Delay Analysis for Sparse Vehicular Sensor Networks with Reliability Considerations

Atef Abdrabou, *Member, IEEE*, Ben Liang, *Senior Member, IEEE*, and Weihua Zhuang, *Fellow, IEEE*

***Abstract*—This paper addresses the relation between message delivery delay and reliability for the communication between a vehicle and a road side unit (RSU). We focus on sparse vehicular sensor networks (VSNs), where timely message delivery and reliable transmission are of significant importance. We present a mathematical framework for the message delivery delay distribution for a two-lane road, where vehicles in one direction act as message carriers for the ones in the other direction and have the freedom to leave the road from randomly distributed road junctions with a certain probability. Packet generator vehicles store the original packets till meeting an RSU while sending multiple copies of each packet to packet carrier vehicles. Our analysis offers an analytical tool for an intelligent transportation system (ITS) service provider to determine the minimum RSU density required to cover a road for meeting a probabilistic requirement of the message delay. Extensive computer simulation results show the accuracy of our analysis and clearly indicate the relation of packet delay and the number of packet replicas.**

***Index Terms*—Delay, vehicular sensor networks, vehicle-to-infrastructure transmission, disrupted connectivity, road side unit placement, information delivery reliability.**

I. INTRODUCTION

VEHICULAR sensor networks (VSNs) constitute a new networking trend with a viable capability. In these networks, vehicles can gather important data, while on the road, and process the sensed data to extract valuable information. Unlike ad hoc sensor networks, VSNs have no tight restrictions on processing power or storage capacity.

By the aid of a fast and reliable VSN, intelligent transportation systems can provide substantial benefits to transport infrastructure. For instance, they can be used to avoid roadway congestion, which adversely affects travel times and fuel consumption. They also can monitor air pollution levels and collect information about driving habits. For all intents and purposes, a VSN that is capable of providing a timely and reliable data transfer is crucial for the successful operation of an ITS.

In essence, VSNs are formed on top of vehicular ad hoc networks by supporting vehicles with sensors that collect data and use wireless communication to send information to the ITS. However, the deployment of a fully infrastructure-based ITS is known to be very costly [2]. Indeed, it is very difficult to cover rural areas with vehicular sensors and RSUs such that every vehicle can always be connected to at least one nearby RSU during its trip within an area. Moreover, in these areas, cellular connectivity may not have full coverage. Furthermore, the placement of RSUs that can enhance VANET connectivity has different considerations and design aspects [3] [4] compared to the factors that are taken into account when designing/planning the coverage of a cellular network (such as interference, required coverage area, propagation model, and deployment model). This, in turn, makes the locations of cellular network base stations, if they exist, suboptimal to serve the design objectives of a sparse VSN such as connectivity and packet delivery delay. Consequently, using vehicle-to-vehicle communication is crucial to facilitate the reporting of sensed data to RSUs, which represent the gateways to the Internet and/or the rest of the ITS infrastructure.

Therefore, many researchers currently focus on studying VSNs in both industry and academia [5]-[8]. In addition, the US Federal Communications Commission (FCC) has allocated $5.850-5.925$ GHz band to promote vehicular communications for safe and efficient highways. This band will be used in the emerging radio standard for Dedicated Short-Range Communications (DSRC) [9] that supports roadside-to-vehicle and inter-vehicle communications.

For VSNs to become a reality, a number of technical challenges have to be addressed. First, it is difficult to maintain an end-to-end connection between vehicles and an RSU, while the vehicles are moving at high speeds, especially on roads with a low vehicle density. Second, data packets carrying sensed information may suffer from excessive delays when delivered to RSUs if they are transfered by their originator vehicles to the nearest RSU. However, vehicle-to-vehicle communication can shorten the packet delivery delay if vehicles moving in the opposite direction are used. At the same time, vehicle-to-vehicle communication with vehicles moving in the opposite direction may not be reliable as those vehicles may exit the road to uncovered areas before reaching any RSU.

Our objective in this paper is to analyze packet delivery delay with a reliable packet transfer for vehicle-to-infrastructure communications in a sparse VSN where sensed information is destined to RSUs. Our analysis aims at characterizing the packet delivery delay distribution for a two-lane road. Vehicles in one lane of this road are packet generators moving in a certain direction while vehicles in the other lane are packet carriers moving in the opposite direction and carrying the

Manuscript received September 12, 2012; revised January 22 and April 25, 2013; accepted June 19, 2013. The associate editor coordinating the review of this paper and approving it for publication was C.-P. Li.

