominant traffic type in VANETs, their safety applications will face a challenge in managing the channel capacity to insure good performance in terms of throughput, delay, fairness and broadcast coverage. In this paper we analyze the performance of the broadcast scheme of IEEE 802.11p standard analytically and verify the model by simulation. We then derive the optimal values of its parameters considering the probability of packets successful reception, throughput, delay and collision probability in a harsh vehicular environment.

Keywords: VANET, MAC, Broadcast, DSRC, Simulation.

I. INTRODUCTION AND RELATED WORK

The research in VANETs is driven by the Dedicated Short Range Communications (DSRC) or IEEE 802.11p technology [1] which is intended to enhance the IEEE 802.11 to support the Intelligent Transportation System applications where reliability and low latency are crucial. These applications are intended to help drivers to travel more safely and reduce the number of fatalities due to road accidents. The IEEE 802.11p MAC layer is equivalent to the Enhanced Distribution Coordination Function (EDCF) IEEE 802.11e that has four different access classes (ACs). Each AC has a queue where messages from different applications are queued based on their priorities. The packets from different ACs will contend internally and the winner will contend externally with other vehicles in the network for the channel use. It is clear that warning messages within safety-related applications will use AC3 since it has the highest priority based on the contention parameters of the control channel (CCH) listed in Table 1. Each class has different Arbitration Inter Frame Space Number (AIFS) to insure less waiting time for high priority class.

Table 1: Contention parameters for IEEE802.11p CCH [1]

<table>
<thead>
<tr>
<th>AC No.</th>
<th>Access Class</th>
<th>L.Min</th>
<th>L.Max</th>
<th>AIFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Background Traffic (BK)</td>
<td>15</td>
<td>1023</td>
<td>9</td>
</tr>
<tr>
<td>1</td>
<td>Best Effort (BE)</td>
<td>7</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>Voice (VO)</td>
<td>3</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>Video (VI)</td>
<td>3</td>
<td>7</td>
<td>2</td>
</tr>
</tbody>
</table>

VANETs’ safety applications will rely on broadcasting as the major block for localization, routing and dissemination of safety and warning messages to all vehicles in their neighborhood. Vehicles will be equipped with sensors and GPS systems to collect information about their position, speed, acceleration and direction to be broadcasted to all vehicles within their range. Upon receiving and processing this information, vehicles will detect and avoid potential dangers. In IEEE 802.11p, vehicles will not send an acknowledgement (ACK) for the received broadcast messages. Therefore, the transmitter could not detect the failure of the packet’s reception and hence will not retransmit the packet. This is a serious problem in collision warning applications where all vehicles behind the accident have to receive the warning message successfully in a short time to avoid chain collisions.

In the literature, there are many studies that investigated the DSRC [1] performance, for example [2]-[6]. The authors in [2] and [3] studied the effects of radio propagation models in VANETs based on the probability of successful reception rate. In [4] the authors analyzed the system using the average delay for each access class and did not take into account the back-off delay. In [5], the authors proposed a method to control the load of periodic messages to insure the successful reception of warning messages. However, all these analysis and observations are mainly based on simulation. In [6], the authors provided an analytical model for the impact of the hidden terminals in multi-hop networks using a two state Markov chain. In [7], the authors introduced a one dimensional Markov chain to calculate the delay and reception rate but did not include the time delay in each stage due to busy channel. The authors in [8] and [9] analyzed the EDCA while Bianchi in [10] analyzed the IEEE 802.11 for unicast communication. Although, WAVE protocol is based on IEEE 802.11 and EDCA, their analytical models for performance evaluation of unicast communications cannot be used for the analysis of broadcast communication mode in IEEE 802.11p where no ACK will be sent by any of the recipients. Therefore, the transmitter could not detect a collision from a successful transmission. This gives more chance for the current transmitter to take control of the channel if it has more packets to send after a DIFS time while other stations are freezing their back-off counter. This phenomenon is known as consecutive freezing process (CFP). In [11], the authors studied the saturation performance of the broadcast scheme in IEEE 802.11.

In this paper, in contrast to previous models where saturation conditions, ideal channel and no hidden terminal problem are assumed, we propose an analytical model for the analysis of broadcast services in DSRC protocol. More specifically, two Markov chains are used to derive the probabilities of transmitting status and emergency packets. We also include the probability of busy channel and the traffic priority to derive the collision free and interfering probabilities from vehicles within the range and hidden terminal areas respectively. From these probabilities and the packet error free probability we derive the probability of packets’ successful reception in order to derive the optimal values for the recommended maximum range, data rate, message size and frequency. We validate our analytical results by simulation using ns2.33 [12].
II. SYSTEM MODEL AND PERFORMANCE PARAMETERS

In VANETs safety applications, vehicles broadcast two types of messages: warning (event driven) and status messages. While warning messages usually contain dangerous information, status messages are sent periodically to all vehicles within their range and contain vehicle’s state information such as speed, acceleration, direction and position. Therefore, emergency messages will use AC3 since it has the highest priority as listed in Table 1 while status message will use AC0.

