Performance Modeling of Message Dissemination In Vehicular Ad Hoc Networks with Priority

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Performance Modeling of Message Dissemination In Vehicular Ad Hoc Networks with Priority

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***Abstract*—In this paper, we present an analytical study for the performance of message dissemination in vehicular ad hoc networks (VANETs) with two priority classes. It is assumed that the message traffic generated by event-driven safety applications has higher priority compared to the remaining network traffic. First, we derive the distribution of the number of concurrent transmissions of lower priority messages in the system at the steady state, through a birth-death process analysis. The distribution has a simple product form solution. We also derive the percentage of destination node population which cannot receive the message error free due to interference. Subsequently, we determine the average forwarding distance and the number of nodes which receive a high-priority message in the presence of low-priority traffic. Numerical results are provided along with simulation results that confirm the accuracy of the proposed analysis. The distribution of the number of concurrent transmissions is shown to have a bell-shape curve. Results also show that larger transmission ranges do not necessarily improve the per hop safety-message forwarding distance as more nodes may be exposed to interference, especially in networks with higher node densities.**

***Index Terms*—Vehicular ad hoc networks, performance analysis, message dissemination, traffic priority.**

I. Introduction

VEHICULAR ad hoc networks (VANETs) are emerging as a potential technology for intelligent transportation systems (ITS) to provide safety and comfort applications through wireless vehicle-to-vehicle communications. Comfort applications are expected to improve the passengers' comfort and optimize traffic efficiency, while the safety applications aim at improving driving safety. Safety applications can further be categorized into periodic and event-driven applications. The first category has an informative nature, as messages are disseminated among vehicles regularly to inform them about their local parameters such as speed and position. On the other hand, in the second category, namely event-driven applications, a safety message is broadcast by a specific vehicle which experiences or detects a hazard or an unusual event. Then the message will propagate from a source outwards as far as possible informing as many nodes in the network about the situation. As a result, such applications have the highest priority. We note that in the steady state, comfort and periodic messages are expected to constitute the major part of the message traffic among the nodes in the network, which may reduce the resource availability for the higher priority event-driven messages and affect, hence, the delivery of high-priority messages, which may in turn yield serious consequences. For example, if a vehicle misses an event-driven safety message from an application such as crash-avoidance from a leading neighbor, this may have disastrous consequences. Thus, dependability of VANETs is a very important issue. The study of the performance of such networks can help protocol developers design efficient networking solutions and smartly decide about their implementation and parameter tradeoffs.

Next, we discuss previous works on dissemination of safety messages. In [1], the authors present a lower bound for the probability that a vehicle receives a safety message through multi-hop communication from a source at a distance d away and within t seconds. This probability is derived as a function of single-hop communication reliability denoted by a constant probability p. The analysis studies the tradeoff between the parameters t, p and the inter-vehicle distance, d, assuming that inter-vehicles distances are constant, which is not practical. The work in [2] analyzes the problem of dissemination of safety messages from another perspective. A safety area around the point where a hazard happens is introduced and the goal is to optimize the message dissemination strategy such that all vehicles within this area can receive the message. Multiple broadcast cycles are assumed so that within a certain time all the designated vehicles are guaranteed to be informed. Performance measures such as the average delay, the probability that a vehicle is informed, and the average number of duplicate messages received by a vehicle within this area, are derived. however, it is assumed that all vehicles within the transmission range of a source node can forward the safety message correctly and collisions are not taken into consideration. On the other hand, [3] presents a medium access scheme to speed up safety message dissemination. In the corresponding approach, a spatial differentiation is introduced at the MAC layer where the potential relay nodes are assigned different access priorities through different contention window sizes. Therefore, a relay node with a higher distance from the source node is assigned a shorter contention window size. Several metrics such as message blocking probability and average message delivery delay are derived. Finally, [4] studies the influence of safety message generation rate on the mean delivery delay and the probability of successful message reception in one-hop communication scenario based on IEEE

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802.11p VANET standard. It is assumed that messages may be lost due to factors such as noise, collisions and replacement of old messages by newly arriving ones.

All of the above analyses ignore the effect of hidden terminal activity in the communications. IEEE 802.11 broadcasting mode assumes no RTS/CTS handshaking since all nodes within the transmission range of a sender are considered as recipients. As a result, the size of the area with potential hidden terminals in the network can be dramatically larger than that of unicast mode, which makes the communications more sensitive to the hidden terminal effect.

To the best of the authors' knowledge, studies which address the collision and hidden terminal effects assume a single-hop scenario, and then extends the results to multi-hop communications under independence assumption. This approach fails to model hidden node activities and collisions between the nodes adequately and, therefore, fails to capture the dynamics of the system. For example, [5] finds the probability that a receiving node is exposed to the hidden terminal effect. Therein, the hidden terminal, which is out of the transmission range of the sender, is assumed to be in isolation, however, in reality the hidden node itself may be exposed to hidden node activity in multi-hop communications. [6] also makes use of the independence assumption to evaluate the throughput and collision probabilities for all nodes within the transmission range of the sender in a single-hop network. Among the broadcasting algorithms, [7] and [8] evaluate the mean message forwarding distance and the probability of successful message reception based on the same independence assumption.

Furthermore, previous works assume only a single type of traffic in the network. In reality, the network will most of the time handle low-priority traffic and in emergency situations will have to transfer also high-priority messages.

In this work, we present an analytical model to determine the main performance measures of VANETs with two priority classes of traffic. We assume that the traffic generated by comfort and periodic applications have low priority, while the event-driven safety messages have high priority. We assume that the message dissemination in VANETs is based on IEEE 802.11 broadcasting mode, which is appropriate for service differentiations [9]. Our modelling also takes a multi-hop perspective rather than generalization of single-hop results. In the network, interference may occur between two transmitting nodes because of the overlapping between their transmission ranges. If the transmitting nodes themselves are within the overlap area we refer to this interference as internal, otherwise as external interference, which are traditionally known as collision and hidden terminal activities, respectively. In our analysis, we carefully take care of the internal and external interferences. We assume that a destination can correctly receive a message as long as it is not exposed to the hidden terminal effect and that the message does not experience collision. First, we derive the probability of interference between two nodes. Then, using a birth-death process analysis, we derive the probability distribution of the number of concurrent transmissions in the system at the steady-state, and the percentage of destination nodes population which cannot receive the message correctly due to interference. We also study the performance of high-priority traffic which represents a relatively small component of the overall traffic volume in the presence of lower-priority traffic. We determine important performance measures such as the average number of nodes which receive the high-priority safety message, the average message forwarding distance per hop, and the average number of hops that the message will travel.