A. Abdrabou is with the Department of Electrical Engineering, UAE University, Al-Ain, Abu Dhabi, 15551, UAE (e-mail: atef.abdrabou@uaeu.ac.ae).

B. Liang is with the Department of Electrical and Computer Engineering, University of Toronto, Toronto, Ontario, M5S 3G4, Canada (e-mail: liang@comm.utoronto.ca).

W. Zhuang is with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada (e-mail: wzhuang@bbcr.uwaterloo.ca).

This paper was presented in part at IEEE Globecom 2010 [1].

Digital Object Identifier 10.1109/TW.2013.072313.121397

packet to the nearest RSU. Our analysis focuses on a simple, but reliable, packet delivery scheme where the original packet is stored by its generator vehicle till it meets an RSU. At the same time, the generator vehicle sends one or more replicas of each packet to different carrier vehicles (one for each). We introduce a mathematical framework for characterizing the packet delivery delay distribution for this scheme. The packet delay distribution offers a design tool that can determine the maximum separation distance between two adjacent RSUs or the minimum number of RSUs covering a road segment for satisfying a probabilistic requirement of packet delivery delay. The proposed analytical framework takes into account the likelihood of a carrier vehicle exiting the road, the spatial distribution of road junctions, and the vehicle distribution over a road segment.

The rest of this paper is organized as follows. Section II highlights the most relevant research works in the literature. Section III describes the system model under consideration. Problem formulation, our mathematical framework, and a case study for known probability distributions are presented in Section IV. Section V presents simulation and analytical results for different system parameters and provides a comparative discussion about another scheme providing no reliable packet delivery. Finally, Section VI concludes the research.

II. Related Works

In the literature, most research works related to disrupted connectivity in vehicular communication networks focus mainly on connectivity analysis [10]-[12] and average message delay evaluation [11] [13] not on characterizing message delay distribution and its relation to reliable message delivery. Wu et al. in [14] present analytical models to study spatial propagation of information for one and two-lane straight roads. They focus mainly on information propagation speed for vehicle-to-vehicle communications. In [15], the authors analyze the probability of connectivity using RSUs. The average length of a connected path from any given vehicle to an RSU is also calculated. However, no study about packet delivery delay is provided. The feasibility of information dissemination using stationary supporting units (SSUs) is investigated in [16] mainly based on computer simulations. However, vehicle-to-RSU packet delivery delay is not addressed.

To the best of our knowledge, no other existing study in the literature characterizes the delay and reliability of vehicle-to-infrastructure packet delivery via vehicle-to-vehicle communication.

III. System Model

Consider a two-lane road segment. Each lane is a straight line with a fixed length a meters and has two RSUs at its ends. The road segment length a is the distance between the two points where the transmission ranges of both RSUs end. We are interested in a network scenario on highways or rural areas, where the vehicle density (defined as the average number of vehicles per unit road length) is low enough to have disrupted vehicle-to-vehicle and vehicle-to-RSU connectivity. With a high vehicle density, a multihop end-to-end path can be found between a vehicle and an RSU with a high probability; however, this case is out of the scope of this research.

Vehicles over the two lanes are moving in opposite directions as in Fig. 1. Assume that all vehicles in the first lane are moving in the forward direction with a constant speed V_f. Conversely, in the other lane, vehicles move in the backward direction with another speed V_b. Although vehicles moving in the same direction may meet due to their different locations, such meeting opportunities are more rare and are less useful in shortening packet delivery delay since these vehicles have similar speeds. The constant speed assumption helps to investigate a worst case scenario of a vehicle sensor network that relies on a sparse VANET where vehicles moving in one lane have the same speed between two adjacent RSUs. Therefore, packets are carried either by their originator vehicles or carrier vehicles moving in the opposite direction. This scenario serves two important objectives. First, it helps the service provider of an ITS system to plan for the number of the RSUs that can cover a road segment in order to satisfy probabilistically a delay bound on the message delivery delay in the worst case. In fact, the possibility of packet relaying by intermediate vehicles reduces the probability of exceeding the packet delivery delay bound for the same separation distance between adjacent RSUs. Second, it gives useful insights about the effect of varying vehicle speed with the other parameters (such as vehicle density, road junction density, and vehicle exit probability) on packet delivery delay. Also, with a mathematically tractable analytical framework, the feasibility of sending multiple copies of the same packet in terms of packet delivery delay reduction can be investigated.

