Performance Modeling of Safety Messages Broadcast in Vehicular Ad Hoc Networks

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***Abstract*—In vehicular ad hoc networks (VANETs), because all vehicles in range are shown as destination nodes and less time is spent for the medium access process, broadcast communication is considered a highly appropriate technique for the dissemination of safety messages in such networks. However, the lack of request-to-send/clear-to-send handshaking and packet acknowledgment makes the communication more vulnerable to interferences, thus resulting in lower communication reliability. In this paper, we present an analytical model for the performance evaluation of safety message dissemination in vehicular ad hoc networks with two priority classes. In particular, considering the IEEE 802.11 broadcast protocol and using 2-D Markov modeling, we derive the joint distribution of the numbers of low-priority periodic messages, which are in transmission mode and in a backoff process in a highway. Then, the result is used to derive the average dissemination delay of high-priority event-driven messages in the presence of the low-priority traffic in the network. The results are helpful in determining a good tradeoff between network parameters such as vehicles' transmission range, safety traffic generation rate, and medium access control (MAC) parameters to satisfy the required delay bounds for the critical high-priority traffic.**

***Index Terms*—Average delay, broadcast, medium access control (MAC), message dissemination, performance analysis, vehicular ad hoc networks (VANETs).**

I. Introduction

VEHICULAR ad hoc networks (VANETs) are emerging as a promising technology for providing safety and comfort applications for vehicular transportation. VANETs are receiving growing attention from the research community and from the transportation industry because of their great potential to improve traffic safety on roads. However, handling time-critical safety applications in these networks poses many challenges, particularly because such applications may have to share the communication channel with other applications. In this context, considering the network operation mode proposed for the Dedicated Short-Range Communication (DSRC) standardization [1], we assume the coexistence of periodic applications and event-driven safety applications. Messages that belong to periodic applications are broadcast among vehicles, as frequently as necessary, to inform each other about their local parameters such as speed and position. On the other hand, a message that belongs to event-driven applications is a safety message that is generated by a specific vehicle, which detects or experiences a hazard or an unusual event. A safety message is broadcast to accordingly notify neighbors and as far as possible [2], [3]. In the network, a high ratio of the traffic will consist of messages that were generated by the first type of applications, which may reduce the resource availability for the second type of messages. However, because safety messages are time critical, they have to be given higher priority compared to messages of periodic applications. The modeling of message traffic that is related to safety applications has been lagging because of various difficulties [4]. In this paper, we present an analytical model for the performance evaluation of safety message dissemination in VANETs with two priority classes.

Lower reliability in broadcast communication due to higher collision rates and hidden-terminal activities is another challenge that needs to properly be handled in VANETs [5]. The IEEE 802.11 broadcasting mode considers no request-to-send/clear-to-send (RTS/CTS) handshaking process, because all of the nodes within the range of a sending node are assumed as recipients. Thus, the size of the potential hidden node activity's area is dramatically larger than the 802.11 unicast mode, which makes the communications more unreliable.

The traditional approach for studying the collision and hidden-terminal effects is to assume a single-hop scenario and then extend the results to a multihop scenario with independence assumption. As a result, it fails to adequately model the hidden-terminal effect and collisions between the nodes, and it does not appropriately capture the dynamics of the system. Example studies in [2], [6], and [10] determined different VANETs' performance measures, all based on this independence assumption. For example, [6] makes use of this assumption to evaluate the collision probabilities and throughput of the recipients within the transmission range of a sender in a single-hop communication. In [7], the probability that a recipient is exposed to the hidden-terminal effect is derived. In that study, the hidden terminal, which is located out of the range of a sender, is considered to be in isolation; however, in multihop communications, that hidden node itself can be exposed to hidden-node activities. Among the analyses that were proposed to study the performance of broadcasting algorithms, [2] and [8]–[10] are some examples that evaluate the probability of successful message receptions and average message

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dissemination distance, all based on the same multihop independence assumption. Furthermore, these works assume only a single type of traffic in the network, whereas as aforementioned, in reality, VANETs are expected to regularly transmit periodic messages and emergent high-priority messages when necessary.

In [11], we developed a novel analytical model to determine the main performance measures of VANETs with two traffic priority classes. Unlike other studies, the modeling took a multihop perspective rather than the generalization of single-hop results, which captures the dynamics of the system such as the hidden-terminal activity better. The latter work, however, assumes that the arrival time of a message to the channel corresponds to the moment that its backoff counter reaches zero, after which the message is transmitted. Therefore, the medium access control (MAC) backoff time was considered part of the message interarrival time, and the effect of the messages in a backoff process was neglected due to mathematical complexities.

This paper relaxes the aforementioned major limitation. Thus, it considers the IEEE 802.11 MAC protocol in broadcast mode, as suggested for VANETs' safety applications. Briefly, in broadcast, unlike unicast communication, a backoff process is performed only once for a new generated message, and no binary backoff process is employed. Broadcasting is highly appropriate to disseminate safety messages in VANETs, because all nearby vehicles are considered destination nodes, and less time will be spent for medium access process. However, the lack of RTS/CTS handshaking and packet acknowledgment makes the communication more vulnerable to interferences and hence results in lower communication reliability [12].