Based on our analysis, we present numerical results which show that selection of a large transmission range does not necessarily improve the per-hop forwarding distances of high-priority safety messages, due to the fact that more receiving nodes may be exposed to interference. Further, the probability that a receiving node is exposed to interference is shown to increase with the network node density. We also present simulation results that confirm the accuracy of our analysis.

The rest of this paper is organized as follows: Section II describes the system model; Section III presents the analysis of the signal coverage of low-priority messages at the steady state; Section IV presents the modelling of the number of transmissions; Section V provides the analysis of high-priority messages in the presence of low-priority traffic; Section VI describes the simulation setup; Section VII discusses the numerical and simulation results, followed by the paper's conclusions.

II. Network Model

In this study, we assume a one-dimensional VANET modelling communications in a highway with length R meters. The nodes have constant transmission ranges of d meters, therefore, each transmission covers a section of the highway with length $2d$ meters. We consider the message traffic among vehicles moving in the same direction and neglect mobility since nodes remain almost stationary within a message transmission time. However, a mobility model is considered in the simulation to confirm the validity of this assumption. Based on the experimental results presented in [10], we assume that the nodes are dispersed in the highway according to a Poisson process with a parameter of ϕ nodes per unit length. Hence, from the properties of Poisson distribution, the location of nodes will have a uniform distribution.

We assume that the low-priority traffic arrives to the VANET according to a Poisson process with parameter λ_0 message/veh/sec. The assumption of Poisson distribution for traffic arrivals has been made in many studies such as [5], [6], [7], and [11]. Then, as shown in Appendix I, the inter-arrival time of the lower priority messages per unit length of the highway will be exponentially distributed with parameter $\lambda = \phi\lambda_0$ message/veh/sec.

A message will be transmitted in the channel following a randomly chosen back-off time. The slot durations of a back-off counter is denoted by a constant value of σ seconds. We assume that the arrival time of a message to the channel corresponds to the moment its back-off counter reaches zero, after which the message is transmitted. Therefore, it is assumed that the MAC back-off time is part of the message inter-arrival time. The accuracy of this assumption is also verified by the simulations provided in section VI. We also consider that the transmission time of a message is exponentially distributed with parameter μ.

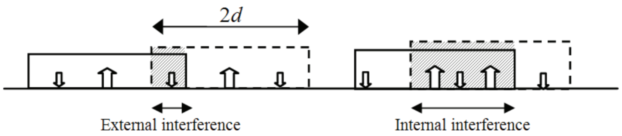

Fig. 1. Transmission interferences.

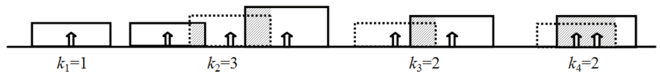

Fig. 2. An example of activity regions in a VANET with n = 8 transmissions.

In the network under consideration, two concurrent transmissions interfere with each other whenever the distance between the transmitting nodes is less than $2d$. As stated earlier, we classify the interference as $internal$ or $external$, which are traditionally known as collision and hidden terminal activity, respectively. The interference is referred to as internal if the distance between two transmitting nodes is less than d, and external otherwise. Fig. 1 shows the two cases of interference, where the crossed areas correspond to the interference regions, and the transmitting and receiving nodes are shown with upward and downwards arrows, respectively [12].

III. Signal Coverage Analysis of Lower Priority Messages at the Steady State

In this section, we derive several measures which are needed to determine the probability distribution of the number of concurrent transmissions of low-priority messages in the VANET at steady-state. Specifically, we derive the total length of activity regions, total length of interference sub-regions and the distribution of the number of activity regions.

A. Total Length of Activity Regions and Interference Sub-regions

First, we determine the total length of the network where there is signal activity. As shown in Fig. 2, the number of concurrent transmissions may divide the network into alternating regions of activity and inactivity at any given time. In an activity region, there is at least one on-going transmission; however the number of active signals may vary in an active region from one point to the next. Let us assume that the number of concurrent transmissions is n and the number of activity regions in the channel is m at a point in time. In each activity region, a number of transmissions may interfere with each other. Assuming that two transmissions interfere with each other, we denote the probabilities of internal and external interference by P_c and P_h, respectively, where $P_c + P_h = 1$. These probabilities are derived in Appendix B. Let k_i denote the number of overlapping transmissions in the i-th activity region, where $\sum_{i=1}^{m} k_i = n$ and $1 \leq m \leq n$. We note that the special case of $k_i = 1$ corresponds to an isolated transmission. In the case where $k_i \geqslant 3$, for simplicity of the analysis, we assume that each transmission will overlap with two other transmissions, except for the two transmissions at the opposite end points of an activity region. These border transmissions will overlap with a single transmission only. An example for this case is shown in Fig. 2 for $k_2 = 3$. First, we determine the average length of the i-th activity region in the network.

$Lemma$ 1: Denote r_{k_i} as the random variable which defines the length of the i-th activity region with k_i transmitting nodes, then the expected value of r_{k_i} is given by,

$$E(r_{k_i}) = [2 + (k_i - 1)(0.5P_c + 1.5P_h)]d \quad \text{for } k_i \geqslant 1, \quad (1)$$

where $\sum_{i=1}^{m} k_i = n$.

Proof: Let us assume that there are $k_i - 1$ transmitting nodes in the i-th activity region and a new transmission joins this activity region. The new transmission may join only either ends of the activity region and the distance between the new transmission node and the border transmission nodes will be within the intervals [0, d] or [d, $2d$] depending on the type of interference. Therefore, following the assumption of uniformly distributed nodes' location, the new transmission extends the length of the activity region on average by $0.5d$ or $1.5d$, depending on whether it causes an internal or external interference, respectively. Thus, we have the following recursive relation for the expected value of the length of the i-th activity region:

$$E(r_{k_i}) = E(r_{k_i - 1}) + (0.5P_c + 1.5P_h)d, \quad (2)$$

with the initial value $E(r_1) = 2d$. The repeated application of the above recursion gives the average length for the i-th activity region as shown in (1). ■

Each activity region consists of alternating sub-regions of interference and non-interference. In a non-interference region, only a single signal is active, while in the interference region, multiple signals are active. The nodes in a non-interference sub-regions will be able to receive the message correctly. For example, the second activity region shown in Fig. 2 consists of two interference sub-regions which are illustrated by crossed areas.

