Performance and Reliability Analysis of Prioritized Safety Messages Broadcasting in DSRC With Hidden Terminals

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ABSTRACT
In this paper, we design a mathematical model for performance and reliability evaluation of the IEEE 802.11p Enhanced Distributed Channel Access (EDCA) broadcast scheme in Dedicated Short-Range Communication (DSRC) with the presence of hidden terminals. Specifically, we first introduce a more accurate semi-Markov process (SMP) model to portray the channel contention among multiple types of safety messages and their backoff behavior in DSRC based vehicular ad hoc networks (VANETs) with the influence of hidden terminals. Each type of safety message’s generation and service in an individual vehicular node is modeled leveraging a unique $M/G/1/K$ queue. For the channel contention, the SMP model interrelates with the $M/G/1/K$ queue via fixed-point iteration. Additionally, grounded on the solution of fixed-point iteration, we acquire the performance indices such as packet delay (PD), packet delivery rate (PDR), and packet reception rate (PRR). The new SMP model considers the IEEE 802.11p EDCA backoff counter process, unsaturated packet arrivals, limited MAC queue length, hidden terminals, Nakagami-m fading channel with distance-related path loss, and distinct transmission, carrier sensing and interference ranges. Eventually, we validate the correctness of the model through the comparison between the numerical and simulation results under different network parameters and prove that the proposed model has an advantage over the existing models in analyzing the impact of hidden terminals on PDR and PRR.

INDEX TERMS
DSRC, IEEE 802.11p EDCA, safety message broadcasting, semi-Markov process, VANETs.

I. INTRODUCTION
With the rapid development of the economy, the number of vehicles is increasing, and traffic accidents are rising. Intelligent Transportation System (ITS) provides a solution to the traffic safety problem with the help of new technologies. As a crucial component of ITS, intervehicle communication (IVC) has received much attention from both the auto industry and academia. The main candidate wireless technologies to realize IVC including Cellular Vehicle to everything (C-V2X) and Dedicated Short-Range Communication (DSRC) [1]. As DSRC has been proven to outperform C-V2X when the vehicle density increases [2], the discussion in this paper is restricted to DSRC. It works at the 5.9-GHz band with assigned 75 MHz bandwidth consisting of a 10-MHz wide control channel (CCH) intended for common safety communications and six 10-MHz wide service channels (SCHs) who are responsible for non-safety applications. The protocols of the physical layer and medium access control (MAC) sublayer of DSRC are specified by IEEE 802.11-2012 where the IEEE 802.11p enhanced distributed channel access (EDCA) mechanism is exploited to access a channel [3]. Because of the highly dynamic network topology and severe latency constrains in DSRC-based vehicular ad hoc networks (VANETs), single-hop broadcasting on the CCH is an effective way for vehicular nodes to spread the safety messages to their neighbors, which is one of the elementary services in DSRC. As for the safety messages, they are endowed with diverse priorities according to their criticalities to the traffic safety and divided into four access categories (ACs) by the IEEE 802.11p EDCA mechanism: 1) the highest priority AC[3] is granted to emergency information displayed at the roadside unit or generated by vehicles; 2) the second priority AC[2] is granted to basic safety message (BSM) that advertises the vehicles’ presence; 3) a lower priority AC[1] is granted to non-urgent messages asking for help sent by vehicles who are not a danger to other vehicles; 4) the lowest priority AC[0] is granted to the solicited messages starting new non-safety-related conversations over the SCHs. What is noteworthy is that all these messages are broadcast via CCH.
Since vehicular safety communication concerns more about the quality, i.e., fast and reliable, but not the quantity of safety messages deliveries, thus packet delay (PD), packet delivery rate (PDR), and packet reception rate (PRR) are usually selected as the indices to assess its performance rather than throughput. In [4] and [5], PDR and PRR were respectively introduced as the average metrics to quantify the performance through simulations or experiments. For the theoretical analysis of vehicular safety communication performance, most of the active researches are based on the discrete-time Markov chain (DTMC) model initially proposed by Bianchi [6]. The DTMC model successfully characterized the performance of the IEEE 802.11 MAC protocol. Subsequently, various works further analyzed other IEEE 802.11 series standards by improving this accurate model, such as [7], [8] where the performance of IEEE 802.11e EDCA was studied. DTMC analyses have been applied to the IEEE 802.11p EDCA broadcast for vehicular safety communications. In [9], DTMC based models were proposed to mathematically analyze the IEEE 802.11p EDCA’s performance on the CCH without considering the hidden terminal effects which is unreasonable because the underlying hidden terminal region in it can be much bigger than that in unicast so that broadcast communication is extremely sensitive to hidden terminals [10]. Zhou et al. [11] developed a DTMC based model for the performance analysis of prioritized broadcast service in WAVE/IEEE 802.11p under saturation condition which is unrealistic in a VANET environment as fast delivery of messages is vital. The authors in [12] leveraged the M/M/1 queue model to obtain the packet delay (PD) and packet delivery rate (PDR) expressions when evaluating the performance of the IEEE 802.11p EDCA broadcast. Luong et al. [13] analyzed the performance of the IEEE 802.11p single-class EDCA broadcast taking hidden terminal problems, direct collision, and vehicle densities into account yet neglecting the channel fading with path loss. An analytic model where a DTMC interacting with an M/G/1 queue was built by [14]–[17] to evaluate the two types of safety messages broadcast services performance involving the backoff counter process, unsaturated packet arrivals, and hidden terminals. Concretely, the authors in [14], [16], [17] assumed that the interference range and transmission range were identical which is not a good approximation. Meanwhile, [14] and [17] reflected the channel impairment by simply introducing the packet error rate which cannot accurately represent the channel fading characteristics. Moreover, [15] defined new PDR and PRR as the functions of the distance between the receiver and the sender which created bigger pictures of how each node receives the broadcast message. Other works such as [18]–[21] investigated four classes of safety messages broadcast exploiting the IEEE 802.11p EDCA scheme. However, these models are all derived from Bianchi’s DTMC model which are based on the per-slot statistics and cannot precisely capture the backoff counter freezing behavior.