We define the state of the network as (n, k), where n and k, respectively, denote the number of concurrent low-priority transmissions and the number of low-priority messages that are in the backoff process. Then, we model the number of messages in the transmission and backoff process with a 2-D Markov process, which enables us to determine their joint probability distribution at the steady state, hence yielding the main contribution of this paper. The proposed modeling can also be used to derive all the performance measures that were considered in [11] with a higher accuracy, as well as to derive new performance measures. Herein, focusing on delay as a new performance metric for the network under study, we determine the end-to-end high-priority message dissemination delay in the presence of low-priority traffic.[1] Finally, simulation results are presented, and it confirms the accuracy of the analysis.

In this paper, Section II describes the network modeling, Section III presents the main analysis, Section IV details the proposed delay analysis for high-priority messages, and Section V discusses the numerical and simulation results, followed by this paper's conclusion.

II. Network Model

In this paper, we consider a 1-D VANET model in a highway with length R (in meters). The nodes have constant transmission ranges d (in meters), and their mobility is neglected, because they remain almost stationary within a message transmission time. However, a mobility model is integrated in the simulation program to confirm the accuracy of this assumption.

Based on the experimental results that were reported in [13], we assume that the nodes enter the highway according to a Poisson process with the parameter ϕ nodes per unit length of the highway. Thus, the location of nodes follows a uniform distribution. We will refer to nodes with or without a message to transmit as busy and idle nodes, respectively. A busy node is either transmitting a message or is in a backoff process.

Two classes of message traffic are considered. The first class is low-priority traffic, which arrives at the VANET according to a Poisson process with the parameter λ_0 messages per vehicle per second. The well-known assumption of Poisson distribution for traffic arrivals has been made in several studies, such as [6]–[8].

We assume that only idle nodes generate new messages. Thus, each node may have only a single outstanding message that waits for transmission. Let us define λ as the parameter of the Poisson message arrival rate per unit length of the highway, with all the nodes being in idle state. Then, $\lambda = \phi\lambda_0$.

The second class is event-driven high-priority messages, which are generated by a randomly selected node such that at most one message of this type will propagate in the network at any given time. The arrival time of a message to the channel corresponds to the moment that it is passed to the MAC layer for transmission. The transmission time of a message for both traffic classes is exponentially distributed with parameter μ, and it is assumed that each node can have at most one message for transmission.

At any given time, the number of concurrent transmissions may divide the network into alternating activity and inactivity regions, where in an activity region, there is at least one ongoing transmission. Let us define an interference subregion as the overlap area between the transmission ranges of two concurrent transmitting nodes in an activity region. We assume that a destination node can correctly receive a message, as long as it is not located in an interference subregion. Furthermore, if the transmitting nodes themselves are within the interference subregion, this interference is referred to as internal (otherwise, external interference), which are traditionally known as collision and hidden-terminal activities, respectively. The readers are referred to [11] for a more comprehensive and illustrative presentation of the network model adopted. In that work, the average lengths of the sum of the activity regions and the sum of the interference subregions for a VANET with n concurrent transmissions, denoted by $\ell(n)$ and $h(n)$, respectively, has been derived by

$$\ell(n) = \begin{cases} [2\bar{m}(n) + (0.5P_c + 1.5P_h)(n - \bar{m}(n))]\,d, & \text{if } n > 0 \\ 0, & \text{if } n = 0 \end{cases} \tag{1}$$

$$h(n) = \begin{cases} (1.5P_c + 0.5P_h)(n - \bar{m}(n))d, & \text{if } n > 1 \\ 0, & \text{if } n = 0, 1 \end{cases} \tag{2}$$

where P_c and P_h denote the probabilities of internal and external interferences, respectively, based on [11], i.e.,

$$P_h = \frac{P'_h}{P'_c + P'_h} \tag{3}$$

$$P_c = \frac{P'_c}{P'_c + P'_h} \tag{4}$$

[1] As stated previously, MAC knowledge is not considered in [11], and as such, delay evaluation is not only out of scope therein but is also impossible to conduct.

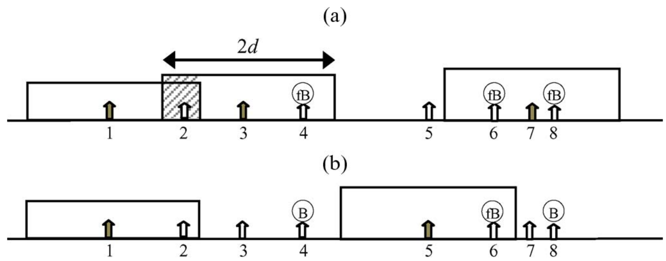

Fig. 1. Example of transmission activities (a) before Δt and (b) after Δt (in seconds).

where P'_c and P'_h, respectively, represent the probabilities of two transmissions' overlapping due to internal and external interferences, which are given by [11]

$$P'_c = 1 - e^{-\lambda d \varepsilon} \tag{5}$$

where ε is the duration of contention time slot, and

$$P'_h = \frac{\lambda d}{\lambda d + \mu}. \tag{6}$$

Finally, in (1) and (2), $\bar{m}(n)$ denotes the average number of activity regions with n concurrent transmissions, and it can be determined by $\bar{m}(n) = \sum_{m=1}^{n} m Q_m(n)$, where $Q_m(n)$ is the probability distribution function of the number of activity regions with n concurrent transmissions, as given in [11, eq. (19)] .

