Performance Evaluation for DSRC Vehicular Safety Communication

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Abstract— In this paper, an analytic model is proposed for performance evaluation of vehicular safety related services in dedicated short range communications (DSRC) system on highway. The generation and service of safety messages in each vehicle is modeled by an M/G/1 queue. But since vehicles share a medium, the service time distribution of a message needs to take contention and backoff into account. We develop a detailed semi-Markov process model to capture these effects. Furthermore, this SMP interacts with the M/G/1 queue. We use fixed point iteration to capture this interaction. Based on the fixed-point solution, performance indices including transmission delay, packet delivery ratio (PDR) are derived. Analytic-numeric results are verified through extensive simulations under various network parameters.

Keywords-VANET; analytic model; SMP model; safety message; performance evaluation; DSRC;

I. INTRODUCTION

Inter-Vehicle Communication (IVC), as a vital part of Intelligent Transportation System (ITS) [1], has been extensively researched in the recent years. In the vehicular ad hoc network (VANET), the transportation safety is one of the most crucial features needed to be addressed. Safety applications usually demand direct vehicle-to-vehicle ad hoc communication due to highly dynamic network topology and strict delay requirements. Such direct safety communication will involve a broadcast service because safety information can be beneficial to all vehicles around a sender. Broadcasting safety messages is one of the fundamental services in DSRC [1], which is adopted by IEEE and ASTM.

The performance of vehicular safety communication in DSRC system has been studied in [2][3][4]. However, the evaluations are mainly based on simulations. The analytic models based on discrete time Markov chain (DTMC) are developed in [5][6][7] to analyze the performance of the broadcast service incorporating the backoff counter process, hidden terminals and message generation interval. Nevertheless, these cited papers conduct performance assessments in a discrete time fashion by synchronizing system behavior to unit time slot, which will lead to some approximations in the results. In addition, according to 802.11 DSRC MAC layer protocol, a vehicle can directly transmit a packet without going through backoff process. Such phenomena has been ignored in the previous work [5][6][7] which will result in further approximations.

In this paper, we develop more accurate analytic models based on semi-Markov process (SMP) [8][9] for performance evaluation of the broadcast service in DSRC safety communication system. Fixed point iteration algorithm [10] is applied to derive the converged solution in the steady state. New approaches to calculate the transmission delay of safety related messages and PDR utilizing the feature of SMP models are also developed in this paper. The analytic results are verified by simulations.

This paper is organized as follows. Section II briefly describes the system behavior in 802.11 MAC layer protocol and assumption in the system to produce a simplified model. Section III presents the analytic models and the fixed point iteration algorithm. Based on the results, performance indices include delay and PDR are derived in Section IV. The analytic and simulation results are compared in Section V. Conclusion is presented in the last section.

II. SYSTEM DESCRIPTION

A. Broadcast protocol

In the 802.11 MAC protocol [11], distributed coordinate function (DCF) is the primary medium access control technique for broadcast services. This section briefly explains the basic access mechanism of DCF.

Each vehicle in the network can occasionally generate safety related packets and compete for the channel resource to transmit the packet. For a newly generated packet in a vehicle, the vehicle senses the channel activity before it starts to transmit the packet. If the channel is sensed idle for a time period of distributed inter-frame space (DIFS), the packet can be directly transmitted. Otherwise, the vehicle continues to monitor the channel until channel is detected to be idle for DIFS time period. Subsequently, according to the collision avoidance feature of the protocol, the vehicle generates an initial random backoff counter and goes through the backoff process before transmitting the packet. Moreover, a vehicle must go through the backoff process between two consecutive packets transmission even if the channel is sensed idle for the duration of DIFS time for the second packet. Therefore, a packet can directly transmit without going through the backoff process only when the following two conditions are satisfied:

- The packet is generated when the queue is empty;
- The channel is sensed idle for DIFS time period starting from the time instant that the packet is generated;

Regarding to the backoff process for a packet transmission, the initial backoff counter is chosen randomly from a uniform density over the range \((0, W_{\text{b}}I)\), where \(W_{\text{b}}\) is the backoff window size. The backoff time counter is decreased by one if the channel is sensed idle for a time slot.
\[ \begin{align*}
\sigma \text{. The counter is “frozen” when channel is sensed busy and reactivated when the channel is sensed idle again for more than the DIFS duration. The packet is transmitted as soon as the backoff counter reaches zero.}
\end{align*} \]

In broadcast services, the transmitting vehicle does not receive any feedback from the receivers and will not retransmit a packet. The detailed descriptions for IEEE 802.11 standard can be found in [11].