Recently, an analytical model where a semi-Markov process (SMP) [22] interrelating with an M/G/1 queuing was proposed in [23] to examine the performance of one type of safety message over CCH. This SMP model was demonstrated to be more precise than the DTMC based models as it can describe the continuous-time system behavior beyond the per-slot statistics incorporating the backoff counter freezing process. Yin et al. [24], [25] extended the SMP model to beacon message dissemination with multichannel services and D/G/1/1 LCFS (last-come-first-served) generation and service pattern. Ma and Trivedi [26] applied the approach to a universal two-dimensional (2-D) broadcast wireless network.

In this paper, a new SMP based analytical model is developed to accurately characterize the continuous-time behavior of different types of broadcast services over CCH adopting IEEE 802.11p EDCA which is of great significance as it is a default MAC protocol of DSRC and whether it can afford differentiated broadcasting services in terms of performance and reliability is vital for safety applications. Contrasted to the existing works for performance evaluation of safety message broadcast in the DSRC-based VANETs, the improvements of this work including the following aspects.

- a) The SMP model is introduced to the multiple safety messages broadcast performance analysis of IEEE 802.11p EDCA with unsaturated message arrivals and hidden terminals.
- b) Instead of assuming a MAC layer queue with infinite capacity, the M/G/1/K queuing model with limited capacity is leveraged to provide a more precise analytical result.
- c) A more general applicable Nakagami-m channel fading with distance-related path loss model is used to study the influence of imperfect channel on the network performance.
- d) We define distinct rather than identical transmission, carrier sensing, and interference ranges, which is a better approximation for practical.
- e) Different from the existing PDR and PRR metrics that obtained by averaging all the receivers within the sender’s transmission range, the new PDR and PRR expressions in our work are the functions of the distance between the receiver and transmitter, which gives a deeper insight of broadcast reliability as the distance changes.

The rest of the paper is unfolded as follows. Section II briefly describes the IEEE 802.11p EDCA broadcast mechanism and the VANET model abstracted from a typical highway scenario and lists the necessary assumptions for model formulation. Section III proposes the analytic models and presents the fixed-point iteration procedure. The closed-form expressions for key performance indices including PD, PDR, PRR are derived in Section IV. The numerical and simulation results are compared in Section V and Section VI summarizes this work.

II. SYSTEM DESCRIPTION AND ASSUMPTIONS

Firstly, we present the details of the IEEE 802.11p EDCA broadcast mechanism in this section. Then, the simplified
VANET model in the highway scenario is described. Finally, some imperative assumptions are listed out.

A. IEEE 802.11p EDCA BROADCAST MECHANISM

The IEEE 802.11-2012 defines Hybrid Coordination Function (HCF) for the MAC protocol of DSRC, which consists of both HCF Controlled Channel Access (HCCA) and Enhanced Distributed Channel Access (EDCA). The former is for the contention-free channel access and the latter is for contention-based channel access [3]. In this paper, we focus on the contention-based EDCA protocol which supports prioritized services by setting different parameters. The IEEE 802.11p EDCA broadcast protocol deletes all control frames including Request-to-Send/Clear-to-Send (RTS/CTS) and Acknowledgement (ACK) to work in a vehicular environment with high mobility, thus it does not have RTS/CTS and ACK mechanisms.

To be specific, when a new packet with a certain priority arrives at the MAC layer, it will be stored in its corresponding queue. As the backoff window sizes defined in the IEEE 802.11p EDCA are large and all types of safety messages except BSM occasionally occur, the internal collision probability between different ACs in a node is small and we assume that the backoff instances of them are independent from each other, i.e., the virtual collisions are neglected (similar assumptions can be found in [14], [17] and [27] and the results considering the internal contention will appear in our future work). Then, if the channel is sensed free by the AC[i] (i = 0, 1, 2, 3) packet for some time equal to its corresponding arbitration interframe space (AIFS[i]), it will transmit; or if the channel is detected to be busy immediately or during the AIFS[i], it will keep monitoring the channel status until the idle state lasts for AIFS[i] where the duration of AIFS[i] refers to

\[ AIFS[i] = SIFS + AIFS[i] \times \sigma \]  

and \( \sigma \) is the time slot, SIFS denotes the short interframe space, the AIFS number (AIFS[i]) of AC[i] satisfies AIFS[i] ≥ 2 and AIFS[i] equals to distributed interframe space (DIFS) when AIFS[i] = 2. At this moment, a backoff operation is started and the initial value of the backoff counter equals to distributed interframe space (DIFS) when AIFS[i] = 2. At this moment, a backoff operation is started and the initial value of the backoff counter is randomly selected from the interval [0, W_i – 1]. W_i stands for the minimum contention window size (CW_min) of AC[i], the values of which for different ACs are listed in Table 1. The backoff process will be suspended if the channel becomes busy again and reactivated only if the channel maintains the idle state for a duration of AIFS[i]. Then, the packet will be sent out immediately when the backoff counter drops to 0. As there is no ACK frame sent back from the destination node after the transmission is completed and the source node cannot perceive the collision by itself, no retransmission will be invoked by the external collision and the impaired packet will be discarded directly.

B. VANET MODEL DESCRIPTION

We consider a typical highway scenario in this work where a set of vehicles travel on a bidirectional highway, and each direction has one lane. Since the lane width is ignorable when compared with the maximum transmission range (up to 1 km which is defined in IEEE 802.11-2012 standard), we simplify it as a one-dimensional (1-D) VANET model, which is depicted in Fig. 1. In the figure, one vehicle is represented by one node.

In this VANET model, the transmission range equals \( \frac{R}{L} \), which indicates a pair of transceivers can successfully communicate with each other if the space between them is less than \( \frac{R}{L} \). The value is decided by the transmission power and the quality of the channel. The carrier sensing range \( L_{cs} \) defines a distance that a transmitting signal can be detected, which is an important parameter in the CSMA/CA mechanism. The interference range \( L_{int} \) belongs to the interval \((R, L_{cs})\) because a signal whose strength does not reach the reception threshold may still have an impact on the normal receiving. The blue nodes in Fig. 1 represent the hidden terminals who are beyond the carrier sensing range but can still disturb the nodes in the reference node’s transmission range.

C. SYSTEM ASSUMPTIONS

To construct an abstracted yet high fidelity model to analyze the IEEE 802.11p EDCA broadcast performance over the CCH, several reasonable assumptions are made.