III. Analytical Model

In this section, we will develop an analytical model for the communication of low-priority traffic. According to the IEEE 802.11 MAC broadcast mode which is a CSMA/CA based protocol, when a message is generated in an idle node, it will be transmitted immediately if that node finds the medium free for a distributed interframe space (DIFS) time period. Otherwise, it randomizes a one-time backoff counter and decrements it whenever the medium is sensed free [14]. As such, any message arrival to the idle nodes that are located within an activity region results in backoff initiation, whereas messages that arrive at the idle nodes located within a nonactivity region will immediately be transmitted. Furthermore, nodes that are in a backoff process and located in activity regions cannot decrement their counters. Fig. 1 shows an example of transmission activities within Δt (in seconds) in a segment of the network. In Fig. 1(a), nodes 1, 3, and 7 are transmitting, whereas nodes 2, 4, 6, and 8 are receiving. Nodes 4, 6, and 8 have received a message at the MAC layer for transmission; however, because they are within an activity region, they have scheduled their backoff timers, which are frozen. We note that idle node 2 is located within an interference area. Fig. 1(b) shows the evolution of the network after Δt (in seconds), where nodes 3 and 7 finished their transmissions, whereas node 1 is still transmitting. Node 5 has received a message after node 7's transmission has terminated and immediately started its transmission. Furthermore, nodes 4 and 8 sensed the medium free and started to decrement their backoff counter, whereas node 6 still senses the medium busy and continues freezing its backoff counter.

Let w and α denote the backoff contention window size and the duration of the backoff time slot, respectively. We assume that the backoff times are sampled from an exponential distribution, with its mean for a single backoff broadcasting network given by $1/\beta = \alpha w/2$ [15, p. 1498]. First, we let the following conditions hold.

- *A new message arrives at the MAC layer of an idle node in an activity region and changes the state of the network from* (n, k) *to* $(n, k+1)$. The number of idle nodes per meter in activity regions is given by $\phi - n/\ell(n) - k/R$, where $\ell(n)$ denotes the average lengths of the activity regions. Thus, the number of idle nodes within activity regions can be written as $(\phi - n/\ell(n) - k/R)\ell(n)$. We note that no message buffering is considered in this paper and new messages that were generated in transmitting nodes or nodes in a backoff process are dropped. As a result, the rate of the messages that arrive at the MAC layer of the idle nodes in activity regions is given by $\lambda_0(\phi - n/\ell(n) - k/R)\ell(n)$ messages per second.
- *A new message arrives at the MAC layer of a node in a nonactivity region and changes the state of the network from* (n, k) *to* $(n+1, k)$. We note that there cannot be transmitting nodes in nonactivity regions. Thus, the number of idle nodes per meter in nonactivity regions can be written as $\phi - k/R$. Because the average lengths of nonactivity regions in the network are given by $R - \ell(n)$, the number of idle nodes in nonactivity regions will be $(\phi - k/R)(R - \ell(n))$. As a result, the rate of messages that are generated by the nodes in nonactivity regions is given by $\lambda_0(\phi - k/R)(R - \ell(n))$.
- *A message transmission is completed, and the state of the network is changed from* (n, k) *to* $(n-1, k)$. For n messages in transmission, this rate can be written as $n\mu$.
- *A message backoff is completed within the nonactivity regions, and the state of the network is changed from* (n, k) *to* $(n+1, k-1)$. The corresponding flow rate out of state (n, k) can be written as $k\beta/R(R - \ell(n))$.

Second, the system may enter the state (n, k) if any of the following four events occurs.

- *A message transmission is completed when the state of the system is* $(n+1, k)$. For $n+1$ messages in transmission, this rate can be written as $(n+1)\mu$.
- *A new message arrives at the MAC layer in an activity region when the state of the system is* $(n, k-1)$. Similarly, this rate is given by $\lambda_0(\phi - n/\ell(n) - (k-1)/R)\ell(n)$ messages per second.
- *A new message arrives at the MAC layer in a nonactivity region when the state is* $(n-1, k)$. The corresponding rate is given by $\lambda_0(\phi - k/R)(R - \ell(n-1))$.
- *A message backoff process is completed in a nonactivity region when the state is* $(n-1, k+1)$. The corresponding rate can be written as $(k+1)\beta/R(R - \ell(n-1))$. We note that a message backoff counter is frozen in an activity region. In addition, we have no such event of backoff completion in an activity region.

Next, let $p_{n,k}(n,k)$ denote the joint probability that the state of the system is (n,k) at the steady state. The system may be described as a 2-D Markov process with state space, i.e.,

$$S = \{(n,k) | 0 \le n \le n_{max}, 0 \le k \le k_{max}\} \tag{7}$$

where n_{max} and k_{max} are the upper bounds on the numbers of messages in transmission and backoff process, respectively. Based on the given state transition rates, we can write the steady-state global balance equation (8) for the system at state (n,k) as

$$\begin{aligned}
&\left[\lambda_0\left(\phi - \frac{n}{\ell(n)} - \frac{k}{R}\right)\ell(n) + \lambda_0\left(\phi - \frac{k}{R}\right)[R - \ell(n)]\right. \\
&\left.\quad + n\mu + \frac{k\beta}{R}[R - \ell(n)]\right] p_{n,k}(n,k) \\
&\quad = (n+1)\mu p_{n,k}(n+1,k) \\
&\qquad + \lambda_0\left(\phi - \frac{n}{\ell(n)} - \frac{(k-1)}{R}\right)\ell(n) p_{n,k}(n,k-1) \\
&\qquad + \lambda_0\left(\phi - \frac{k}{R}\right)[R - \ell(n-1)]\, p_{n,k}(n-1,k) \\
&\qquad + \frac{(k+1)\beta}{R}[R - \ell(n-1)]\, p_{n,k}(n-1,k+1).
\end{aligned} \tag{8}$$