### B. System assumptions

Several assumptions are made in the broadcast system to produce a simplified yet a high fidelity model.

- The vehicle ad hoc network is considered to be one-dimensional. The number of vehicles in a lane is Poisson distributed with parameter \( \beta \) (vehicle density), i.e., the probability \( P(i, \ell) \) of finding \( i \) vehicles in a lane of length of \( \ell \) is given by:

\[
P(i, \ell) = \frac{(\beta \ell)^i}{i!} e^{-\beta \ell}
\]

- All vehicles have the same transmission range as well as receiving range \( R \).
- Each vehicle is assumed to generate packets as a Poisson stream with rate \( \lambda \) (packets per second).
- Each vehicle has an infinite queue to store the packets at the MAC layer. Hence, each vehicle can be modeled as an M/G/1 queue.

Due to the contention medium, the overall problem can be seen as a set of interacting M/G/1 queues. We simplify the problem by developing an SMP model for the tagged vehicle that does not directly keep track of the queued requests channel contention. This SMP model interacts with the M/G/1 queue hence we need to use fixed-point iteration to solve the overall model.

### III. ANALYTIC MODELS

#### A. SMP model

The behavior of a tagged vehicle for packet transmission can be characterized using the SMP model shown in Figure 1. The tagged vehicle is in idle state if there is no packet in its queue. After a packet is generated, the vehicle senses channel activity for DIFS time period. If channel is detected to be busy during this period (with probability \( p_b \)), the vehicle will go from idle to XMT state and wait for a new incoming packet. If there are packets left in the queue after a packet transmission (with probability \( \rho \)), the vehicle will sense the channel again for DIFS time and then randomly choose a backoff counter before transmitting the next packet.

Define the sojourn time in state \( j \) as \( T_j \). The mean and variance of \( T_j \) in the SMP model are:

\[
E[T_j] = \tau_j = \begin{cases}
\sigma & j = 0, 1, 2, \ldots, W_0 - 1 \\
T & j = D_0, D_1, \ldots, D_{w_2} \\
1 / \lambda + \text{DIFS} & j = \text{idle}
\end{cases}
\]

\[
\text{Var}[T_j] = \theta_j^2 = \begin{cases}
0 & j = 0, 1, 2, \ldots, W_0 - 1 \\
\text{Var}[PA] & j = \text{XMT} \\
1 / \lambda^2 & j = \text{idle}
\end{cases}
\]

where \( T = E[PA] + T_D + \text{DIFS} + \delta \). The mean and variance of the packet length are \( E[PA] \) and \( \text{Var}[PA] \) respectively. \( T_D \) presents the packet header including physical layer header and MAC layer header. \( \delta \) is the propagation delay.

For the model in Figure 1, the embedded DTMC is first solved for its steady-state probabilities:

\[
\nu_j = \begin{cases}
(W_0 - j) \cdot \nu_{w_1, j} & j = 0, 1, 2, \ldots, W_0 - 1 \\
(W_0 - j - 1) \cdot p_b \cdot \nu_{w_1, j} & j = D_0, D_1, \ldots, D_{w_2} \\
\frac{W_0}{\rho + q_b (1-\rho)} \cdot \nu_{w_1, j} & j = \text{XMT} \\
\frac{(1-\rho)W_0}{\rho + q_b (1-\rho)} \cdot \nu_{w_1, j} & j = \text{idle}
\end{cases}
\]

\[
\nu_{w_1, j} = \frac{2(\rho + q_b (1-\rho))}{W_0 + 1 + p_b(W_0 - 1) + \rho + q_b (1-\rho)} W_0 + 2(2 - \rho)W_0
\]

Taking into account the mean sojourn time in each state, the steady-state probabilities of the semi-Markov process are given by:

\[
\pi_j = \sum \nu_j \tau_j
\]

Therefore, the steady-state probability that a vehicle is in the XMT state is given by:
that a packet starts its service from state $i$ instead of $0$ as specified in the model, we correct the mean of $\sigma$ in the results.