Each AC will choose uniformly and randomly a contention window \((W_c)\) first from \((0-\text{CW}_{\text{min}})\) and will wait for \((\text{AIFS}_{\text{N}} + W_c)\) before it can use the channel, where \(t_s = 16\mu s\) is the time slot \([1]\). The vehicle will decrement this counter \((\text{AIFS}_{\text{N}} + W_c)\) if it senses an idle channel in any time slot, halt otherwise, and reactivate when the channel is sensed idle again in a new time slot.

We built our model based on a highway scenario. Since the communication range is much larger than the road’s width, we simplify the network in each direction as one dimensional mobile ad hoc network as shown in Fig. 1. We assume that vehicles have a Poisson distribution with average rate of \(\beta\) vehicles/m in each direction of the road. Therefore, the number of vehicles within the range of a tagged vehicle is \(N_b = 4/3R\) and the number of vehicles in the two hidden terminal areas is \(N_h = 4/3R\).

\[\text{Fig. 1: Simplified one dimensional highway scenario.}\]

In our model, vehicles send status and emergency packets according to a Poisson distribution with average rates \(\lambda_s\) and \(\lambda_e\) respectively. We assume that all packets have the same length \(L\) bits and all vehicles have the same transmission range \((R)\). All vehicles within this range will hear the transmission while vehicles outside this range will not since the received signal level is less than \(R_{\text{STh}}\) threshold. In the following, we analyze different parameters that affect the IEEE802.11p performance:

A. Back-off Process and Contention Window

To construct a model for the back-off counter process, we model each vehicle as a two independent \((M/G/1)\) process machines: one for emergency and the other for status packets. If a vehicle initially has a packet and sensed a free channel for \(\text{AIFS}_{\text{N}}\) \(\times t_s\), it will broadcast it, otherwise it will select a contention window from \((0-\text{CW}_{\text{min}})\) when \(\text{CW}_{\text{min}}\) is the minimum contention window specified in Table 1 for the specified class AC3 or AC0. The process will decrement the back-off counter with probability \((1-p)\) if it senses an idle channel in any time slot; otherwise it will halt the counter for the whole period of the ongoing transmission \((T_s = L/R_d + \text{TDFS} + \delta)\), where \(\delta\) is the channel propagation delay, \(R_d\) is the data rate and \(\text{TDFS}\) is the Distributed Coordination Function Inter Frame Space time. When the back-off timer reaches zero state the vehicle will broadcast the packet.

Fig. 2 shows the Markov chain for both emergency and status processes. We define \(b_k \in \{0, W_{\text{min}}\}\) as the random process for each queue, where \(W_{\text{min}} = W_s\) and \(W_e\) for emergency and status processes respectively. We assume that the back-off counter will stay at the same state \(b_k\) with probability \(p\) if it senses a busy channel. This is a conditional busy channel probability seen by a packet about to be transmitted and independent from other vehicles on the road.

\[\text{Fig. 2: Emergency and status packets Markov chain.}\]

From the stationary distribution of the Markov chain in Fig. 2, we derive the following relationships: Let \(b_k\) denote the probability that the process is in state \((k)\), then we can solve the discrete Markov chain as follows:

\[\begin{align*}
  b_k &= \frac{W_e - k}{W_e - 1} - p \cdot b_0, \quad 1 \leq k \leq (W_e - 1) \\
  b_0 &= \frac{2(1-p)}{2 - 3p + pW_e}. 
\end{align*} \tag{1}\]

By using \((1)\) and the normalized condition \(1 = \sum_{k=0}^{W_e-1} b_k\), we can solve for \(b_0\) as follows:

\[b_0 = \frac{2(1-p)}{2 - 3p + pW_e}. \tag{2}\]

To derive the probability \(\tau_s\) that a vehicle transmits an emergency packet in a randomly selected slot: First the vehicle has to have an emergency packet ready for transmission. Second, it will transmit this packet only when the back-off counter is in or reaches zero state \(b_0\) with probability of \((1-p)\):

\[\tau_s = \frac{2(1-p)^2}{2 + pW_e - 3p} \left(1 - e^{-\lambda_e \tau_s}\right), \tag{3}\]

where \(T_{ss}\) is the average service time needed to transmit the packet since it is arrived.