Equation (8) presents $n_{max} \times k_{max}$ balance equations that need to be solved to find the $n_{max} \times k_{max}$ unknown joint probabilities. However, such a solution is not necessarily feasible, because the dimension of the state space $(n_{max} \times k_{max})$ could be quite large. As a result, we proceed with an alternative solution. Let $p_{n|k}(n|k)$ and $p_{k|n}(k|n)$ denote the conditional distributions of having n concurrent transmissions when k messages are in backoff, and vice versa, respectively. Operating with exponential arrival rates, as aforementioned, $p_{n|k}(n|k)$ and $p_{k|n}(k|n)$ can be modeled with Markovian birth–death processes. Therefore, for the process $p_{n|k}(n|k)$, birth and death refer to the events that result in increasing and decreasing n by one in a short time interval, respectively, when the state of the system is (n,k). A similar definition is applicable to the process $p_{k|n}(k|n)$. Next, we introduce several useful definitions.

- $a_{n|k}(n)$ Birth rate of the number of concurrent transmissions when the state of the system is (n,k).
- $b_{n|k}(n)$ Death rate of the number of concurrent transmissions when the state of the system is (n,k).
- $a_{k|n}(k)$ Birth rate of the number of messages in the backoff when the state of the system is (n,k).
- $b_{k|n}(k)$ Death rate of the number of messages in the backoff when the state of the system is (n,k).

Based on the given rates in (8), we have

$$a_{n|k}(n) = \lambda_0\left(\phi - \frac{k}{R}\right)[R - \ell(n)] + \frac{k\beta}{R}[R - \ell(n)] \tag{9}$$

$$b_{n|k}(n) = n\mu \tag{10}$$

$$a_{k|n}(k) = \lambda_0\left(\phi - \frac{n}{\ell(n)} - \frac{k}{R}\right)\ell(n) \tag{11}$$

$$b_{k|n}(k) = \frac{k\beta}{R}[R - \ell(n)] \tag{12}$$

and based on the product-form solution [16], we have

$$p_{n|k}(n|k) = p_{0|k}\prod_{i=0}^{n-1}\frac{a_{i|k}(i)}{b_{i+1|k}(i+1)}, \quad 0 \le n \le n_{\max} \tag{13}$$

$$p_{k|n}(k|n) = p_{0|n}\prod_{i=0}^{k-1}\frac{a_{i|n}(i)}{b_{i+1|n}(i+1)}, \quad 0 \le k \le k_{\max} \tag{14}$$

where $p_{0|k}$ and $p_{0|n}$ are found from the normalization condition.

The maximum value of concurrent transmissions n_{max} can be found by solving the inequality $\ell(n) \le R$, because it must be always valid. However, for the rest of the analysis, we set $k_{\max} = n_{\max} = \max(k_{\max}, n_{\max})$, and the missing probabilities will be nulled. Next, let $p_k(k)$ and $p_n(n)$ be the marginal distributions of n and k, respectively, which are related by the following expressions:

$$p(n) = \sum_{k=0}^{n_{\max}} p_{n|k}(n|k)p_k(k), \quad 0 \le n,k \le n_{\max} \tag{15}$$

$$p(k) = \sum_{n=0}^{n_{\max}} p_{k|n}(k|n)p_n(n), \quad 0 \le n,k \le n_{\max}. \tag{16}$$

To find these marginal distributions, we proceed by expressing the aforementioned equations in matrix form. Define the $n_{\max} \times n_{\max}$ square matrix $\mathrm{P}_{n|k}$, with the (n,k)th element given by $p_{n|k}(n|k)$. In addition, let $\mathrm{P}_{k|n}$ define the $n_{\max} \times n_{\max}$ square matrix whose (k,n)th element is given by $p_{k|n}(k|n)$. Finally, denote the vectors of the marginal distributions of n and k by P_n and P_k, respectively. Then, based on (15) and (16), we can write

$$\mathrm{P}_n = \mathrm{P}_{n|k}\mathrm{P}_k \tag{17}$$

$$\mathrm{P}_k = \mathrm{P}_{k|n}\mathrm{P}_n \tag{18}$$

which, after further manipulation, yields

$$\mathrm{P}_n = \mathrm{P}_{n|k}\mathrm{P}_{k|n}\mathrm{P}_n \tag{19}$$

$$\mathrm{P}_k = \mathrm{P}_{k|n}\mathrm{P}_{n|k}\mathrm{P}_k. \tag{20}$$

We note that the bases for the null spaces of square matrices $\mathrm{P}_{n|k}\mathrm{P}_{k|n}$ and $\mathrm{P}_{k|n}\mathrm{P}_{n|k}$ are the solutions for the marginal distribution vectors P_n and P_k, respectively. These bases can numerically be found using MATLAB, for example, and need to be normalized to represent valid probability vectors.