The service time for a packet transmission starting from state $i$ is given by:

$$S_i = \sum_{j} E[T_{ij} \cdot X_{i,j}]$$

$$E[X_t]=\sum_{j} E[T_{ij} \cdot X_{i,j}] = \sum_{j} E[T] \cdot E[X] = \sum_{j} E[T_{ij} \cdot m_{ij}]$$

The service time for a packet transmission starting from state $i$ is given by:

$$E[S] = E[\sum_{j} T_{ij} \cdot X_{i,j}] = \sum_{j} E[T_{ij} \cdot m_{ij}]$$

(14)

(15)

(16)

Since the sojourn time in state 0 is zero in the protocol instead of $\sigma$ as specified in the model, we correct the mean of $S_i$ starting from $i=0,1,...,W_p-1$ by decreasing $\sigma$ in the results. Hence, we can obtain:
The variance of \( S \) is given by (18).

\[
\text{Var}[S] = \text{Var} \left[ \sum_{i} X_i \right] - \sum_i \text{Var}[X_i]
\]

\[
= \sum_i \left( \text{Var}[x_i] + \langle x_i \rangle^2 \right) - \sum_i \text{Var}[x_i]
\]

\[
\text{Var}[S] = \sum_i \text{Var}[x_i] + \sum_i \langle x_i \rangle^2 - \sum_i \text{Var}[x_i]
\]

Equation (7) shows that the probability that a vehicle transmits a packet in steady state is \( \pi_{XM} T_{DIFS}/T \). In addition, the time to transmit a packet is \( T_{DIFS} \). Therefore, we can abstractly define the total time to be \( T_{total} \) as shown in Figure 3. Hence, \( \pi_{XM} T_{DIFS}/T = (T_{DIFS})/T_{total} \).

Suppose a neighbor of the tagged vehicle transmits a packet as shown in Figure 3 in time duration \( T_{total} \), a backoff time slot of the tagged vehicle can occupy any one time slot within \( T_{total} \).

For the first backoff time slot, the backoff time slot of the tagged vehicle, the time duration that can capture the transmission of the neighbor is \( T_{DIFS} + 2\sigma \). One extra time slot \( \tau \) is the one just before transmission and another is the one just after transmission, which can capture the starting time instant and ending time instant of the packet transmission. Therefore, the probability that a neighbor’s transmission is detected in the first backoff time slot of the tagged vehicle is \( \pi_{XM} T_{DIFS} + 2\sigma)/T \).

For a backoff time slot that is not the first backoff time slot of the tagged vehicle, the time duration that can capture the transmission of the neighbor is \( 2\sigma \), which capturing the starting time instant and the transmission. This is because when the neighbor’s transmission is detected in the first backoff time slot by the tagged vehicle, the backoff counter will suspend and wait until the end of this transmission for further decrease. Therefore, if the first backoff time slot detects the transmission, there is no chance for the later backoff time slots to detect the same transmission. As a result, the non-first backoff time slot can only detect the transmission when the starting point of the transmission falls within this time slot. Therefore, the probability that a neighbor’s transmission is detected in non-first backoff time slot of the tagged vehicle is \( \pi_{XM} T_{DIFS} + 2\sigma)/T \).

Since the probability that a backoff time slot is the first backoff time slot is \( 1/W_0 \) and non-first backoff time slot is \( (1-1/W_0) \), the probability that a neighbor’s transmission is detected by a backoff time slot of the tagged vehicle is given by (25).

\[
P_{XM} = \frac{T - T_{DIFS} + 2\sigma}{T} \pi_{XM} + \left(1 - \frac{1}{W_0}\right) \frac{2\sigma}{T} \pi_{XM} + \frac{1}{T} \pi_{XM} T_{DIFS} + \frac{T_{DIFS}}{T} \pi_{XM} T_{DIFS}
\]

For \( q_b \), it denotes the probability that channel is detected busy by the tagged vehicle in DIFS duration. Therefore, we can similarly define \( P_{XM} \) to be the probability that a neighbor’s transmission is detected in DIFS time by the tagged vehicle.

\[
P_{XM} = \frac{T - T_{DIFS} + 2T_{DIFS}}{T} \pi_{XM} + \left(1 - \frac{1}{W_0}\right) \frac{2\sigma}{T} \pi_{XM} + \frac{1}{T} \pi_{XM} T_{DIFS} + \frac{T_{DIFS}}{T} \pi_{XM} T_{DIFS}
\]