$Lemma$ 2: Denote h_{k_i} as the random variable defining the total length of the interference sub-regions within the i-th activity region in the network. The average length of these sub-regions, $E(h_{k_i})$, is given by:

$$E(h_{k_i}) = (k_i - 1)(1.5P_c + 0.5P_h)d \quad \text{for } k_i \geqslant 1. \quad (3)$$

Proof: Since the total range of a transmission is $2d$ and the average non-interference region is either $0.5d$ or $1.5d$, depending on whether the interference is internal or external, then the average length of interference sub-region added by a new transmission will be either $1.5d$ or $0.5d$. As a result, similar to (1), the average length of interference sub-regions within the i-th activity region may be determined according to (3). ■

Let $\ell_m(n)$ and $h_m(n)$ denote the total lengths of the activity regions and interference sub-regions that contain n transmissions with m activity regions, respectively. Then, the averages of these random variables are given by,

$$E[\ell_m(n)] = \sum_{i=1}^{m} E(r_{k_i}), \tag{4}$$

$$E[h_m(n)] = \sum_{i=1}^{m} E(h_{k_i}). \tag{5}$$

Substituting (1) and (3) in the above expressions and noting that $\sum_{i=1}^{m} k_i = n$ yields,

$$E[\ell_m(n)] = [2m + (0.5P_c + 1.5P_h)(n-m)]d, \tag{6}$$

$$E[h_m(n)] = (1.5P_c + 0.5P_h)(n-m)d. \tag{7}$$

Next, we uncondition the above expected values with respect to the number of activity regions, m:

$$E[\ell(n)] = \sum_{m=1}^{n} E[\ell_m(n)]P_m(n), \tag{8}$$

$$E[h(n)] = \sum_{m=1}^{n} E[h_m(n)]P_m(n). \tag{9}$$

Then, substituting (6) and (7) into the above expressions, we obtain,

$$E[\ell(n)] = \begin{cases} [2\bar{m}(n) + (0.5P_c + 1.5P_h)(n - \bar{m}(n))]d \\ \qquad \text{if } n > 0, \\ 0 \qquad \text{if } n = 0, \end{cases} \tag{10}$$

$$E[h(n)] = \begin{cases} (1.5P_c + 0.5P_h)(n - \bar{m}(n))d \\ \qquad \text{if } n > 1, \\ 0 \qquad \text{if } n = 0, 1, \end{cases} \tag{11}$$

where $\bar{m}(n) = \sum_{m=1}^{n} mP_m(n)$ and $P_m(n)$ is the probability distribution of the number of activity regions with n concurrent transmissions, which will be determined in the following section.

B. Distribution of the Number of Activity Regions

Next, we derive the probability distribution of the number of activity regions given that there are n concurrent transmissions in the network. This problem is closely related to the number of partitions of a positive integer n into exactly m positive integer parts where, in our study, n and m refer to the number of transmissions and activity regions, respectively. From the result in [13], we obtain the following recursion where $Q(n, m)$ denotes the number of partitions of n into m parts:

$$Q(n, m) = \sum_{i=1}^{n-m+1} Q(n-i, m-1), \tag{12}$$

such that,

$$Q(n, m) = \begin{cases} 0 & \text{if } n < m \text{ or } n < 1 \text{ or } m < 1, \\ 1 & \text{if } n = m \text{ or } m = 1. \end{cases} \tag{13}$$

For the application of the above result to our problem, we need to discretize our model. Assume that the lengths of the individual activity and inactivity regions in the network are integer multiples of the transmission range d. We consider that the highway is divided into cells of equal length d, and that the activity and inactivity regions always occupy a number of cells completely. Let us define Γ as the total number of cells in the network, and $\theta_m(n)$ as the number of cells in the inactivity regions when there are n transmissions with m partitions. Further, let $L_m(n)$ denote the number of cells whose total length is closest to the length $\ell_m(n)$. Thus, we have,

$$\theta_m(n) = \Gamma - L_m(n). \tag{14}$$

When the number of activity regions is m, then the number of inactivity regions must be $m-1$, m or $m+1$, given that the activity and inactivity regions alternate with each other. As a result, the total number of ways that the activity and inactivity regions may be partitioned to is given by,

$$C'_n(m) = Q(n, m) \sum_{i=m-1}^{m+1} Q(\theta_m(n), i), \tag{15}$$

$$C'_n(1) = \begin{cases} 1 & \text{if } \theta_m(n) = 0, \\ 0 & \text{otherwise.} \end{cases} \tag{16}$$

However, the above partitions are not equally likely, since the total length of the activity regions, $E[\ell_m(n)]$, depends on m. Clearly, the shorter the length $E[\ell_m(n)]$, the lower will be the probability of having n transmissions in the activity regions. This probability may be written as,

$$A_n(m) = \left(\frac{E[\ell_m(n)]}{R}\right)^n, \tag{17}$$

where R denotes the length of the highway. Thus, we have to weigh the number of ways for each partition with this probability. Let $C_n(m)$ denote the weighted number of ways for each partition, we have,

$$C_n(m) = A_n(m)C'_n(m). \tag{18}$$

Then, the probability that n transmissions will be partitioned into m activity regions is given by,

$$P_m(n) = \frac{C_n(m)}{C_n}, \tag{19}$$

where $C_n = \sum_{m=1}^{n} C_n(m)$.

IV. Birth-Death Modeling of the Number of Transmissions

In this section, we determine the distribution of the number of concurrent transmissions of lower priority messages in the network at the steady-state. Since the arrival of these messages follows a Poisson distribution and their transmission times are exponentially distributed with parameter μ, the number of transmissions in the system may be modelled as a birth-death process. Thus, the arrival of a message corresponds to a birth and the completion of the transmission of a message to a death. Let us introduce the following notations.

n_t: random variable denoting the number of concurrent transmissions within the network. The range of n_t is given by $1 \le n_t < n_{\max}$ where $n_{\max}$ will be determined shortly.

$a_t(n)$, $b_t(n)$: birth and death rates, respectively, when the number of transmissions is $n_t = n$.