Next, we define $\bar{n}$ and $\bar{k}$ as the average number of messages in transmission and in backoff in the network under consideration, respectively. Therefore, we have

$$\bar{n} = \sum_{i=0}^{n_{\max}} i p_n(i) \tag{21}$$

$$\bar{k} = \sum_{j=0}^{n_{\max}} j p_k(j) \tag{22}$$

where marginal probabilities $p_n(i)$ and $p_k(j)$ are given by the ith and jth elements of the vectors P_n and P_k, respectively. We note that our former analysis, as reported in [11], does not allow determining the average number of messages in a backoff process, which is an important performance measure. Finally, the joint probability $p_{n,k}(n,k)$ can be found as

$$\begin{aligned} p_{n,k}(n,k) &= p_{n|k}(n|k)p_k(k) \\ &= p_{k|n}(k|n)p_n(n), \quad 0 \leq n,k \leq n_{\max}. \end{aligned} \tag{23}$$

We have observed that (23) satisfies the equality in the global equations (8) with less than 1% error for the state space S. This result validates the main assumption in its derivation, i.e., modeling the distributions of n and k with two conditional Markovian birth–death processes $p_{n|k}(n|k)$ and $p_{k|n}(k|n)$. The simulation results, as reported in Section V, also validated the assumption. The distribution in (23) is helpful in determining many performance measures for the VANET model under consideration. A case study is given in the next section.

IV. Dissemination of High-Priority Messages: Delay Analysis

In this section, we determine the average delay of message dissemination for event-driven safety traffic in the presence of low-priority traffic in a multihop scenario. We consider a connected network that corresponds to a highway with moderate traffic [13]. Therefore, the message dissemination delay is higher due to a higher number of transmissions and possible collisions. The impact of network discontinuity on dissemination delay in sparse scenarios is discussed in [17]–[20].

Because high-priority traffic is event driven and infrequently generated, it is reasonable to assume that a node that forwards a high-priority message will see the low-priority traffic at the equilibrium, i.e., with the arrival rate to the network of $a_{n|k}(n)$ given by (9). Because the nodes are uniformly distributed, the probability density function of the interarrival time of a new low-priority transmission within the transmission range of a high-priority forwarding node $(2d)$ is exponentially distributed with parameter

$$\Gamma_{n,k} = a_{n|k}(n)\frac{2d}{R} \tag{24}$$

for state (n,k). Denote $P_s(n,k)$ as the probability that no new low-priority transmission starts in the transmission range of a forwarding node within a time slot α. Given that the state of the system is (n,k), based on the memory-less property of exponential distributions, we have $P_s(n,k) = e^{-\Gamma_{n,k}\alpha}$. Finally, denote P_s as the unconditional probability of $P_s(n,k)$, which is given by

$$\begin{aligned} P_s &= \sum_{k=0}^{n\_\max}\sum_{n=0}^{n\_\max} P_s(n,k)p_{n,k}(n,k) \\ &= \sum_{k=0}^{n\_\max}\sum_{n=0}^{n\_\max} e^{-\Gamma_{n,k}\alpha}p_{n,k}(n,k) \end{aligned} \tag{25}$$

where $p_{n,k}(n,k)$ is given in (23).

Next, we determine the transmission delay at the hth intermediate forwarding node. The derivation of transmission delay at the source node, $h = 1$, slightly differs from intermediate forwarding nodes, which will be discussed later. Because the hth forwarding node has received the high-priority message from the $(h-1)$-th forwarding node, it cannot be in an activity region, and it starts sensing the medium for a DIFS period. Thus, with probability P_s, it finds it free and proceeds with the transmission in the consecutive slot. In this case, the forwarding delay will be $\alpha + \bar{x}$. On the other hand, with a probability of $1 - P_s$, it may sense the medium busy during a DIFS period, and it defers the transmission after the completion of the ongoing transmission and a backoff process. In this case, the forwarding delay will be $0.5\alpha + \bar{x} + E[\text{backoff time}] + \bar{x}$. Therefore, as a result of a single backoff procedure in the broadcasting mode, the average delay experienced by the hth forwarding node can be written as

$$\bar{d}_h = P_s(\alpha + \bar{x}) + (1 - P_s)(0.5\alpha + \bar{x} + E[\text{backoff time}] + \bar{x}) \tag{26}$$

where $\bar{x}$ is the average message transmission time given by $\bar{x} = 1/\mu$.

Next, we determine the average backoff waiting time in (26). Without loss of generality, we assume that the backoff window size for high-priority messages equals that of low-priority messages; however, a smaller window size can be considered for high-priority messages to conform with the packet differentiation introduced in the IEEE 802.11e MAC protocol. Let i denote the backoff value chosen by the hth forwarding node, $i = 0, 1, \ldots w - 1$. We note that the start-up of a low-priority transmission freezes the backoff counter in the forwarding node and extends its waiting time by the average message transmission time plus a time slot. Because a low-priority transmission may start with probability $1 - P_s$ within a slot duration, the average waiting time for each counted slot, shown by the forwarding node and denoted by T_{st}, can be written as

$$T_{st} = P_s\alpha + (1 - P_s)(0.5\alpha + \bar{x} + T_{st}) \tag{27}$$

which, after simplification, yields

$$T_{st} = \frac{P_s\alpha + (1 - P_s)(0.5\alpha + \bar{x})}{P_s}. \tag{28}$$

Given that the ith slot is uniformly selected, the average backoff waiting time for the forwarding node is given by

$$E[\text{backoff time}] = \frac{w}{2}T_{st}. \tag{29}$$

Then, substituting (29) into (26), we obtain the average transmission delay at the hth forwarding node.