1) The number of vehicles in a 1-D highway system follows the Poisson point process with the vehicle density \( \beta \) (vehicles per meter); the probability of finding \( i \) vehicles located within the length of \( l \) is given as

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

2) Each safety message is encapsulated in a single packet as it is very short (usually hundreds of bytes). A packet consists of two portions: the data packet from the upper layer and the packet header from MAC and physical layers, the length of which are \( P \), \( MAC_H \), and \( PHY_H \) separately. The transmission power for all the packets is the same and the basic rate and data rate are \( R_b \) and \( R_d \).
3) The generation of each AC[i] packet is random and independent obeying the Poisson process with different rate $\lambda_i$ (in packets per second).

4) Each AC is equipped with a MAC queue entity to access the medium by the IEEE 802.11p EDCA and each entity is modeled as an $M/G/1/K$ queue with limited capacity.

5) The characteristic of channel contention and path loss is described as the Nakagami-m distribution.

6) We omit the impact of vehicle mobility in this paper since vehicular nodes are almost stationary during one packet transmission time and the estimated link breaking probabilities between connected vehicles are very small and approximate to zero at high velocities which have been demonstrated in [14] and [17].

### III. ANALYTICAL MODEL

Since all the ACs from different nodes contend with the shared channel and the queues they are in interact with each other, hence the whole problem can be treated as a group of interacting $M/G/1/K$ queues. To predigest this problem, we build an SMP model for a certain AC[i] in the reference node which grasps the medium contention and backoff behavior instead of tracing the queued requests directly. Because the SMP model of the AC[i] interacts with its corresponding $M/G/1/K$ queue, it demands a fixed-point iteration to solve the overall problem.

#### A. THE OVERALL MODEL

The arrival and service of each AC packet in a vehicle is modeled as a universal $M/G/1/K$ queue, where the services for two patterns of packet arrivals are incorporated utilizing Welch’s method [28]. As illustrated in Fig. 2a, the overall model is a set of interrelating $M/G/1/K$ queues, four queues for each vehicle, and the interrelation is that the server is shared since it is the common medium for the safety message dissemination. The behavior of the shared medium is revealed using the SMP model from the view of a single reference vehicle, where the channel contention and backoff process of one type of service AC[i] and the influences from the same vehicle and other vehicles are included as shown in Fig. 2b. Different from the previous DTMC models which describe the server’s discrete-time behavior, this SMP model directly merges the queue’s unsaturation condition in a continuous-time manner. It interplays with the $M/G/1/K$ queue of reference vehicle’s AC[i] via the fixed-point iteration.

#### B. SMP MODEL FOR AC[i]

Fig. 3 presents the SMP model of the AC[i] packet which captures its transmission behavior. We assume the initial state of AC[i] is $idle$ which indicates the queue is empty. When a new packet comes, the node keeps monitoring the channel activity for AIFS[i]. If it is free during this interval (with probability $1 - q_{b_i}$, where $q_{b_i}$ is the possibility that the channel is sensed occupied during AIFS[i] by the AC[i]), it transfers to state $XMT$ which represents that a packet is transmitting. Otherwise, it insists to check the channel status until it keeps idle for an AIFS[i]; then the backoff procedure is invoked and a backoff counter is uniformly selected from the range $[0, W_i - 1]$, which indicates it enters state $W_i - j$ with probability $q_{b_i}/W_i$. The counter is reduced by 1 once the channel is measured unoccupied for a time slot $\sigma$ (with probability $1 - p_{b_i}$, where $p_{b_i}$ is the probability that the channel is active during one-time slot), which is characterized by the switch from state $W_i - j$ to state $W_i - j - 1$. If the channel is in use by another node to transmit a packet, then the backoff counter is frozen for the period of average packet transmission time $TM_i$, which is represented by the transition from state $W_i - j$ to state $D_{w_i,j}$. Once the backoff counter falls to 0, the packet will be sent out directly which implies the state transition probability from $0$ to $XMT$ is 1. After the packet transmission, the AC[i] goes back to state $idle$ and waits for a new packet arrival if no more packet is left in the queue (with probability $1 - \rho_i$); if there still have packets left in the queue, the node will detect the medium again for AIFS[i] and then uniformly select a backoff counter before sending next queued packet.

Let $T_{i,j}$ denotes the sojourn time for AC[i] in state $j$, and its mean is derived as

$$E[T_{i,j}] = \tau_{i,j} = \begin{cases} \sigma & j = 0, 1, 2, \ldots, W_i - 1 \\ TM_i & j = D_0, D_1, \ldots, D_{W_i - 2} \\ TD_i & j = XMT \\ 1/\lambda_i + AIFS[i] & j = idle \end{cases}$$

(3)

where $TD_i = T_{i,tr} + \delta + AIFS[i]$ and $TM_i = \tilde{T}_{tr} + \delta + AIFS[i]$, $\delta$ is the propagation delay. $T_{i,tr}$ is the time needed for the AC[i]
Consequently, the steady-state probability of AC\[ packet transmission, which are computed by
\[
T_{i,tr} = \frac{PHY_H}{R_b} + \frac{MAC_H + P_i}{R_d}
\]
(4)
\[
\bar{T}_{tr} = \frac{PHY_H}{R_b} + \frac{MAC_H + \sum_{i=0}^{3} \gamma_i P_i}{R_d}
\]
(5)
\[
\gamma_i
\]
is the steady-state probability for transmitting an AC[i] packet and \(P_i\) is its corresponding data packet size.

We first solve the embedded DTMC in the SMP model for its steady-state probabilities:
\[
\begin{align*}
\pi_{i,j} &= (W_i - j) \cdot \pi_{i,W_i} \\
\pi_{i,D_j} &= (W_i - j - 1) \cdot \pi_{i-1,W_i-j} \\
\pi_{i,XMT} &= \frac{\rho_i + q_{bi}(1 - \rho_i)}{(1 - \rho_i) W_i} \cdot \pi_{i,W_i-1} \\
\pi_{i,Idle} &= \frac{\rho_i + q_{bi}(1 - \rho_i)}{\rho_i} \cdot \pi_{i,W_i-1}
\end{align*}
\]
(6)
From these above equations, we have
\[
\pi_{i,W_i} = 2[\rho_i + q_{bi}(1 - \rho_i)]/[W_i + 1 + p_{bi}(W_i - 1)]
\cdot [\rho_i + q_{bi}(1 - \rho_i)] \cdot W_i + 2(2 - \rho_i) \cdot W_i
\]
(7)
Referring to [29], the steady-state probabilities of the SMP can be calculated exploiting the average sojourn time in each state:
\[
\pi_i = \frac{v_i T_i}{\sum_j v_j T_j}
\]
(8)
Consequently, the steady-state probability of AC[i] in state XMT is obtained as:
\[
\pi_{i,XMT} = \frac{2 \cdot TD_i}{[\rho_i + q_{bi}(1 - \rho_i)]([\sigma + p_{bi} \cdot TM_i]W_i + [\sigma - p_{bi} \cdot TM_i] + 2 \cdot TD_i + 2(1 - \rho_i) \cdot \lambda_i}
\times (1/\lambda_i + AIFS[i])
\]
(9)
Though the time AC[i] stays in state XMT is \(TD_i\), only part of it is used for packet transmission, that is \(T_{i,tr} + \delta = TD_i - AIFS[i]\). Therefore, \(\gamma_i = \pi_{i,XMT}(TD_i - AIFS[i])/TD_i\).