Hence, \( q_b \) is given by (27).

\[
q_b = \frac{1}{1-q_{\pi}} \frac{N_a}{l_j} e^{-q_{\pi}} = 1 - e^{-q_{\pi} T_{DIFS}}
\]

\[
(25)
\]

\[
(27)
\]
Based on equation (24)(25)(26)(27), $q_b$ can be expressed in terms of $p_b$ as shown in (28) to simplify the iteration algorithm.

$$q_b = 1 - (1 - p_b)^{(T-DIFS)\rho_{b}}$$

(28)

From the above analysis of the relationship between two parameters $\rho$ and $p_b$ ($q_b$ can be expressed in terms of $p_b$), we notice that $p_b$ depends on $\rho$ and $p_b$ itself. Hence, we denote $p_b=g(\rho,p_b)$ and the reciprocal of mean service time for M/G/1 queue to be $\mu=h(\rho,p_b)$. The fixed point iteration algorithm is outlined as follows according to the relationship graph shown in Figure 4.

**Fixed point iteration algorithm:**

Step 1: Initialize $\rho=1$, which is the saturation condition;

Step 2: With $\rho$, solve $p_b$ according to (24)(25)(7)(28);

Step 3: With $\rho$ and $p_b$, calculate service rate $\mu=1/E[S]$ according to (20);

Step 4: If $\lambda<\mu$, $\rho=\lambda/\mu$; otherwise, $\rho=1$;

Step 5: If $\rho$ converges with the previous value, then stop the iteration algorithm; otherwise, go to step 2 with the updated $\rho$.

By utilizing the fixed point iteration algorithm, the parameters $\rho$, $p_b$, $q_b$, $\pi_{\text{XMT}}$ as well as the mean and the variance of the service time can be determined, which will be subsequently used for performance indices computation in the next section.

IV. PERFORMANCE INDICES

A. Transmission delay

The packet transmission delay is defined as the average delay a packet experiences from the time at which the packet is generated, and the time at which the packet is successfully received by all neighbors of the vehicle that generates the packet. The transmission delay $E[D]$ includes the queuing delay and medium service time (due to backoff, packet transmission, and propagation delay, etc.).

The expected queuing delay can be obtained from the Pollaczek-Khinchin mean value formula of the M/G/1 queue:

$$E[D_q] = \frac{\lambda [\text{Var}[S] + (E[S])^2]}{2(1-\lambda E[S])}$$

(29)

The average packet transmission delay is then calculated as:

$$E[D] = E[D_q] + E[S]$$

(30)

B. Packet Delivery Ratio (PDR)

Packet delivery ratio can be interpreted as, given a broadcast packet sent in the tagged vehicle, the probability that all vehicles in its transmission range receive the packet successfully. Taking into account of hidden terminal, we have

$$PDR = P(N_{\text{cs}})P(N_{\text{ph}})$$

(31)

where $P(N_{\text{cs}})$ is the probability that no vehicles in the transmission range of the tagged vehicle (i.e., neighbor) transmits when the tagged vehicle starts transmission, and $P(N_{\text{ph}})$ is the probability that no transmission from the vehicles in the potential hidden terminal area collides with the broadcast packet from the tagged vehicle.

$P(N_{\text{cs}})$ can also interpreted as the non-concurrent transmission probability, i.e., two packets do not start transmission at the same time. Since DCF employs a discrete-time backoff scale, if the backoff process is involved, a vehicle is only allowed to transmit at the beginning of each slot time after an idle DIFS. Therefore, if the tagged vehicle has not go through the backoff process before transmitting the packet (probability $(1-\rho)(1-q_b)$), the concurrent transmission will not occur. Otherwise, the packet transmission is synchronized to the beginning of a slot time, and concurrent transmission may happen if other vehicles’ transmission is also synchronized by the backoff process. From the model, we know that the probability that a neighbor starts to transmit a packet at the beginning of the same time slot with the tagged vehicle is $\pi_0 = \pi_{\text{XMT}}/T$. This is because the sojourn time in state $0$ is one time slot $\sigma$ as shown in the SMP model, hence, $\pi_0$ is the probability that a vehicle starts to transmit in the beginning of a time slot immediately after the backoff process. Hence, $P(N_{\text{cs}})$ is:

$$P(N_{\text{cs}}) = \left[1-(1-\rho)(1-q_b)\right] \sum_{i=0}^{\infty} (\pi_0 - \frac{1}{i!}) e^{-\pi_0}$$