Next, we determine the transmission delay of the safety message at the source node, $h = 1$. We note that a source node may be located in an activity region when it generates a high-priority message. We denote the probability of this event as P_i. In this case, the node randomizes a backoff value and waits until the medium becomes free to decrement the counter. Because the arrival of a high-priority message within an activity region is uniformly distributed, the average waiting time for the source node to sense the medium free is given by $0.5\bar{x}$, where $\bar{x}$ is the average transmission time. On the other hand, if the source node is not located in an activity region, it experiences a delay similar to one of the other forwarding nodes, as given in (26).

TABLE I
PARAMETERS SETTINGS

Parameter	Description	Value
δ	Vehicles mobility epoch rate	1
η	Vehicles mean speed	100 km/hr
σ	Vehicles speed standard deviation	6 m/s
R	Highway length	20 Km
w	MAC contention window size	32 slots
α	Time slot duration	34 μs
μ	Message transmission rate	500 messages/s

Therefore, the average transmission delay that is experienced by the source node can be written as

$$\begin{aligned}\bar{d}_1 &= P_i\,(0.5\bar{x} + E[\text{ backoff waiting time}] + \bar{x}) + (1 - P_i)\bar{d}_h \\ &= P_i\left[\frac{w}{2}T_{st} + 1.5\bar{x}\right] + (1 - P_i)\bar{d}_h. \end{aligned} \tag{30}$$

P_i has been derived in [11] as $P_i = \sum_{j=1}^{n\_max} h(j)/\ell(j)p_n(j)$, where $h(n)$ and $\ell(n)$ are given by (1) and (2), respectively, and $p_n(i)$ is given by the ith element of the vector P_n, given by (19).

Finally, the average total dissemination delay for H hops of communications, denoted by $\bar{D}_H$, is given by

$$\bar{D}_H = \bar{d}_1 + (H - 1)\bar{d}_h. \tag{31}$$

V. ILLUSTRATIVE NUMERICAL AND SIMULATION RESULTS

In this section, we present illustrative numerical results with regard to the analysis proposed in the previous sections. An event-driven simulation platform was developed using the MATLAB software to confirm the accuracy of the analysis. We have implemented the IEEE 802.11p MAC protocol with two priorities in the simulation platform. To verify the assumption for neglecting mobility in the analysis, we integrated the mobility model based on [21] in the simulation. Briefly, this mobility considers that nodes arrive at a unidirectional highway with length R (in meters) according to a Poisson process with the parameter ρ vehicles per second. The movement of each node consists of random time intervals, called mobility epochs, which are exponentially distributed with parameter δ. During each epoch, a node moves with a constant speed that is independently chosen from a Gaussian distribution with parameters $G(\eta, \sigma^2)$. This mobility model has the advantage of being mathematically tractable [21]. Its accuracy in capturing the main characteristics of vehicles' mobility in a highway network was also discussed in [22] using traffic emulator software and comparisons. Table I presents the parameter settings that were used for the derivation of simulation and numerical results. The node density of the network is set to $\phi = 0.1$ vehicles per meter for the analysis, which corresponds to a node's arrival rate of $\rho = 2.73$ vehicles per second in the simulation [11]. Three per-node message arrival rates are considered, i.e., $\lambda_0 = 10, 20,$ and 30 messages per vehicle per second. Therefore, following the expression $\lambda = \phi\lambda_0$, three message arrival rates to the per unit-highway length with idle-node population are obtained, which are $\lambda = 1$, 2 and 3 messages per meter per second.

Fig. 2 shows the results for the average numbers of concurrent transmissions $\bar{n}$ and the messages in the backoff process $\bar{k}$ based on (21) and (22), respectively, as functions of the transmission range and with the unit-length message arrival rate

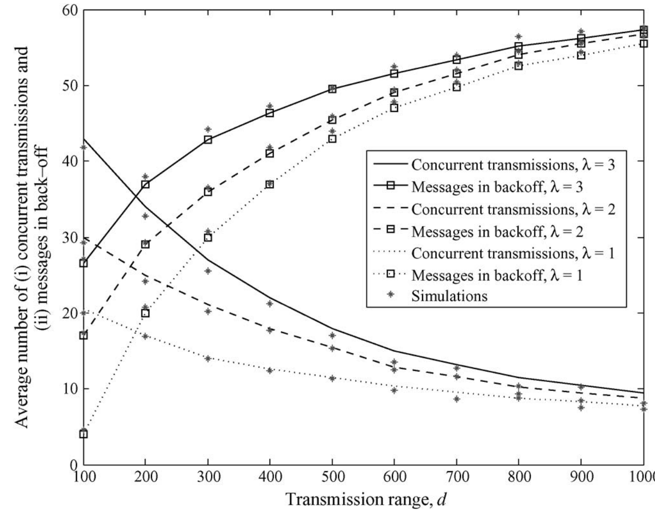

Fig. 2. Average numbers of concurrent transmissions and messages in a backoff process as a function of the transmission range for different message arrival rates.