So far, there are 12 unknowns \(\rho_i, p_{bi}, q_{bi}\), which are interdependent with each other. Besides, the SMP model for AC[i] is correlated with its M/G/1/K queue as \(\rho_i\) hinges on the mean service time. As a result, we will first calculate the service time and subsequently utilize the fixed-point iteration algorithm to compute these parameters numerically.

C. SERVICE TIME CALCULATION

The service time of the MAC layer is the time duration from the point a packet becomes the head of the queue and begins to compete for the channel access to the point the packet is decoded. Since the SMP model in Fig. 3 captures the continuous packet transmissions behavior of AC[i] in its queue, to derive the service time for every single packet, we need to alter it to a new one comprising an absorbing state which is presented in Fig. 4. From this model, we can readily obtain the service time by counting the time started from a properly allocated state to the moment reaching the absorbing state.

According to [22], the transition probability matrix of a Markov chain including an absorbing state can be written in block matrix:
\[
P = \begin{bmatrix} Q & C \\ 0 & 1 \end{bmatrix}
\]
(10)
where \(Q\) is a \(2W_i \times 2W_i\) sub-stochastic matrix that depicts only the transition probabilities of the transient states. The fundamental matrix is:
\[
M = (I - Q)^{-1}
\]
(11)
Denote \(X_{i,n,j}\) as the random variable standing for the times an AC[i] packet visits state \(j\) before it reaches to the absorbing state, conditioned that the imbedded DTMC initiated in state \(n\). The expectation of \(X_{i,n,j}\) is provided by the \((n, j)\) th entry of the fundamental matrix \(M\), that is
\[
E[X_{i,n,j}] = m_{i,n,j}
\]
(12)
Thanks to the acyclic character of the SMP model in Fig. 4, it is easy to get the fundamental matrix via the definition of \(X_{i,n,j}\) rather than computing Eq. (11). Equation (13), as shown at the bottom of the next page.

The service time beginning from state \(n\) is expressed as
\[
S_{i,n} = \sum_j T_{i,j} \cdot X_{i,n,j}
\]
(14)
Eventually, the expectation of \(S_{i,n}\) is:
\[
E[S_{i,n}] = E\left[\sum_j T_{i,j} \cdot X_{i,n,j}\right] = \sum_j E[T_{i,j}] \cdot E[X_{i,n,j}] = \sum_j \tau_{i,j} \cdot m_{i,n,j}
\]
\[
= \left\{\begin{array}{ll}
(n + 1) \sigma + n \cdot p_{bi} \cdot TM_i + TD_i &\text{for } n = 0, 1, \ldots, W_i - 1 \\
TD_i &\text{for } n = XMT
\end{array}\right.
\]
\[
\cdot \left\{\begin{array}{l}
j \in \{0, 1, \ldots, W_i - 1, D_0, D_1, \ldots, D_{W_i-2}, XMT\}. \\
\end{array}\right.
\]
(15)
As the sojourn time in state \(\theta\) is zero in the 802.11 protocol but not \(\sigma\) stated in the model, we modify the \(E[S_{i,n}]\) beginning...
where \( n = 0, 1, \ldots, W_i - 1 \) by subtracting \( \sigma \) in the expression, that is
\[
E[S_{i,n}] = \begin{cases} 
  n (\sigma + p_{b_i} \cdot T_M) + TD_i & \text{for } n = 0, 1, \ldots, W_i - 1 \\
  TD_i & \text{for } n = XMT 
\end{cases}
\] (16)

To calculate the average service time, we first derive the service time distribution which is classified into two cases:

(i) the AC\([i]\) queue is vacant when the new packet comes;

(ii) the AC\([i]\) queue is not vacant when the new packet comes.

For case (i), the service time distribution is expressed as:
\[
S_{i,v} = \begin{cases} 
  S_{i,0} + T_{i,w} & w.p. q_{i,0,v} = q_{b_i} / W_i \\
  S_{i,1} + T_{i,w} & w.p. q_{i,1,v} = q_{b_i} / W_i \\
  \vdots & \vdots \\
  S_{i,W_i-1} + T_{i,w} & w.p. q_{i,W_i-1,v} = q_{b_i} / W_i \\
  S_{i,XMT} & w.p. q_{i,XMT,v} = 1 - q_{b_i} 
\end{cases}
\] (17)

where \( T_{i,w} = (T_M - AIFS[i]) / 2 \) is the average waiting time for the new arrival packet when the medium is sensed busy during the AIFS[i].

Therefore, if the new packet arrives and the AC\([i]\) queue is vacant currently, its average service time is
\[
\beta_{i,v} = E[S_{i,v}] = \sum_{n} E[S_{i,n}] \cdot q_{i,n,v} + q_{b_i} \cdot T_{i,w} 
\]
\[
= \frac{(W_i - 1) (\sigma + p_{b_i} \cdot T_M) \cdot q_{b_i}}{2} + TD_i + q_{b_i} \cdot T_{i,w} 
\] (18)

For Case (ii), we similarly derive the service time distribution:
\[
S_{i,b} = \begin{cases} 
  S_{i,1} & w.p. q_{i,1,b} = 1 / W_i \\
  S_{i,2} & w.p. q_{i,2,b} = 1 / W_i \\
  \vdots & \vdots \\
  S_{i,W_i} & w.p. q_{i,W_i,b} = 1 / W_i 
\end{cases}
\] (19)

and if the new packet arrives and the AC\([i]\) queue is not vacant currently, the expectation of which is:
\[
\beta_{i,b} = E[S_{i,b}] = \frac{(W_i - 1) (\sigma + p_{b_i} \cdot T_M) + TD_i}{2} 
\] (20)

Based on Welch’s methods [22], the average service time for an AC\([i]\) packet initiated from any arbitrary state is:
\[
E[S_i] = \frac{\beta_{i,v}}{1 - \lambda_i (\beta_{i,b} - \beta_{i,v})} 
\] (21)

D. FIXED-POINT ITERATION

To calculate the interdependent 12 unknown parameters \( \rho_i, p_{b_i}, q_{b_i} \) \((i = 0, 1, 2, 3)\) in this subsection, we resort to the fixed-point iteration.