For status packets, we can derive \(\tau_s\) the probability that a vehicle will transmit a status packet in a randomly selected slot as when the vehicle has a status packet in the queue ready for transmission and no emergency packets arrived so far:

\[\tau_s = \frac{2(1-p)^2}{2 + pW_e - 3p} \left(1 - e^{-\lambda_s \tau_s}\right) \left(1 - e^{-\lambda_e \tau_s}\right), \tag{4}\]

where \(T_{ss}\) is the average service time for the status packet to be sent on the channel since it is arrived and will be derived in the delay section.

To find \(p\), we know that the channel is sensed busy by the tagged vehicle if there is at least one vehicle within its transmission range is transmitting either an emergency or status packet in the same time slot. Therefore we can express \(p\) as:

\[p = 1 - \sum_{i=0}^{\infty} (1 - \tau_e - \tau_s)^i (N_i - 1)! e^{-\lambda_e} e^{-\lambda_s} = 1 - e^{-(N_i - 1)(\tau_e + \tau_s)}. \tag{5}\]

To solve \((3)\), \((4)\) and \((5)\), we used Newton-Raphson technique for solving non linear systems. The system has a unique solution in the range of \(p \in [0, 1]\) as we will show in the analysis section.

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B. Delay

The average status packet’s time delay $T_{ss} = T_{eq} + E[T_e] + T_t$ includes the time delay due to back-off process $T_{eq}$, transmission time $T_t = \frac{1}{G} + T_{\text{DIFS}} + \delta$ and queuing delay $T_{eq}$. The average time delay $T_{eq}$ and its second moment that a status packet encounters due to the back-off process can be derived from the Markov chain in Fig. 2 as:

$$E \left[ T_{eq} \right] = \sum_{i=0}^{W_e-1} \frac{p}{W_e} \sum_{k=0}^{i} (pT_t) = \frac{p^2 T_t(W_e - 1)}{2}. \quad (6)$$

$$E \left[ T_{eq}^2 \right] = \sum_{i=0}^{W_e-1} \frac{p}{W_e} \left( \sum_{k=0}^{i} (pT_t) \right)^2 = \frac{p^3 T_t^2(W_e - 1)(2W_e - 1)}{6}. \quad (7)$$

From (6) and (7), we calculate the average status packet’s service time $T_{s\text{serv}} = E[T_{eq}] + T_t$ and its second moment as $E[T_{s\text{serv}}^2] = E[(T_{eq} + T_t)^2]$.

We follow the same approach to derive the average emergency packet’s time delay $T_{se} = T_{eq} + E[T_e] + T_t$. The emergency packets’ service time is $T_{s\text{serv}} = E[T_{eq}] + T_t$ and its second moment $E \left[ T_{s\text{serv}}^2 \right] = E[(T_{eq} + T_t)^2]$, where $E[T_{eq}]$ is the back-off delay for emergency packets and can be derived as in the status packets case:

$$E[T_{eq}] = \sum_{i=0}^{W_e-1} \frac{p}{W_e} \sum_{k=0}^{i} (pT_t) = \frac{p^2 T_t(W_e - 1)}{2}. \quad (8)$$

$$E \left[ T_{eq}^2 \right] = \sum_{i=0}^{W_e-1} \frac{p}{W_e} \left( \sum_{k=0}^{i} (pT_t) \right)^2 = \frac{p^3 T_t^2(W_e - 1)(2W_e - 1)}{6}. \quad (9)$$

For the system to be stable, we need to make sure that the total load $\rho = (\lambda_e T_{s\text{serv}} + \lambda_s T_{s\text{serv}}) < 1$, hence we can derive the queuing delay $T_{eq}$ for emergency and status packets respectively as in Pollaczek-Khintchine formula [13]:

$$T_{eq} = \frac{\lambda_e E \left[ T_{s\text{serv}}^2 \right]}{2(1 - \lambda_e T_{s\text{serv}})}. \quad (10)$$

$$T_{eq} = \frac{\lambda_s E \left[ T_{s\text{serv}}^2 \right]}{2(1 - \lambda_s T_{s\text{serv}})}. \quad (11)$$