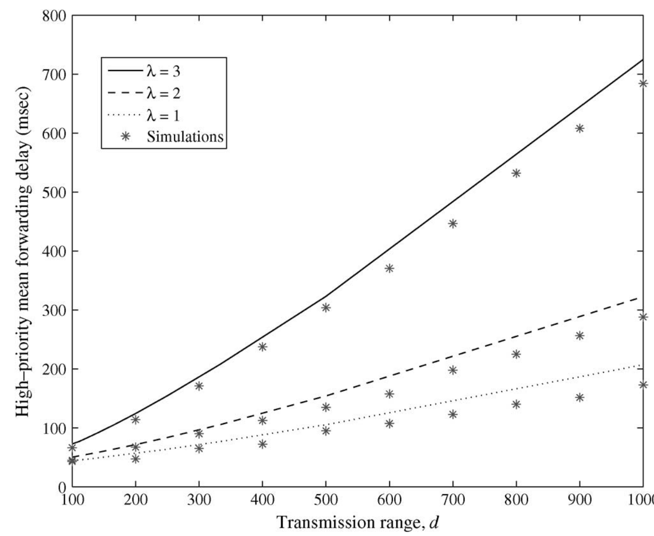

Fig. 3. Average delay of high-priority message dissemination for $H = 5$ hops of communication as functions of the transmission range, with the unit-length message arrival rate λ taken as a parameter.

λ taken as a parameter. It can be observed that $\bar{n}$ and $\bar{k}$ are decreasing and increasing functions of the transmission range, respectively. Furthermore, for a constant transmission range, when the message arrival rate increases, $\bar{n}$ and $\bar{k}$ increase with smaller values for higher transmission ranges.

Figs. 3 and 4 present the average delay for the dissemination of high-priority messages based on (31) for $H = 5$ hops of communication. Fig. 3 plots the delay as a function of nodes' transmission range d, with the message arrival rate per unit length λ as a parameter, whereas in Fig. 4, the message arrival rate is taken as the variable, and the transmission range is considered a parameter. It may be seen that the average delay increases as functions of d and λ, because in both cases, the contentions for the channel access increase in each hop of communication. In addition, the average delay as a function of transmission range almost linearly increases, whereas this increase takes a higher slope when λ is taken as a variable. The results are helpful in determining the maximum transmission

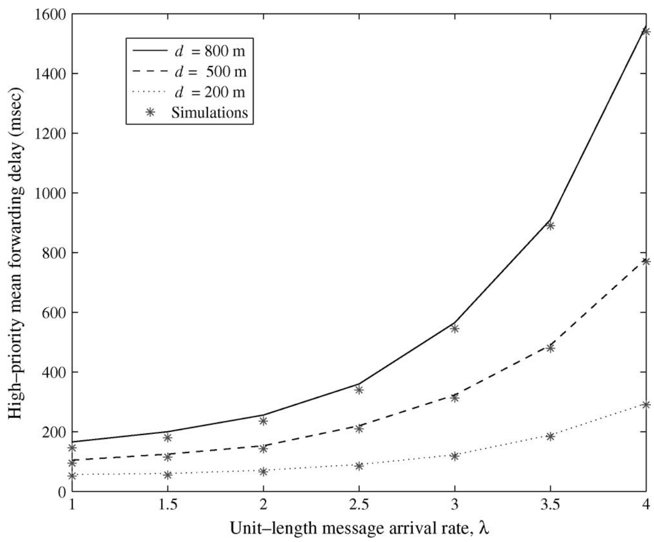

Fig. 4. Average delay of high-priority message dissemination for $H = 5$ hops of communication as a function of the unit-length message arrival rate, with the transmission range d taken as a parameter.

range for a reliable communication or in employing an adaptive transmission range mechanism. For example, for $\lambda = 3$ and $d = 700$ in Fig. 3, the mean forwarding delay is approximately 500 ms for five hops of communication, which indicates a mean forwarding delay of 100 ms per communication hop. On the other hand, a maximum acceptable delay for safety message dissemination is defined as 100 ms by DSRC [1]. Thus, the transmission range should not be chosen higher than 700 m to keep the communication reliable. As another example, for $d = 800$ in Fig. 4, the forwarding delay exceeds 500 ms when the message arrival rate approaches 2.7. Thus, the transmission range should be reduced to keep the transmission reliable. As it may be observed, there is a good agreement between the numerical and simulation results. This case confirms the accuracy of the assumptions made in the analysis.

VI. Conclusion

The broadcasting and transmission of safety messages with different priorities, such as those for frequent and event-driven applications, are some of the main concerns for the adequate implementation of a VANET. In this paper, by the employment of the IEEE 802.11 MAC protocol for broadcasting safety messages in a VANET, we have derived the joint distribution of the number of low-priority messages in transmission and backoff processes. It was stated that the proposed modeling is general and it can be used to derive different performance measures for highway-based VANETs. As a case study, we derived the average multihop delay for infrequent yet high-priority messages in the presence of low-priority messages. It is a well-known phenomenon that increasing the transmission range increases the network connectivity. On the other hand, it increases the backoff time for the messages, which results in a higher multihop transmission delay. Therefore, a good tradeoff must be made between the transmission range and the end-to-end transmission delay, particularly for event-driven applications that are sensitive to delay. Furthermore, the traffic of frequent low-priority applications should be controlled to satisfy the required delay bounds for the immediate high-priority traffic. As aforementioned, to adapt to IEEE 802.11p requirements, we may also consider a smaller contention window size for high-priority messages to assess its optimum value. As our future work, we will consider the performance modeling of VANETs with multiple types of traffic. We would also like to study the very challenging problem of allowing a node to have more than one message waiting for transmission.