From the perspective of the reference vehicle, the probability \( p_{b_i} \) is interpreted as the channel is sensed busy at one timeslot during the backoff process of its AC\([i]\) service, which have two possibilities:

a) The reference vehicle is transmitting other types of AC packet during this interval, or

b) At least one vehicle within the carrier sensing range of the reference vehicle is transmitting any types of packets during this interval.

Thus, we have:
\[
p_{b_i} = 1 - \left[ \prod_{j=0, j\neq i}^{3} (1 - P_{i,j,XMT}) \right] \cdot \sum_{k=0}^{\infty} \left[ \prod_{j=0, j\neq i}^{3} (1 - P_{i,j,XMT}) \right]^{k} \frac{(2\beta L_{cs} - 1)^{k}}{k!} e^{-(2\beta L_{cs} - 1)} 
\]
\[
= 1 - \left[ \prod_{j=0, j\neq i}^{3} (1 - P_{i,j,XMT}) \right] \cdot e^{-(2\beta L_{cs} - 1)} \left[ 1 - \frac{3}{3} (1 - P_{i,j,XMT}) \right] 
\] (22)

where \( P_{i,j,XMT} \) denotes the probability that an AC\([j]\) packet is caught transmitting by the reference vehicle during one
time-slot of its backoff process when it is trying to send out the AC[i] packet. The derivation of \( P_{i,j,XMT} \) should also be divided into two situations: the reference vehicle capture the neighbor’s transmission at its first backoff timeslot within the duration \( TD_j - AIFS[i] + 2\sigma \) and the corresponding value of \( P_{i,j,XMT} \) is \( \pi_{j,XMT} \{ TD_j - AIFS[i] + 2\sigma \}/TD_j \); the reference vehicle captures the neighbor’s transmission at its non-first backoff timeslot within the duration \( 2\sigma \) and the corresponding value of \( P_{i,j,XMT} \) is \( \pi_{j,XMT} \times 2\sigma /TD_j \). Since the probability that a backoff timeslot is the first one is \( 1/W_i \) and its complement that a backoff timeslot is not the first one is \( 1-1/W_i \), then the formula of \( P_{i,j,XMT} \) is given by

\[
P_{i,j,XMT} = \frac{1}{W_i} \left( \frac{TD_j - AIFS[i] + 2\sigma}{TD_j} \right)^{\pi_{j,XMT} \{ TD_j - AIFS[i] + 2\sigma \}} + \left( 1 - \frac{1}{W_i} \right) \frac{2\sigma}{TD_j} \pi_{j,XMT} = \frac{TD_j - AIFS[i] + 2\sigma W_i}{TD_j \cdot W_i} \pi_{j,XMT} \tag{23}
\]

Analogously, \( q_{bi} \) is the possibility that the channel is detected busy by the reference vehicle during its AIFS[i] and we define \( Q_{i,j,XMT} \) as the probability that an AC[i] packet is caught transmitting by the reference vehicle during its AIFS[i] when it is trying to send out the AC[i] packet, then \( Q_{i,j,XMT} \), and \( q_{bi} \) are obtained as

\[
Q_{i,j,XMT} = \frac{TD_j - AIFS[i] + 2AIFS[i]}{TD_j} \cdot \pi_{j,XMT} \tag{24}
\]

\[
q_{bi} = 1 - \left[ \prod_{j=0, j\neq i}^{3} (1 - Q_{i,j,XMT}) \right] \\
\left\{ \sum_{k=0}^{\infty} \left[ \prod_{j=0}^{3} (1 - Q_{i,j,XMT}) \right]^k \right. \\
\times \left. \frac{(2\beta L_{ec} - 1)^k}{k!} \right\} \\
= 1 - \left[ \prod_{j=0, j\neq i}^{3} (1 - Q_{i,j,XMT}) \right] \\
\cdot e^{-\left(2\beta L_{ec} - 1\right)} \cdot \left[ 1 - \prod_{j=0}^{3} (1 - Q_{i,j,XMT}) \right] \tag{25}
\]

Next, we outline the steps of the fixed-point iteration that calculate the converged solutions for \( \rho_i, p_{bi}, q_{bi} \) as follows:

\[\text{Step 1: Initialize } \rho_i = 1, \text{ which is a saturated condition; }\]

\[\text{Step 2: Solve } p_{bi} \text{ and } q_{bi} \text{ with known } \rho_i \text{ based on Eq. (21), Eq. (22), Eq. (25); }\]

\[\text{Step 3: With } p_{bi} \text{ and } q_{bi}, \text{ solve the service rate } \mu_i = 1/E[S_i]; \]

\[\text{Step 4: If } \lambda_i/\mu_i \leq 1, \rho_i = \lambda_i/\mu_i; \text{ else, set } \rho_i = 1; \]

\[\text{Step 5: If the error of two consecutive iterative } \rho_i \text{ is less than the predefined bound } \varepsilon, \text{ the iteration is terminated; otherwise, return to Step 2 and restart with the updated } \rho_i. \]