Consider a straight road with road junctions or cross roads distributed randomly on the second lane as depicted in Fig. 1. Consider only the data packets originated from vehicles in the first lane such as vehicle A. Some vehicles may leave and others may join at any exit point along the road segment. Thus, a vehicle may leave the road segment under study either to another road segment covered by RSUs or to uncovered road. The former case repeats the problem under research as when a carrier vehicle leaves the road segment under study to another segment, the packets it carries will not be delivered to the ITS system via the RSUs on the road segment under study. Instead, these packets may be delivered by another RSU on the other road segment. The location of the RSU receiving the packet on the other road segment (to satisfy probabilistically the packet delivery delay) can be determined the same way taking into account the distance the carrier vehicle has to move in order to reach this RSU. On the other hand, when a carrier vehicle leaves the road to uncovered segment this implies that the data packets carried by this vehicle will be lost.

Since packet carrier vehicles may leave the road segment without delivering the packets they have received, each generator vehicle, such as vehicle A in Fig. 1, keeps the original packet in a buffer until the vehicle meets the first RSU on its way while N duplicates are sent consecutively to N approaching vehicles (one for each) in the opposite direction. Fig. 1 shows vehicle B as the first approaching vehicle for vehicle A. This approach is to increase the reliability of message delivery, which is required for data messages containing critical information.

The vehicle densities N_1 and N_2 for the first lane and the second lane, respectively, are assumed to be constant over an observation period, i.e., the average number of vehicles that leave the road segment under consideration is the same as the average number of vehicles that enter it. Vehicle transmission range is assumed to be much smaller than the distance a between two adjacent RSUs. In general, increasing (or decreasing) either the transmission range or vehicle density has the same effect on the packet delivery delay as both increase (or decrease) the connectivity probability among vehicles [7]. Thus, we represent their influence on our study in terms of vehicle density only.

Certainly, in a realistic sparse VANET scenario, vehicle density may change with time as the average number of vehicles entering the road segment under study may not be equal to the average number of vehicles leaving the road segment. However, the objective of our study is to find the maximum separation distance between two adjacent RSUs such as the packet delivery delay is bounded probabilistically. Decreasing the vehicle density in a sparse VANET leads to decreasing the separation distance between adjacent RSUs that can satisfy probabilistically a certain packet delivery delay bound (due to the availability of small number of carrier vehicles). Thus, a constant worst case vehicle density can be used by the service provider to plan for the number of RSUs that can cover a road in a rural area using our mathematical framework. The bound on the packet delivery delay will stay satisfied probabilistically if the vehicle density increases over the worst case value as long as the VSN remains sparse.

As our objective in this paper is to analyze message delivery delay with reliable packet transmission in mind, we abstract the packet transmission process for simplicity. In our analysis, we assume that all messages held by a vehicle will be transmitted during a meeting opportunity with a carrier vehicle with no bandwidth constraint or wireless transmission impairments. This assumption is adopted by other researchers such as in [14]. Consequently, we neglect here the queuing delay as we address vehicle sensor networks in a sparse VANET scenario where vehicles report events to the RSUs normally at a low rate compared to the available transmission rate (e.g., 64 Kbps for a 3 Mbps transmission rate). The assumption is reasonable as the lowest data rate supported by IEEE 802.11p is 3 Mbps [19] and the maximum transmission unit (MTU) is around 1500 bytes in size. This implies that, at the worst case, an MTU takes 4 ms to be transmitted to a carrier vehicle or to an RSU. Two vehicles that are moving in the opposite direction with speeds such as 30 m/s (a relative speed of 60 m/s) will have a meeting time of around 2 seconds assuming they have a small transmission range of only 120 meters. This meeting opportunity is sufficient to transfer 500 MTUs. When a vehicle with the same speed is communicating with an RSU over the same transmission range, the meeting time will be around 8 seconds (i.e., sufficient to transfer 2000 MTUs). Taking into account that IEEE 802.11p allows a data rate up to 27 Mbps and the transmission range can be up to 300 m, the number of transmitted MTUs can grow to a much larger value while the actual message size can be smaller than the size of an MTU. Therefore, the introduction of the queuing delay in this research, complicates the mathematical analysis, specially when multiple replicas are considered, but with insignificant effect on the message delivery delay.