Next, we determine the birth and death rates when the state of the system is $n_t = n$. The expected total length of the activity regions at this state is given by $E[\ell(n)]$. Since only nodes in the inactivity regions may generate messages, the birth rate at this state is given by,

$$a_t(n) = (R - E[\ell(n)])\lambda, \tag{20}$$

where as aforementioned earlier, λ is the message arrival rate per unit length of the highway. We note that the above rate cannot be a negative number and $E[\ell(n)] \leq R$ must be always valid. Solving this inequality for n determines the maximum number of concurrent transmissions, $n_{\max}$, that may exist in the network. The death rate at this state will be given by,

$$b_t(n) = n\mu. \tag{21}$$

Finally, applying the product form solution [14] to our transmission model, the probability distribution of the number of concurrent transmissions at the steady-state is given by:

$$P_t(n) = P_t(0) \prod_{i=0}^{n-1} \frac{a_t(i)}{b_t(i+1)}, \quad 1 \leq n < n_{\max}, \tag{22}$$

where $P_t(0)$ is found from the normalization condition. Next, let $\bar{n}_t$ and $\bar{\ell}$ denote the average number of concurrent transmissions and the average of total size of the activity regions at the steady state, respectively. Then, we have:

$$\bar{n}_t = \sum_{n=0}^{n_{\max}} n P_t(n), \tag{23}$$

and

$$\bar{\ell} = \sum_{n=1}^{n_{\max}} E[\ell(n)] P_t(n), \tag{24}$$

where $E[\ell(n)]$ is given by (10). In (24), index n starts from 1, given that for $n = 0$, we have $E[\ell(0)] = 0$.

Next, we determine the probability that a destination node will not be able to receive a message. The destination nodes which happen to be in the interference sub-regions will not be able to receive a message transmission. Let us define P_i as the probability that a destination node is in an interference region. Then, P_i is given by,

$$P_i = \sum_{n=1}^{n_{\max}} \frac{E[h(n)]}{E[\ell(n)]} P_t(n). \tag{25}$$

The probability P_i may be interpreted as the percentage of destination node population which cannot receive the message correctly due to interference. P_i plays an important role in the design of an effective forwarding algorithm. This probability may be interpreted as the possibility that a node within the transmission range of a sender is blocked and cannot participate as a next forwarder. Interestingly, it can be concluded, as long as the physical layer is not an issue, that all nodes within the transmission range of a sender experience the same probability of being blocked, which is independent from their distances to the sending node.

V. Analysis of Higher Priority Message Dissemination in the Presence of Lower Priority Traffic

In the broadcast mode of VANETs, all receivers within the transmission range of a sending node collaborate to forward a high-priority message to a further distance in an opportunistic way. The next forwarder may be selected using different methods. In general, opportunistic forwarding methods in VANETs can be divided into timer-based or MAC-based approaches [15]. Irrespective of the chosen method, hidden node activity and collisions reduce the number of receivers and consequently they can alter the forwarding distance.

In the following, we do not aim to propose or optimize a forwarding mechanism. We are rather interested in studying the effects of the aforementioned external and internal interferences on the possible receivers within the transmission range of the sending nodes. As an example, we consider contention-based forwarding (CBF) mechanism which is a timer-based forwarding algorithm [16]. In CBF, when a sending node broadcasts a message, the recipients of the message decide among themselves who will be the next one to forward the packet. The forwarding node is selected by the use of a contention period, where each node selects a waiting time depending on its distance to the final destination. Therefore, the node that offers the maximum progress selects the smallest waiting time and forwards the message at the end of this period, which implicitly informs the other nodes not to forward the message.

In this section, we apply the results provided in the previous section to analyze CBF performance in broadcasting high-priority event-driven safety messages in the presence of low-priority traffic. We assume that high-priority messages will be generated infrequently and at anytime there will be at most one such message propagating in the network. Further, it is assumed that the propagation of a high-priority safety message is unidirectional, either in the same direction as the flow of vehicle traffic or in the opposite direction. A new arriving high-priority message will see the low-priority traffic in equilibrium. In the following, we determine important performance measures, namely, the average message forwarding distance in a hop, the average number of message recipients, and the average number of communication hops that a message travels in the network.

A. Average Per-Hop Message Forwarding Distance

We determine the distance covered by a high-priority safety message in each hop of communication. The probability distribution of the node population size within the transmission range of a sending node is given by the following Poisson distribution,

$$P_d(j) = \frac{e^{-\psi}\psi^j}{j!} \qquad j = 0, 1, ..., \tag{26}$$

where parameter $\psi = \phi d$, which represents the mean node population within the transmission range of the sending node. The interference splits a transmission range into two, with a node being in the interference or non-interference region with probability P_i or $(1 - P_i)$, respectively, where P_i is given by (25). Let ω be the distance of the border point between the non-interference and interference regions from the sending node. This distance can be approximated as $\omega = (1 - P_i)d$. According to the CBF algorithm, the distance covered in a hop equals the distance of the node farthest from the sending node in the non-interference region, as the farthest node will choose the smallest waiting time. Assuming that there are k nodes in the non-interference region, then the probability density function (pdf) of this distance is given by the k-th order statistics of k uniformly distributed numbers in (0, ω) [17]. This pdf can be written as,

$$f_{y_k}(x) = \frac{k}{\omega^k} x^{k-1}, \quad 0 \leq x \leq \omega. \tag{27}$$

Let $f_y(x)$ denote the pdf of the distance covered in a single hop, then we have,

$$f_y(x) = \frac{1}{1 - P_s(0)} \sum_{k=1}^{\infty} f_{y_k}(x) P_s(k), \quad 0 \leq x \leq \omega, \tag{28}$$

where $P_s(k)$ denotes the probability that k nodes receive the high-priority message successfully or, equivalently, k nodes exist in the non-interference region of a sending node. Since each node in the reception area will be in the interference sub-region according to a Bernoulli trial with probability P_i, the number of nodes that will receive the message successfully will have a Poisson distribution with parameter $\psi(1 - P_i)$. Hence, $P_s(k)$ can be written as,

$$P_s(k) = \frac{e^{-\psi(1-P_i)} [\psi(1 - P_i)]^k}{k!}. \tag{29}$$

The normalization constant multiplying the summation in (28) is included to exclude zero population possibility in the non-interference region of one-hop communication. From the above, the average forwarding distance in a hop, $\bar{y}$, can be expressed as,

$$\begin{aligned} \bar{y} &= \int_0^{\omega} x f_y(x) dx, \\ &= \int_0^{\omega} \frac{1}{1 - P_s(0)} \sum_{k=1}^{\infty} \frac{k}{\omega^k} x^k P_s(k) dx, \\ &= \frac{\omega}{1 - P_s(0)} \sum_{k=1}^{\infty} \frac{k P_s(k)}{1 + k}. \end{aligned} \tag{30}$$