C. Collision Probability

The collision probability $P_{\text{coll}}$ is the probability that at least two or more vehicles start transmitting at the same time slot. To find $P_{\text{coll}}$, we need first to find the busy time probability $P_{\text{busy}}$ which is the probability that at least one vehicle is using the channel at the same time slot. Since there are $(4R)$ vehicles contend for the channel and each vehicle transmits emergency and status packets with probability $\tau_e$ and $\tau_s$ respectively, then:

$$P_{\text{busy}} = 1 - (1 - \tau_e - \tau_s)(4R). \quad (12)$$

Now, the probability $P_{T}$ that only one vehicle is using the channel conditioned on $P_{\text{busy}}$ is:

$$P_{T} = \frac{4R(\tau_e + \tau_s)(1 - \tau_e - \tau_s)(4R - 1)}{P_{\text{busy}}}. \quad (13)$$

Therefore, the collision probability $P_{\text{coll}}$ is when the channel is busy and more than one vehicle is transmitting:

$$P_{\text{coll}} = P_{\text{busy}} \times (1 - P_{T}). \quad (14)$$

D. Probability of Successful Reception

To determine that the transmitted packet by the tagged vehicle is received successfully by any other vehicles within its range $R$, we have to make sure of the following: 1) no vehicle within the tagged vehicle’s range transmits at the same time slot in which it is transmitting; 2) no vehicle within the interfering areas will transmit within double of the transmission period $2T_t$ since the un-slotted CSMA needs both the current and the previous transmission periods to be quiet for successful reception from the recipient; 3) the received signals are higher than the threshold $R_{e\text{TX}}$, and the packet is error free. Putting all three conditions together, we can write the probability of successful reception $P_{\text{suc}}$ as:

$$P_{\text{suc}} = \sum_{i=0}^{\infty} (1 - \tau_e - \tau_s)(4R - i) \frac{e^{-(4R - i)}}{i!} \left( \sum_{i=0}^{\infty} (1 - \tau_e - \tau_s)(4R - i) \frac{e^{-(4R - i)}}{i!} \right)^{2T_t}$$

$$= (1 - P_{T}) e^{-2T_t(\tau_e + \tau_s)(4R - 1)(1 + 2\tau_e)} \quad (15)$$

where $P_b$ is the bit error rate, $T_v = \frac{T_s}{\tau_e + \tau_s + \frac{2}{\lambda_e T_{s\text{serv}}} + \frac{1}{\lambda_e T_{s\text{serv}}}}$ is the average vulnerable period since we used the average service time to derive $\tau_e$ and $\tau_s$. This probability expresses the reliability of the designed system. The higher the success rate, the more vehicles will receive the emergency and status packets successfully which will increase the drivers’ awareness of potential dangers on the road ahead.

E. Throughput

We define the normalized throughput as in [10] by the time the vehicle spends on successfully transmitting a payload information in a single time slot $\sigma$ divided by the average length of the time slot. In each time slot the channel could be free, busy due to a collision or busy due to successful transmission. The time the channel is sensed free is $(1 - P_{\text{busy}})\sigma$ while the time the channel is busy due to collision is $P_{\text{coll}}T_t$, where $T_t$ is the time needed for transmitting a packet (data and headers). The time spent on successfully transmitting the packet is $P_{T} \times P_{\text{busy}} \times T_t$ while the time spent on successfully transmitting the payload (data) is $P_{T} \times P_{\text{busy}} \times T_{data}$, where $T_{data} = \frac{\text{no. of data bits}}{R_{data}}$ is the time needed to transmit the information payload.

In contrast to Bianchi in [10], where it is assumed that all transmitted packets are received successfully, we include the probability of successful reception $P_{\text{suc}}$. Since not all transmitted data will be received successfully by all recipients. Therefore, we can derive the throughput $S$ as:

$$S = \frac{P_T \cdot P_{\text{busy}} \cdot T_{data}}{(1 - P_{\text{busy}})\sigma + P_{\text{coll}}T_t + P_T \cdot P_{\text{busy}} \cdot T_t \cdot P_{\text{suc}}} \quad (16)$$

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Table 2: Value of parameters used in simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation and Data rate</td>
<td>BPSK, 3 Mbps</td>
</tr>
<tr>
<td>Message and Header sizes</td>
<td>500, 64 Bytes</td>
</tr>
<tr>
<td>Emergency packets rate $\lambda_e$</td>
<td>1</td>
</tr>
<tr>
<td>Status packets rate $\lambda_s$</td>
<td>5</td>
</tr>
<tr>
<td>Communication range $R$</td>
<td>400</td>
</tr>
<tr>
<td>Transmission power $P_t$</td>
<td>1e-3 W</td>
</tr>
<tr>
<td>Received power threshold $R_{TH}$</td>
<td>3.162e-13</td>
</tr>
<tr>
<td>Noise-floor $N_0$</td>
<td>1.26e-14</td>
</tr>
<tr>
<td>$T_{tx}$ &amp; $T_{rx}$ antenna heights</td>
<td>1.5 m</td>
</tr>
<tr>
<td>$T_{tx}$ &amp; $T_{rx}$ antenna Gain $G_t = G_r$</td>
<td>4</td>
</tr>
<tr>
<td>DIFS</td>
<td>64 $\mu$s</td>
</tr>
</tbody>
</table>