IV. NETWORK PERFORMANCE METRICS

A. PACKET DELAY

We define the packet delay (PD) as the time duration that starts from the point a new packet is generated to the point it is transmitted, which consists of two portions. One is the queuing time from the moment a packet arrives at the queue to the instant it turns into the head of the queue; the other is the average service time which has been calculated by Eq. (21). Based on the assumption that each AC entity is modeled as an \( M/G/1/K \) queue, the queuing time can be analyzed utilizing the imbedded Markov chain approach in [30]. Note that \( K \) implies at most \( K \) packets can be provisionally stored in the buffer waiting for transmission and one is being served. Let \( S = \{ I, A_0, A_1, \ldots, A_K \} \) be the state space of the queuing system, in which \( A_j \) means \( j \) packets waiting in the queue and the server is busy while \( I \) means the queue is empty and the server is idle. Define \( \alpha(k) \) as the possibility that \( k \) packets arrive at the queue of AC[i] within one packet service time. From Fig. 4, we acquire the probability mass function of service time \( S_{i,n} \) as:

\[
S_{i,n} = \begin{cases} 
\alpha_1 k, & 0 \leq h < n, n \in [0, 1, \ldots, W_i - 1] \\
p_{bi} \cdot C^h_n \cdot (1 - p_{bi})^{n-h}, & 0 \leq h < n, n \in [0, 1, \ldots, W_i - 1] \\
\end{cases} \tag{26}
\]

where \( h \) is the times that the backoff process is deferred because of the busy channel and \( C^h_n \) is the binomial coefficient indexed by \( h \) and \( n \). Because the arrival of AC[i] packet obeys the Poisson process with rate \( \lambda_i \), we obtain

\[
\alpha_1(k) = \sum_{n=0}^{W_i-1} \frac{1}{W_i} \sum_{k=0}^{n} \frac{e^{-\lambda_i(n\sigma + hTM_l + TD_i)} \cdot \lambda_i(n\sigma + hTM_l + TD_i)^k}{k!} \\
\times q_{bi} C^h_n \cdot (1 - p_{bi})^{n-h} + (1 - q_{bi}) \cdot e^{-\lambda_i TD_i} \cdot (\lambda_i TD_i)^k \\
\tag{27}
\]

Denote \( p_{r,s} \) as the state transfer probability of AC[i] queue from \( A_r \) to \( A_s \) \( (0 \leq r, s \leq K) \) within one packet service time. From Fig. 5, the transition probability matrix \( P_i \) can be deduced from:

\[
P_i = \begin{bmatrix} 
\alpha_i(0) & \alpha_i(1) & \cdots & \alpha_i(K - 1) & 1 - \sum_{j=0}^{K-1} \alpha_i(j) \\
\alpha_i(0) & \alpha_i(1) & \cdots & \alpha_i(K - 1) & 1 - \sum_{j=0}^{K-1} \alpha_i(j) \\
0 & \alpha_i(0) & \cdots & \alpha_i(K - 2) & 1 - \sum_{j=0}^{K-2} \alpha_i(j) \\
0 & 0 & \cdots & \alpha_i(K - 3) & 1 - \sum_{j=0}^{K-3} \alpha_i(j) \\
0 & 0 & \cdots & 0 & 1 - \alpha_i(0) \\
\end{bmatrix} \tag{28}
\]

Define \( \sigma_{i,j} \) be the steady-state probability that the queue length of AC[i] reaches \( j \) before the new packet enters
the queue. Since $\sigma_i = (\sigma_{i,0}, \sigma_{i,1}, \ldots, \sigma_{i,K})$ meets the following balance equations:

$$\begin{align*}
\sigma_i &= \sigma_i P_i \\
\sum_{k=0}^{K} \sigma_i &= 1
\end{align*}$$

the steady-state probability for the imbedded Markov chain can be solved through

$$p_{i,k} = \frac{\sigma_{i,k}}{\sigma_{i,0} + \rho_i}, \quad 0 \leq k \leq K$$

and the probabilities that the AC[i] queue is empty and full by [31]

$$\begin{align*}
p_{i,0} &= \frac{\sigma_{i,0}}{\sigma_{i,0} + \rho_i} \\
p_{i,K+1} &= 1 - \frac{1}{\sigma_{i,0} + \rho_i}
\end{align*}$$

The probability that the packet is dropped because of queue overflow equals to $p_{i,K+1}$, which is

$$p_{i,dro} = p_{i,K+1}$$

Next, the mean queuing time of AC[i] is computed by

$$E[D_{q,i}] = \frac{1-p_{i,0}}{\lambda_i} \left[ \sum_{k=1}^{K} kp_{i,k} + (K+1) (p_{i,0} + \rho_i - 1) \right]$$

Ultimately, the mean PD of AC[i] is the sum of the mean queuing time and mean service time, that is

$$PD_i = E[D_{q,i}] + E[S_i]$$

### B. PACKET DELIVERY RATIO

We define the packet delivery ratio (PDR) as the possibility of a node dwelling in the sender’s transmission range successfully decoding a packet emitted from the reference vehicle. Three factors influence the PDR performance, which are the hidden terminals, concurrent transmissions collision caused by the vehicles situated in the carrier sensing range of the reference node, and channel fading and path loss. To illustrate the derivation, we pictorially show the transmission scenario in Fig. 6 where a transmitter $O$ is placed at the origin, $A$ is one of the receivers located in the transmission range of the sender $O$, $B$ is a node within the potential hidden terminal area and $C$ is another sender within the carrier sensing range of $O$. The inter-vehicle distance between $A$ and $O$ is $r_0$ ($0 < r_0 \leq R$).

![FIGURE 6. An exemplary transmission scenario.](image)

1) HIDDEN TERMINALS EFFECT

Let $P_{i,ht}(r_0)$ be the probability that the receiver $A$ receiving the AC[i] message from the reference node $O$ exempts from hidden terminal problems. It can be interpreted as the probability that no hidden terminals (e.g., $B$ in Fig. 6) within the interval $[L_{cs}, r_0 + L_{int}]$ (i.e., the line segment in yellow) start packet transmissions during the vulnerable period $T_{D_j} - AIFS[j] + T_{D_i} - AIFS[i]$ if $L_{cs} - L_{int} < r_0 \leq R$. The reason is that on one side, the distances between the hidden terminals situated in the range of $[r_0 + L_{int}, R + L_{int}]$ and $A$ are larger than $L_{int}$ so that their transmissions do not interfere the normal reception of $A$; on the other side, the actual transmission time for AC[j] message is $T_{D_j} - AIFS[j]$ so that the vulnerable period for AC[i] message transmission is $T_{D_i} - AIFS[i]$ if $L_{cs} - L_{int} < r_0 \leq R$. Evidently, $P_{i,ht}(r_0) = 1$ if $0 < r_0 \leq L_{cs} - L_{int}$. Thus, (35) as shown at the bottom of the next page.