(32)

$$+ (1-\rho)(1-q_b) \sum_{i=0}^{\infty} (\pi_0 - \frac{1}{i!}) e^{-\pi_0}$$

Since the transmission time for a packet is $T-DIFS = E[PA] + T_D + \delta$, the transmission from hidden terminals collides with the tagged vehicle’s transmission only happens when hidden terminals start to transmit during the vulnerable period $2(T-DIFS) - 2(E[PA] + T_D + \delta)$. Since $\pi_{\text{XMT}} = \frac{T}{T_{\text{total}}}$ as an abstraction of the steady state behavior shown in Figure 3, the probability that a vehicle starts to transmit during vulnerable period is:

$$\frac{2(T-DIFS)}{T_{\text{total}}} = \pi_{\text{XMT}} = \frac{2(T-DIFS)}{T}$$

(33)

Therefore:

$$P(N_{\text{ph}}) = \sum_{i=0}^{\infty} (1-\pi_{\text{XMT}}) \left(\frac{2(T-DIFS)}{T}\right)^i \frac{1}{i!} e^{-\pi_{\text{XMT}}}$$

(34)
V. NUMERICAL AND SIMULATION RESULTS

Table 1 shows all the parameters used in this paper. Figure 5 and Figure 6 presents the mean transmission delay and PDR, respectively, over the vehicle density $\beta$ (# vehicles per meter), varied data rate $R_d$ (Mbps), packet arrival rate $\lambda$ (packets per second) and average packet length $E[PA]$ (bytes).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tx range $\bar{R}$</td>
<td>500 m</td>
<td>Propagation delay $\delta$</td>
<td>0 us</td>
</tr>
<tr>
<td>Average Packet Length $E[PA]$</td>
<td>variable</td>
<td>Variance of Packet Length $Var[PA]$</td>
<td>0</td>
</tr>
<tr>
<td>PHY preamble</td>
<td>40 us</td>
<td>PLCP header</td>
<td>4 us</td>
</tr>
<tr>
<td>MAC header</td>
<td>272 bits</td>
<td>CWMin $W_c$</td>
<td>15</td>
</tr>
<tr>
<td>Packet arrival rate $\lambda$</td>
<td>variable</td>
<td>Vehicle density $\beta$</td>
<td>variable</td>
</tr>
<tr>
<td>Slot time $\sigma$</td>
<td>16 us</td>
<td>DIFS</td>
<td>64 us</td>
</tr>
</tbody>
</table>

The analytic results from the model and the simulation results show good match.

![Figure 5. Delay of DSRC Highway safety messaging](image)

![Figure 6. PDR of DSRC Highway safety messaging](image)

The maximum delay is 0.45 ms as shown in Figure 5, which can satisfy the latency requirement of 100 ms. Since the new SMP model considers the fact that a packet can be directly transmits without going through backoff process, the delay is lower comparing to [6]. Another observation in Figure 5 is that high data rate and shorter packet length facilitate the decrease of the transmission delay.

The packet delivery ratio decreases fast as the vehicle density increases as shown in Figure 6. Similar to the delay, PDR also benefits from high data rate and shorter packet length.

VI. CONCLUSION

In this paper, an analytic model using SMP has been developed to characterize the behavior of DSRC for highway safety communications. The model has been validated through extensive simulations. Moreover, the performance with different input parameters is analyzed to suggest the better parameter setting to improve the performance in respect of decreasing transmission delay and increasing packet delivery ratio. In the future, performance optimization will be conducted for more parameters including $W_d$. The tradeoff between delay and PDR will be evaluated based on the optimization results. In addition, the SMP model will be extended to incorporate different packet arrival processes such as Markov modulated Poisson process (MMPP), Markov arrival process (MAP) instead of Poisson arrival. Moreover, besides one-hop direct broadcast transmission strategy, multi-hop and multi-cycle transmission strategy will also be taken into consideration in the future work.

ACKNOWLEDGMENT

The authors would like to thank Yang Zhao for his endeavor on simulation and NSF grant to support this research.

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