B. Average Number of High-Priority Message Recipients

Let z denote the distance between two consecutive nodes, then z is exponentially distributed with the following pdf,

$$g(z) = \phi e^{-\phi z}, \quad 0 < z < \infty. \tag{31}$$

Based on the CBF algorithm, even if all nodes in the transmission range fall into the interference region, the transmission of a high-priority message will be repeated until the message is delivered to one of the destination nodes. Therefore, a high-priority message can be forwarded as long as the distance between two consecutive nodes is less than d meters. Thus, the probability that the forwarding of a high-priority message stops, denoted by P_e, is given by,

$$P_e = 1 - \int_0^d \phi e^{-\phi z} dz = e^{-\phi d}. \tag{32}$$

Let u denote the number of nodes which form a single cluster, with a cluster defined as a set of nodes whose consecutive distances are all less than d. As a result of repetitive forwarding, u also corresponds to the number of nodes which will receive the high-priority safety message. The probability distribution of u is geometric and given by,

$$\text{Prob}\,(u = j\,\text{nodes}) = P_e(1 - P_e)^j, \quad j = 0, 1, 2 \ldots. \tag{33}$$

which has the mean value of,

$$\bar{u} = \frac{(1 - P_e)}{P_e}. \tag{34}$$

C. Average Number of Communication Hops

As the distances between all consecutive nodes in a cluster are less than the transmission range, the pdf of such distances is given by,

$$g(z|z < d) = \frac{g(z)}{1 - P_e}, \qquad 0 < z < d, \tag{35}$$

where $g(z)$ is given by (31). Therefore, the average distance between two consecutive nodes in a cluster is given by,

$$\begin{aligned} E(z|z < d) &= \frac{1}{1 - P_e} \int_0^d z g(z) dz, \\ &= \frac{1 - P_e(1 + \phi d)}{(1 - P_e)\phi}. \end{aligned} \tag{36}$$

Let Z denote the total distance that a high-priority safety message covers until its propagation terminates. Then, the average value of this distance is given by,

$$\begin{aligned} \bar{Z} &= \bar{u} E(z|z < d), \\ &= \frac{1 - P_e}{P_e} \cdot \frac{1 - P_e(1 + \phi d)}{(1 - P_e)\phi}, \\ &= \frac{1 - P_e(1 + \phi d)}{P_e \phi}. \end{aligned} \tag{37}$$

Finally, let n_h denote the number of hops it will take for the high-priority message to cover the distance Z. We note that n_h also corresponds to the number of forwarding nodes of the high-priority message. The average of this random variable is given by,

$$\bar{n}_h = \frac{\bar{Z}}{\bar{y}}. \tag{38}$$

VI. Simulation Setup

In this section, we describe the simulation setting which is used to confirm the analysis presented in the previous sections. This is an event-driven simulation platform developed using MATLAB software. We performed multiple independent simulations where each run terminates after a large number of transmissions for the duration of T_s minutes. In each run, statistics are collected after a warm-up period in order to guarantee that the system has reached the steady state. Then, the collected statistics are averaged over the multiple runs.

TABLE I
TRAFFIC PARAMETERS SETTINGS.

ρ (veh/sec)	ϕ (veh/m)	λ_0 (message/veh/sec)	λ (message/m/sec)
2.73	0.1	10	1.0
2.73	0.1	5	0.5
0.13	0.005	10	0.05
0.13	0.005	5	0.025

TABLE II
VEHICLE MOBILITY AND IEEE 802.11 MAC PARAMETERS SETTINGS.

Parameter	Description	Value
β	Vehicles mobility epoch rate	1
δ	Vehicles mean speed	100 km/hr
ζ	Vehicles speed standard deviation	3
CW	MAC contention window size	8 slots
σ	Slot duration	9 μsec
AIFS	Arbitration interframe space	34 μsec

We included the mobility model from [18] in the simulations to verify the assumption for neglecting mobility in the analysis. In this model, nodes arrive at a unidirectional highway with multiple lanes and length of R meters according to a Poisson process. The movement of each node consists of a sequence of random time intervals called mobility epochs. The node epoch durations are i.i.d. exponentially distributed and during each epoch, a node moves with a constant speed chosen independently from a Gaussian distribution. The movement of each node is independent from the others and the nodes may take over each other. A node leaves the system when it reaches the end of the highway.

In section II, we also assumed that the arrival time of a message to the channel corresponds to the moment that its back-off counter reaches zero, after which the message is transmitted. Therefore, the duration of MAC back-off process was assumed as part of the inter-arrival time of messages. To validate this assumption, we implemented IEEE 802.11p MAC functionality in the simulation platform. As described in [19], in the broadcast mode, a node which has a message to send first listens to the medium for an arbitration interframe space (AIFS) period. If it finds the channel free, it sends immediately, otherwise a uniformly distributed back-off time is chosen in the interval [0, CW]. Parameter CW defines the MAC contention window size. The source node decrements its back-off counter only when the channel is detected as idle after AIFS seconds, otherwise it is frozen. Whenever the counter reaches zero, the source node transmits its message immediately. In the broadcast mode, each message is allowed two transmission attempts and the contention window size remains constant.