2) CONCURRENT TRANSMISSIONS

Let $P_{i,cx}(r_0)$ be the probability that the reception of $A$ is invulnerable to the concurrent transmission collisions between any types of packets from the nodes located in the carrier sensing range of the reference node (e.g., $C$ in Fig. 6) or the reference node $O$ itself and the AC[i] packet from the reference node $O$. Because EDCA adopts a slotted backoff scale, a node is only permitted to transmit at the starting of each time slot after an idle AIFS[i] if $L_{cs} - L_{int} < r_0 \leq R$. Then, the reference vehicle can directly transmit the AC[i] message without suffering the backoff process (with probability $(1 - \rho_i)(1 - q_{ht})$), the concurrent transmission will not happen. Else, the reference vehicle is requested to transmit at the starting of a time slot. At this point, even though the transmission of $C$ is synchronized to the starting of the same time slot with the reference node $O$, the reception of $A$ will not be disturbed if $C$ is not in the interval $[r_0 - L_{int}, r_0 + L_{int}]$ when $0 < r_0 \leq L_{cs} - L_{int}$ or in the interval $[r_0 - L_{int}, L_{cs}]$ when $L_{cs} - L_{int} < r_0 \leq R$ (i.e., the line segment in purple) since $A$ is out of the interference range of the senders that beyond the interval but within the carrier sensing range of $O$. Then, the length of the interval $\theta$ can be written as

$$\theta = \begin{cases} 2L_{int} & \text{if } 0 < r_0 \leq L_{cs} - L_{int} \\ L_{cs} + L_{int} - r_0 & \text{if } L_{cs} - L_{int} < r_0 \leq R \end{cases}$$

Observe that the probability that $C$ or $O$ itself initiates an AC[j] packet transmission at the starting of the same time slot with $O$ is $\pi_i = \pi_{i,XMT} \times \sigma/TD_i$ as the duration of a time slot is $\sigma$. Then, the possibility of a node beginning to dispatch the AC[j] packet at the starting of the time slot is
backoff process is also \( \pi_j \). Therefore, we have

\[
P_{i, cs}(r_0) = [1 - (1 - \rho_i) (1 - q_b)] \cdot \left[ \sum_{k=0}^{\infty} \frac{3}{\prod_{j=0}^{3} (1 - \pi_j)} \right]
\]

\[
\cdot \left[ \sum_{k=0}^{\infty} \frac{3}{\prod_{j=0}^{3} (1 - \pi_j)} \right] k! e^{-\beta \rho_i} \cdot e^{-\beta \rho_i} \cdot \left[ \sum_{k=0}^{\infty} \frac{3}{\prod_{j=0}^{3} (1 - \pi_j)} \right] + (1 - \rho_i) (1 - q_b)
\]

(37)

3) CHANNEL FADING WITH PATH LOSS

The Nakagami-\( m \) channel fading model has been demonstrated to be capable of accurately capturing the characteristics of signal amplitude \( X_d \) at a certain distance in the wireless channel [32]:

\[
f(x_d, \omega, m) = \frac{2m^m x_d^{2m-1}}{\Gamma(m) \omega^m} \exp \left( -\frac{m x_d^2}{\omega} \right)
\]

(38)

where \( \Gamma(\cdot) \) represents the Gamma function, \( m \geq 1/2 \) is the amplitude fading parameter and \( \omega > 0 \) is the expectation of received power. The probability distribution function (PDF) and cumulative distribution function (CDF) of signal power \( X = X_d^2 \) respectively yield to:

\[
f(x, \omega, m) = \frac{m^m \omega^{-2m-1}}{\Gamma(m) \omega^m} x^{2m-1} e^{-\frac{m x^2}{\omega}}
\]

(39)

\[
F(x, \omega, m) = \frac{m^m \omega^{-2m}}{\Gamma(m) \omega^m} \int_0^x \frac{m^m \omega^{-2m}}{\Gamma(m) \omega^m} z^{2m-1} e^{-\frac{m z^2}{\omega}} dz
\]

(40)

and the path loss model is presented as

\[
\omega(r_0) = \omega(r) = \left( \frac{r}{r_0} \right)^\gamma
\]

(41)

where \( \omega(r_0) \) and \( \omega(r) \) are the average power received at \( r_0 \) and \( r \) away from the transmitter, separately, and the path loss exponent \( \gamma \) is determined empirically. Usually, the value of \( \gamma \) is 2 in the free-space environment, 1.6~1.8 in line-of-sight indoor, and 2.7~5 in obstructed or shadowed urban [33].

Hence, the probability that the AC\( i \) message is successfully decoded without considering the interference is equivalent to the probability that the received signal power \( X_i \) exceeds the reception threshold \( TR_{X_i} \), that is

\[
P \left( X_i > TR_{X_i} \right) = 1 - F \left( TR_{X_i}, \omega_i, m \right)
\]

\[
= 1 - \frac{m^m}{\Gamma(m) \omega_i^m} \int_0^{TR_{X_i}} z^{m-1} e^{-\left( \frac{z}{\omega_i} \right)} dz
\]

(42)

Let \( z' = z/\omega \) and substitute it into Eq. (41), we obtain

\[
P \left( X_i > TR_{X_i} \right) = 1 - \frac{m^m}{\Gamma(m) \omega_i^m} \int_0^{\frac{TR_{X_i}}{\omega_i}} (z')^{m-1} e^{-m z'} dz'
\]

(43)

furthermore, according to Eq. (41), \( TR_{X_i} \) and \( \omega_i(r_0) \) which are the average received power at the distance the “intended” communication range \( R \) and \( r_0 \) away from the transmitter satisfies:

\[
\frac{TR_{X_i}}{\omega_i(r_0)} = \left( \frac{r_0}{R} \right)^\gamma
\]

(44)

Applying Eq. (44) to Eq. (43), we can rewrite the probability that a receiver at distance \( r_0 \) successfully decode the AC\( i \) message as:

\[
P_{i,F}(r_0) = 1 - \frac{m^m}{\Gamma(m) \omega_i^m} \int_0^{\left( \frac{r_0}{R} \right)^\gamma} (z')^{m-1} e^{-m z'} dz'
\]

(45)

Notice that in the vehicular environment, the value of \( m \) in the above equation is a function of \( r_0 \):

\[
m(r_0) = \begin{cases} 
3 & 0 < r_0 < 50 m \\
1.5 & 50 m \leq r_0 < 150 m \\
1 & r_0 \geq 150 m
\end{cases}
\]