References

[1] *Dedicated Short-Range Communication (DSRC) Working Group*. [Online]. Available: http://grouper.ieee.org/groups/index.html

[2] K. Mershad, H. Artail, and M. Gerla, "We can deliver messages to far vehicles," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 3, pp. 1099–1115, Sep. 2012.

[3] N. An, T. Gaugel, and H. Hartenstein, "VANET: Is 95% probability of packet reception safe?" in *Proc. Int. Conf. ITST*, Aug. 2011, pp. 113–119.

[4] S. Yousefi, M. Fathy, and A. Benslimane, "Performance of beacon safety message dissemination in vehicular ad hoc networks (VANETs)," *J. Zhejiang Univ. Sci. A*, vol. 8, no. 12, pp. 1990–2004, Nov. 2007.

[5] B. Sikdar, "Comparison of broadcasting schemes for infrastructure to vehicular communications," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 2, pp. 492–502, Jun. 2012.

[6] S. Eichler, "Performance evaluation of the IEEE 802.11p WAVE communication standard," in *Proc. 66th IEEE VTC*, Baltimore, Sep. 2007, pp. 2199–2203.

[7] X. Ma, X. Chen, and H. H. Refai, "On the broadcast packet reception rates in one-dimensional MANETs," in *Proc. IEEE GLOBECOM*, New Orleans, LA, Nov. 2008, pp. 1–5.

[8] W. Zhang, "Analysis of packet forwarding in VANETs using probabilistic channel model," in *Proc. 69th IEEE VTC*, Barcelona, Spain, Apr. 2009, pp. 1–5.

[9] A. Vinel, V. Vishnevsky, and Y. Koucheryavy, "A simple analytical model for the periodic broadcasting in vehicular ad hoc networks," in *Proc. IEEE GLOBECOM Workshops*, New Orleans, LA, Nov. 2008, pp. 1–5.

[10] J. Sahoo, E. H. Wu, P. K. Sahu, and M. Gerla, "Binary-partition-assisted MAC-layer broadcast for emergency message dissemination in VANETs," *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 3, pp. 757–770, Sep. 2011.

[11] M. Khabazian, S. Aïssa, and M. Mehmet-Ali, "Performance modeling of message dissemination in vehicular ad hoc networks with priority," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 1, pp. 61–71, Jan. 2011.

[12] R. Chen, W.-L. Jin, and A. Regan, "Broadcasting safety information in vehicular networks: Issues and approaches," *IEEE Netw.*, vol. 24, no. 1, pp. 20–25, Jan./Feb. 2010.

[13] N. Wisitpongphan, F. Bai, P. Mudalige, V. Sadekar, and O. Tonguz, "Routing in sparse vehicular ad hoc wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 8, pp. 1538–1556, Oct. 2007.

[14] K. Bilstrup, E. Uhlemann, and E. G. Strom, "Medium access control in vehicular networks based on the upcoming IEEE 802.11p standard," in *Proc. 15th World Congr. ITS*, New York, Nov. 2008, pp. 1–12.

[15] A. Kumar, D. Manjunath, and J. Kuri, *Communication Networking: An Analytical Approach*. Amsterdam, The Netherlands: Elsevier, 2004.

[16] J. F. Hayes and T. V. J. Ganesh Babu, *Modeling and Analysis of Telecommunications Networks*. Hoboken, NJ: Wiley, 2004, p. 150.

[17] M. Khabazian and M. Mehmet-Ali, "A continuous communication path availability analysis in vehicular ad hoc networks," in *Proc. 69th IEEE VTC*, Barcelona, Spain, Apr. 2009, pp. 1–5.

[18] M. J. Khabbaz, W. F. Fawaz, and C. M. Assi, "A simple free-flow traffic model for vehicular intermittently connected networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 3, pp. 1312–1326, Sep. 2012.

[19] Y. Gongjun and S. Olariu, "A probabilistic analysis of link duration in vehicular ad hoc networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 4, pp. 1227–1236, Dec. 2011.

[20] A. Kesting, M. Treiber, and D. Helbing, "Connectivity statistics of store-and-forward intervehicle communication," *IEEE Trans. Intell. Transp. Syst.*, vol. 11, no. 1, pp. 172–181, Mar. 2010.

[21] M. Khabazian and M. Mehmet Ali, "A performance modeling of connectivity in vehicular ad hoc networks," *IEEE Trans. Veh. Technol.*, vol. 57, no. 4, pp. 2440–2450, Jul. 2008.

[22] M. Khabazian, M. Mehmet-Ali, and S. Aïssa, "Analysis of continuous communication availability in vehicular ad hoc networks," *IEEE Syst. J.*, DOI: 10.1109/JSYST.2012.2185396, IEEE early access.

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