In the following, we describe the simulation in more details. Five main data structures are implemented: An array, called $Event\_scheduler$ keeps track of all future events. The node mobility information is stored in an array called $Node\_array$. This information consists of node and stream IDs, present epoch duration, node speed, and latest registered location of the node. The message information is stored in an array called $Trans\_array$. This information consists of the message number, arrival time, transmission time, source location, source node ID, range of coverage, etc. Loc_array stores the lengths of inactivity regions and the intervals where collisions or hidden node activity may occur. Five types of events have been defined as follows:

- Type-1: *Arrival of a new node to the highway.* When this event happens, a record for the newly arrived node is entered in $Node\_array$ and a Type-2 event is scheduled for the node.
- Type-2: *Termination of a mobility epoch.* When this event happens, the location of a specific node is updated in $Node\_array$ and a new Type-2 event is scheduled for the node.
- Type-3: *Arrival time of a new message to a node and the back-off time.* When a node completes the transmission of its present message, it generates a new message after an exponentially distributed time interval with parameter λ_0. Whenever this event happens, a record of the new message is entered in $Trans\_array$ for the specific node. Further, Loc_array will be checked to determine if the new message is subject to an interference or a back-off process. Then, a Type-4 event is scheduled immediately which specifies when a new transmission terminates with consideration of the back-off time.
- Type-4: *Termination of message transmission time.* When this event happens, the information about that transmission will be removed from $Trans\_array$.
- Type-5: *Generation of a high-priority message.* This event may occur randomly when a new node arrives to the highway and generates a high-priority message. Whenever it happens, an array, called $HPmessage\_array$ stores the high-priority message dissemination parameters such as per-hop covered distance, number of covered hops, etc. At each time, at most one high-priority message is propagating in the network.

Finally, the collected statistics are recorded periodically and processed at the end of the simulation runs.

VII. NUMERICAL AND SIMULATION RESULTS

In this section, we present numerical results regarding the analysis in the paper, as well as simulation results to confirm the accuracy of the analysis. We assume that the message transmission time parameter has value $\mu = 500$ message/sec. Table I presents the vehicle arrival rates to the highway ρ, vehicle densities ϕ, and message arrival rates λ_0 which are used in the numerical and simulation results. As may be seen, there are two vehicle densities that correspond to rush and non-rush hour traffics [10]. We have also chosen two message arrival rates per vehicle. As a result, we have four possible values for the message arrival rate per m/sec, $\lambda = \phi\lambda_0$. Simulation durations were taken as $T_s = 40$ minutes and the highway length assumed to be $R = 20$ Km. Table II also presents the settings for the mobility model and MAC back-off process in the simulation. The values are based on [18] and [19].

Fig. 3 presents both analytical and simulation results for the probability of having n concurrent transmissions at the steady-

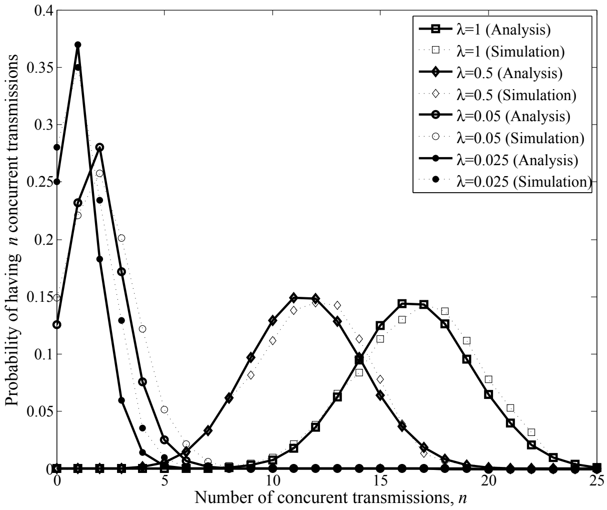

Fig. 3. Probability of having n concurrent transmissions, with the unit-length message arrival rate λ taken as parameter and d=200 m.

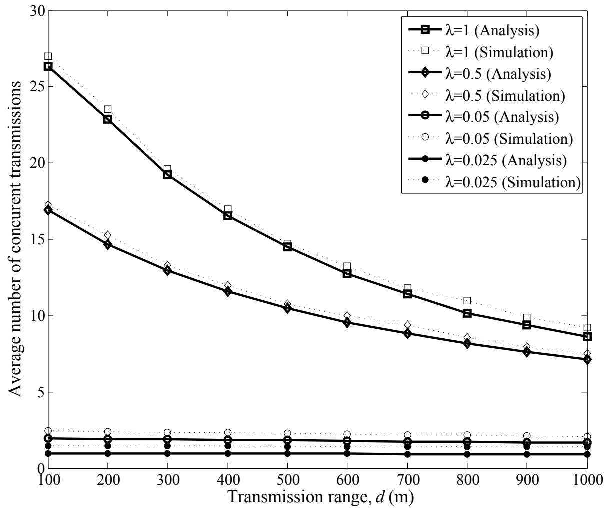

Fig. 4. Average number of concurrent transmissions versus the transmission range d, with the unit-length message arrival rate taken as parameter.

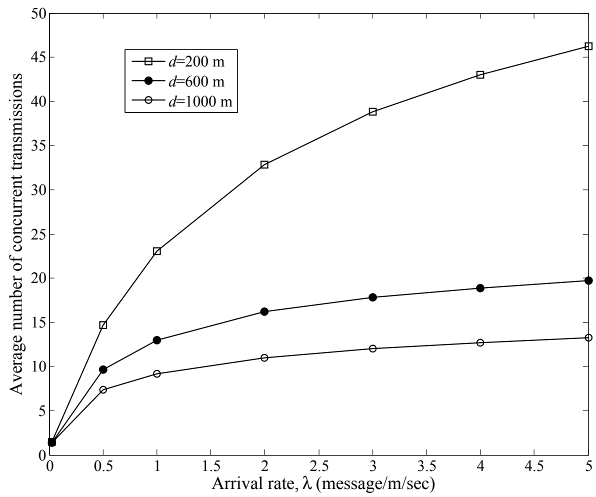

Fig. 5. Average number of concurrent transmissions at the steady-state as a function of the unit-length message arrival rate λ, with the transmission range taken as a parameter.

state (22), with the message arrival rate per unit-length taken as a parameter for a constant value of transmission range. From the figure, we observe that the probability distribution shifts to the right as the message arrival rate increases and has a bell shape curve. As confirmed, there is a good agreement between the numerical and simulation results. This agreement also validates the assumptions of static node consideration and including MAC back-off process in the message inter-arrival time in the analysis.

Fig. 4 presents analytical and simulation results for the mean number of concurrent transmissions (23), as a function of the transmission range with the message arrival rate taken as a parameter. It can be observed that the average number of transmissions remains almost constant for low values of the message arrival rates; on the other hand it is a decreasing function of the transmission range at higher message arrival rates. Again, there is a very good agreement between the numerical and simulation results.