III. MODEL VALIDATION AND ANALYSIS

To validate our model, we used ns2 [12], the well known simulator in analyzing VANETs. Our simulation scenario is built on a bi-directional highway segment of length 4000 m and 4 lanes in each direction. The vehicles’ speed ranges from 80 – 120 km/h. Each vehicle is sending two types of messages: status and emergency messages. We built our model using MOVE [14] which is using SUMO [15] mobility models. We used the Nakagami-m propagation model with configuration parameters as in [16]. Table 2 lists the simulation parameters used unless a change is mentioned explicitly.

Fig. 3a shows the successful rate and normalized throughput versus range $R$, while Fig. 3b shows the time delay for both emergency and status packets for vehicles density $\beta = 0.1$. We can see as the successful rate decreases, the emergency and status packets delay increases dramatically starting at certain distance $R = 200$m. This critical distance is when the throughput $S$ reaches its maximum. This is the recommended maximum range that can be used to keep the delay as low as possible while achieving maximum throughput by reducing the impact of the hidden terminals and collisions.

Fig. 3c shows the recommended maximum range with 90% constraint on successful rate versus vehicles density. This is a reasonable percentage, since if we demand higher successful rate, the communication range must be reduced further which will have a bad impact on the delay performance. It is obvious, as vehicles density increases, the one hop range has to be decreased in order to decrease the number of collisions, the interfering traffic and the delay that packets suffer while waiting for a free channel to transmit. It is clear that the analytical model is accurate since the analytical results (curves) coincide with the simulation results (markers).

To find the impact of the used data rate on the system performance, we used the standard mandatory data rates 3Mbps, 6Mbps and 12Mbps with their respective modulation schemes BPSK, QPSK and 16QAM as specified in the standard [1] with their threshold powers $R_{TH} = -85dB$, $-82dB$ and $-77dB$ respectively. Figs. 4a, 4b and 4c show the success rate, throughput and channel waste time due to collisions as a function of vehicles density respectively. We can see the 6Mbps accounts for the highest successful rate while the 12Mbps has the lowest since 16QAM has the highest bit error rate compared with BPSK and QPSK. Moreover, as the data rate increases, the number of collisions in the channel will decrease as shown in Fig. 4c and as a consequence the throughput will decrease since the channel will be more likely to be free as shown in Fig. 4b. It is obvious that the 6Mbps accounts for the best performance in high dense networks in terms of throughput and successful reception rate.

Fig. 5a, 5b and 5c show the success rate, throughput and waste channel as a function of vehicles density for different packet sizes. We can see the longer the packet size is the lower the success rate will be, due to the increase of interfering traffic from hidden terminal areas and the increase in number of collisions as in Fig. 5c. It is clear from Fig. 5b that the medium packet size (500Bytes) outperforms the others due to the decrease in the time the hidden terminal areas traffic may interfere with the packet transmission and the decrease in the number of collisions compared with 250Bytes packets. At the same time, using the medium size packet results in using the channel more efficiently since it reduces the time the channel is free compared to the (1000Bytes) packets.

IV. CONCLUSION

In this paper, we presented an analytical model to compute the successful reception rate, collision probability and throughput of IEEE 802.11p within VANETs safety applications. We model each vehicle as two one-dimensional Markov chains from which we calculate the transmission probabilities of both the status and emergency packets. We showed analytically and by simulation the recommended maximum range that can be used in certain conditions to achieve certain successful rate, maximize the throughput and minimize the time the emergency packets need to reach the vehicles within the neighborhood. Our simulation results show that the model is accurate in calculating the recommended maximum range, throughput and time delay for both emergency and status packets.

REFERENCES


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Figure 3: (a) Successful rate and Throughput. (b) Time delay for emergency and status packets. (c) Communication range.

Figure 4: Impact of data rate versus vehicles density. (a) Successful rate. (b) Normalized throughput. (c) Channel waste percentage.

Figure 5: Impact of packet size versus vehicles density. (a) Successful rate. (b) Normalized throughput. (c) Channel waste percentage.