(46)

Taking all the impacts including hidden terminals, concurrent transmission, queue overflow, and channel fading with path loss into consideration and suppose that nodes in the network and these four events are independent, the PDR for AC\( i \) message is approximated as

\[
PDR_i(r_0) = P_{i, cs}(r_0) \cdot P_{i, ht}(r_0) \cdot P_{i,F}(r_0) \cdot (1 - p_{i, dvo})
\]

(47)
C. PACKET RECEPTION RATE

We define packet reception rate (PRR) as the percentage of the number of nodes that successfully decode a packet sent by the reference node to the total number of receivers in the sender's transmission range at the instant the packet is emitted. To put it in another way, PRR denotes the ratio of the nodes in the reference node’s transmission range that successfully decodes the AC[i] packet. The derivation of PRR is divided into two steps. First, deduce the probability of the arbitrary individual receiver A successfully receiving the AC[i] message from the transmitter O. Then, integrate the possibilities over the transmission range of O. Recall that the locations of nodes along a 1-D highway obey Poisson distribution, then the average number of nodes within an incremental length $dr$ is $\beta dr$. Given the individual reception probability in Eq. (44), the average number of nodes within $dr$ that successfully decode the AC[i] message from the reference node is $PDR_i(r)\beta dr$. For a range having distance $R$ from O, PRR over a range with distance $y$ ($y < R$) is solved by integrating the possibilities of nodes with distance $r$ to O within an incremental length $dr$ successfully receiving the AC[i] message from O, which is

$$PRR_i(y) = \frac{\int_0^y PDR_i(r) \beta dr}{\int_0^y PDR_i(r)dr} = \frac{1}{y} \int_0^y PDR_i(r)dr \quad (48)$$

V. NUMERICAL AND SIMULATION RESULTS

In this part, the new SMP model is applied to a typical vehicular safety communication environment: DSRC based VANET operating on a segment of bidirectional single-lane highway with a length of 5000 m. Each vehicle is capable of IEEE 802.11p based wireless broadcasting. Table 2 gives the typical network settings for IEEE 802.11p which are also used in both simulation and analytic models unless specified otherwise. Moreover, the free space propagation model is assumed, thus the path loss exponent $\gamma$ equals 2. As for fading parameter $m$, it varies with different values of $r_0$ based on Eq. (46) when considering the effect of Nakagami channel fading and it is set to 3 in other cases. In the following, we will explore the impacts of these varied inputs on the latency and reliability of safety message service and the new proposed SMP model will be compared with previous models.

Since AC[3] concerning emergency information may be seldomly released and AC[2] are periodically broadcast which indicates that different applications may have different workloads, we first want to check the influence of packet arrival rates on the network performance. Fig. 7-10 show the PDs, PDRs, and PRRs of ACs with $\lambda_i$ ($i = 0, 1, 2, 3$) equals to 2, 5, 10, 1 respectively, where Fig. 7, Fig. 8 and Fig. 9 show PDs, PDRs of the receiver A at $r_0 = 50 m$ and PRRs over the whole transmission range $R$ with the increasing vehicle density $\beta$ while Fig. 10 depicts the PDRs of the receiver A at $\beta = 0.1$ with the ascending distance to sender $r_0$. At first sight, we have a straightforward observation that the theoretic results are consistent with the simulation results which proves the correctness of the proposed model. Besides, as $\beta$ increases, the PD increases but
keeps relatively small, whereas PDR and PRR decreases. Meanwhile, the PDR decreases as \( r_0 \) increases which is easy to comprehend. Furthermore, we notice that PDR and PRR are nearly the same for four ACs which means PDR and PRR are robust to arrival rate differentiations. The PD differentiations are mainly caused by differentiated EDCA parameters. Hence, the packet arrival rate has little influence on the performance of prioritized broadcast services.

Next, we exam the influences of channel fading, concurrent transmission collision, and hidden terminals individually on the broadcast performance of multiple types of safety messages. As these factors mainly affect the reliability performance rather than the latency, thus we only present the reliability performance metrics (i.e., PDR and PRR). Particularly, Fig. 11 and Fig. 12 demonstrate the PDR and PRR with/without channel fading effect; Fig. 13 and Fig. 14 illustrates the PDR and PRR considering all the factors and either without concurrent transmission collisions or hidden terminals. Intuitively, these three factors are in varying degrees of impact on safety messages broadcasting reliability. From Fig. 11 and Fig. 12, we know that channel fading does degrade the reliability performance. It is found in Fig. 13 and Fig. 14 that the effect of the hidden terminal is dominated in damaging the broadcasting performance compared with that of concurrent transmission collision which coincides with the fact that broadcast communication in a VANET is susceptible to hidden terminal effects.

Finally, to show the advantage of our proposed model over the previous models in comprehensiveness and accuracy, we compare a few numerical and simulation results from the proposed model, denoted as SMP, with the analytic results...
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FIGURE 14. PRRs of AC(i) over R with all the factors versus without concurrent collisions versus without hidden terminals.

FIGURE 15. PD comparison.

FIGURE 16. PDR comparison.

From previous models. The model in [17], denoted as DTMC, is used for PD, PDR and PRR comparison. Fig. 15 shows that with the same input parameters, the new SMP model has lower PD than DTMC. This is mainly because the new SMP model considers the fact that a packet can be sent directly without experiencing the backoff process, which was neglected in [17]. Also, it demonstrates that the new SMP model has a better match with simulations than DTMC. The PDR and PRR comparisons are presented in Fig. 16 and 17 and the new SMP model reveals a better match than DTMC. As for the reason why the new SMP model has lower PDR and PRR than DTMC is that it takes the impacts of queue overflow and Nakagami channel fading into account.

VI. CONCLUSION

In this paper, a more general yet accurate analytic model is constructed to investigate the performance and reliability of safety message broadcasting DSRC based VANETs with the EDCA mechanism. The newly developed model takes all the factors such as the IEEE 802.11p EDCA backoff counter process, unsaturated packet arrivals, limited MAC queue length, hidden terminals, Nakagami-m fading channel with distance-related path loss, and distinct transmission, carrier sensing, and interference ranges into consideration. Moreover, the accuracy of the model is validated and the impact of each associated factor influencing the network performance is inspected via simulations.

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