Fig. 5 shows the average number of concurrent transmissions at steady-state as a function of the unit-length message arrival rate, λ, with the transmission range taken as parameter, again from (23). This figure indicates the communication capacity of the network. As may be seen, when the unit-length message arrival rate increases, the average number of concurrent transmissions increases asymptotically for a constant transmission range. Furthermore, the average values are not necessarily equal to the maximum number of non-interfering transmissions. For example, for $d = 1000$ m and $\lambda = 5$, the maximum number of non-interfering concurrent transmissions is 10, whereas the plot indicates a value of 14 for the average number of concurrent transmissions. Thus, we conclude that some transmissions are interfering. This phenomenon tends to disappear as the transmission range takes smaller values.

Fig. 6 plots the averages of total size of activity regions at steady-state, (24), as a function of the transmission range, d, with the unit-length message arrival rate taken as parameter. We conclude that the average of total size of activity regions increases linearly for low values of the message arrival rates, while it increases logarithmiclly at higher message arrival rates.

Fig. 7 plots the probability that a receiving node is exposed to interference, (25), as a function of the transmission range with the message arrival rate taken as parameter. We note that the probability of interference is much higher at higher message arrival rates, and that it increases faster as a function of the transmission range. Again, there is a good agreement between numerical and simulation results.

Fig. 8 presents plots for the average forwarding distance per hop that the high-priority safety message advances, (30), as a function of the transmission range and with the message arrival rate as parameter. It may be seen that the average forwarding distance increases with the transmission range. Also, for transmission ranges smaller than 700 m, it is higher for a high vehicle density, while it starts to decrease when the transmission range increases. This is due to the fact that when the transmission range increases, a more populated network

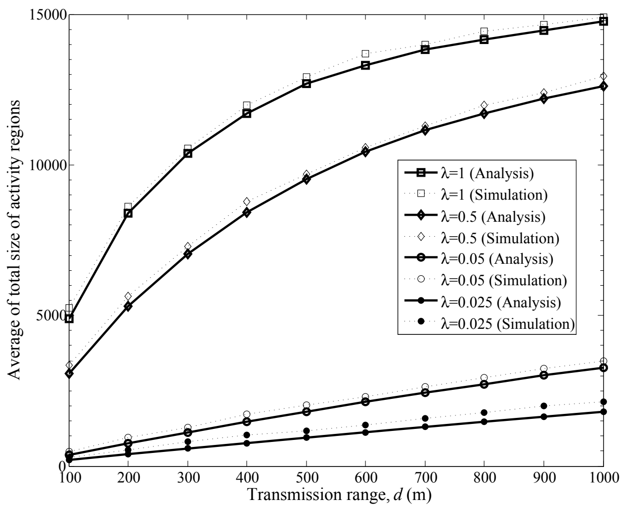

Fig. 6. Average of total size of activity regions versus the transmission range d, with the unit-length message arrival rate taken as parameter.

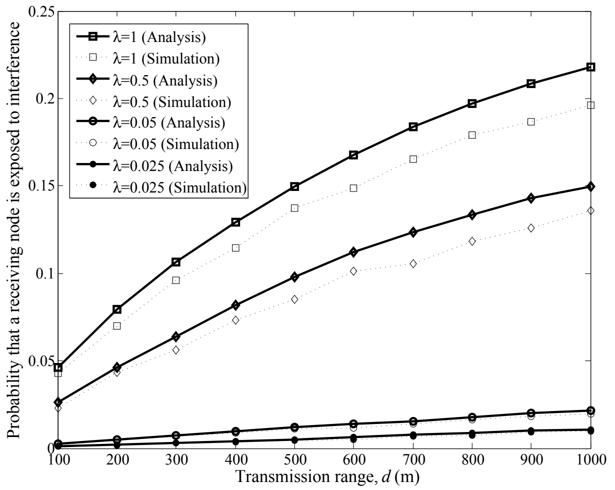

Fig. 7. Probability that a receiving node is exposed to interference versus the transmission range d, with the unit-length message arrival rate taken as parameter.

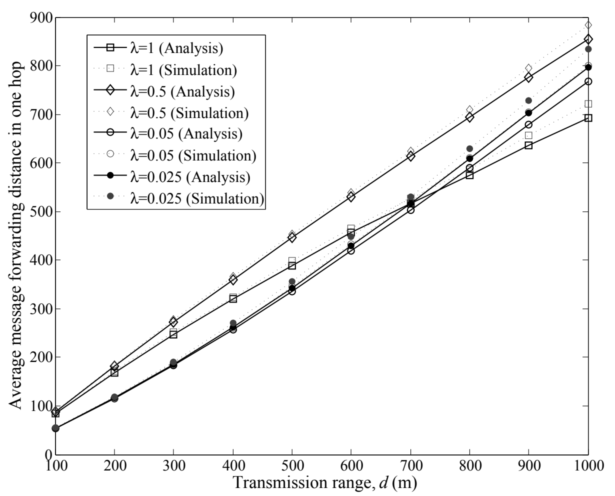

Fig. 8. Average forwarding distance per hop that the high-priority safety message advances $\bar{y}$, as a function of the transmission range, with the unit-length message arrival rate as a parameter.

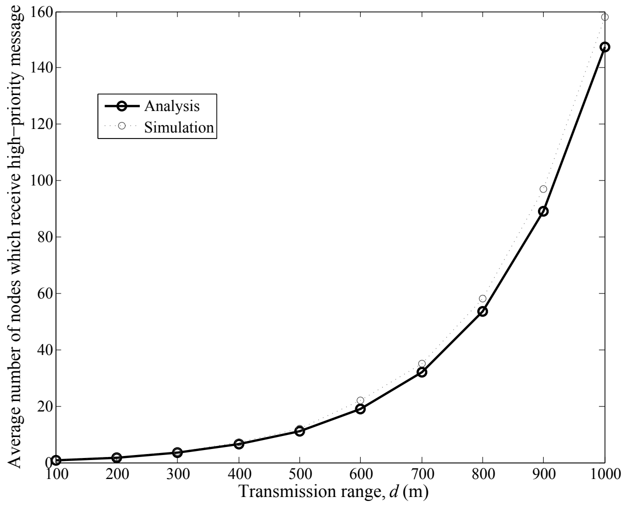

Fig. 9. Average number of nodes which receive a high-priority safety message $\bar{u}$, as a function of the transmission range d, for a network with light vehicle traffic, ϕ=0.005 veh/m.

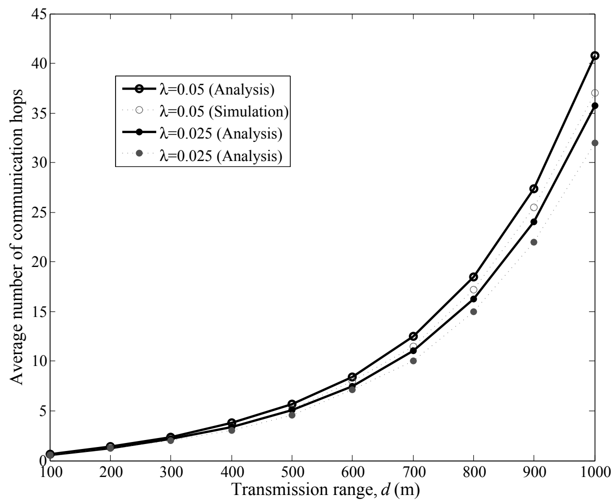

Fig. 10. Average number of hops it takes for the high-priority message to advance, $\bar{n}_h$, as a function of the transmission range, with the unit-length message arrival rate as a parameter for networks with light traffics.

experiences higher collision and hidden terminal activities. This result shows that selecting a larger transmission range does not necessarily improve the message forwarding distance in a dense network.

Fig. 9 presents the average number of nodes which receive a high-priority safety message, (34), as a function of the transmission range for a network with a low message arrival rate ($\phi = 0.005$ veh/m). The result for higher message arrival rates are not shown as the network always experiences full connectivity. We can see that in a network with low message arrival rates, selection of an appropriate transmission range can significantly improve the connectivity and the number of message recipients. For example, in this figure, for a transmission range of $d = 100$ m, almost no node may receive the safety message as vehicles are sparsely distributed, however, for $d = 1000$ m, a safety message may be received by 150 nodes.

Finally, Fig. 10 plots the average number of hops it takes for the high-priority message to advance, until it cannot be delivered any farther, (38), under light vehicle density, for two values of the message arrival rate. The average number of hops or, equivalently, the average number of forwarding nodes, increases with the transmission rate. Again, there is a good agreement between the numerical and simulation results.

VIII. Conclusions

In this work, we studied the performance of message dissemination in VANETs with two priority classes of traffic. The performance modelling of multi-hop communication networks have been lagging because of the complicated interference between concurrent transmissions. In this paper, first, we derived the probability distribution of the number of concurrent low-priority transmissions in the system at the steady-state through a birth-death process analysis. Then, we determined the percentage of destination node population which cannot receive a message error-free due to interference. These results were further used to study important performance measures of high-priority messages. We have determined the average number of nodes that will receive a high-priority message as well as the per-hop message forwarding distance. We found that the probability of a receiving node being exposed to interference increases as a function of the transmission range, and that this increase is faster at higher density node traffic. The results of this paper may also be used to study the performance of different message forwarding algorithms and optimum transmission range assignment problem in VANETs.

Appendix A
Derivation of the Inter-Arrival Time of Low-Priority Messages

In this part, we derive the inter-arrival time of the low-priority messages per unit-length of the network. Let $G(t)$ denote the pdf of non-safety (low-priority) message arrival time of a vehicle, therefore,

$$G(t) = 1 - e^{-\lambda_0 t}. \tag{39}$$

Let $P_w(t|k)$ denote the probability that no message will be generated in t seconds, given that k vehicles exist in the unit-length of the network. $P_w(t|k)$ can be found as,

$$\begin{aligned} P_w(t|k) &= [1 - G(t)]^k, \\ &= (e^{-\lambda_0 t})^k. \end{aligned} \tag{40}$$

Since the node population in a unit-length of the network follows a Poisson distribution with parameter ϕ, the unconditional probability of (40), denoted $P_w(t)$, can be found as,

$$\begin{aligned} P_w(t) &= \sum_{k=0}^{\infty} \frac{e^{-\phi}\phi^k}{k!} (e^{-\lambda_0 t})^k, \\ &= e^{-\phi(1-e^{-\lambda_0 t})}. \end{aligned} \tag{41}$$

Next, we expand $e^{-\lambda_0 t}$ into series,

$$e^{-\lambda_0 t} = 1 - \frac{\lambda_0 t}{1!} + \frac{(\lambda_0 t)^2}{2!} - ..., \tag{42}$$

where for small $\lambda_0 t$, we can approximate (42) with the first two terms. Therefore, (41) can be expressed as:

$$P_w(t) = e^{-\phi\lambda_0 t}. \tag{43}$$

Equation (43) shows that the message inter-arrival time to the unit-length of the network follows an exponential distribution with parameter $\lambda = \phi\lambda_0$ message/m/sec.

Appendix B
Derivation of the Probability of Internal and External Interferences

In the following, we determine the probabilities of internal and external interferences, P_c and P_h, which have been introduced earlier. Let us consider two overlapping transmissions in an activity region to be referred as j-th and $(j+1)$-th, and their starting times denoted as t_j, t_{j+1} with $t_{j+1} \geq t_j$. The overlapping is due to a collision if the distance between the two transmitting nodes is less than d and $t_{j+1} - t_j \leq \sigma$, where σ is the slot duration. Since transmissions arrive to the network according to a Poisson distribution with parameter $\lambda = \phi\lambda_0$, the probability of internal interference is given by,

$$P_c{}' = 1 - e^{-\lambda d \sigma}. \tag{44}$$

The overlapping is due to external interference if the distance between the two transmitting nodes is between d and $2d$ and $t_{j+1} - t_j \leq x$, where x is the transmission time of the j-th message. Since message transmission times are exponentially distributed with parameter μ, the probability of external interference is given by,

$$\begin{aligned} P_h{}' &= \Pr(t_j < t_{j+1}), \\ &= \int_{t_{j+1}=0}^{\infty} \int_{t_j=0}^{t_{j+1}} \lambda d e^{-\lambda d t_j} \mu d e^{-\mu t_{j+1}} dt_j dt_{j+1}, \\ &= \frac{\lambda d}{\lambda d + \mu}. \end{aligned} \tag{45}$$

Finally, since we are interested in the conditional probabilities of internal and external interferences given that an overlapping has occurred, then we have,

$$P_h = \frac{P_h{}'}{P_c{}' + P_h{}'}, \tag{46}$$

and

$$P_c = \frac{P_c{}'}{P_c{}' + P_h{}'}. \tag{47}$$

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