To investigate the effect of the physical layer on the proposed mathematical framework, we implement a vehicle-to-vehicle channel model inside the simulator [17] and show the impact of the physical channel on the analysis in Section V.

IV. Problem Formulation and Modeling

A. Problem Description

The problem can be described by the aid of Fig. 1. Our main objective is to find the maximum value of a that allows a certain required vehicle-to-RSU message delivery delay to be attained for the majority of vehicle packets (i.e., the distance a should be selected to allow only a small fraction of packets to be delayed when arriving at an RSU). Indeed, timely message transfer is vital for information exchange over any ITS as the information content may expire if arrived after a very large delay. Meanwhile, the number of RSUs that cover the road segment under study for a probabilistic delay requirement is directly related to the distance a.

Furthermore, we aim at guaranteeing reliable packet transmission by allowing every packet generator vehicle to store its packets for direct transmission to an RSU whenever there is a meeting opportunity between them. Since every packet has multiple replicas, late replicas will be discarded (in a case more than one replica are successfully received).

In short, our problem is to find the minimum number of RSUs to cover a road segment such that the required vehicle-to-RSU packet delivery delay is probabilistically satisfied for the first arrived packet copy. In addition, we aim at studying the effect of increasing the number of replicas on packet delivery delay. Note that packet carrier vehicles can exit the road with some probability from randomly distributed road junctions.

B. Mathematical Framework

Consider the road segment depicted in Fig. 1. Our target is to obtain a general expression for the packet delivery delay cumulative distribution function (CDF) $F_T(\cdot)$ in terms of the distance a between adjacent RSUs, taking into account that multiple replicas of every packet are submitted but only one is required to be delivered on time. The strategy has two benefits: First, it helps us to study how the delay distribution is affected by varying system parameters such as vehicle speeds (V_b, V_f), vehicle densities (N_1, N_2), p_c, and the average number of road junctions per unit length of the road segment under study λ_c; Second, it can be used to find the maximum value of the design parameter a (or the RSU density $\frac{1}{a}$) that satisfies certain maximum packet delivery delay constraint T_{max} with a violation probability of at most ϵ, as indicated in the following equation

$$\begin{aligned} &\text{maximize} \quad a \\ &\text{s.t.} \quad 1 - F_T(T_{max}) \leq \epsilon. \end{aligned} \tag{1}$$

In (1), the complementary cumulative distribution function (CCDF) of the packet delivery delay depends on the value of the RSU separation distance a. At a certain RSU separation distance, the CCDF may be equal to some violation probability

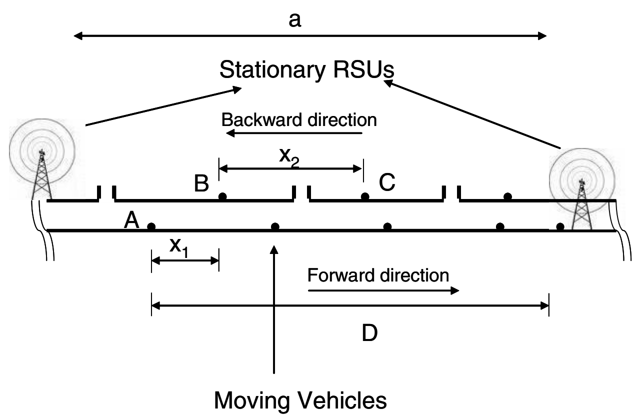


Fig. 1. The road segment under consideration.

ϵ at certain T_{max}. Apparently, increasing the separation distance between adjacent RSUs leads to increasing generally the packet delivery delay. This implies that the maximum value of a that satisfies the constraint in (1) can be obtained by solving the CCDF for a at T_{max}.

The problem can be described analytically by

$$\Pr(T \leq t) = \sum_{i=0}^{N} \Pr(T \leq t, I = i) \tag{2}$$

where T[1] is a random variable that denotes the packet delivery delay and I is a random variable denoting the replica that has been first delivered successfully by a carrier vehicle to an RSU. For instance, ($I = 2$) represents the case where the second replica reaches the nearest RSU successfully while the carrier vehicle holding the first replica has exited the road before meeting an RSU (first replica is not delivered to an RSU since there is no vehicle overtaking). The case ($I = 0$) indicates that all carrier vehicles exit the road before meeting an RSU.

In order to find the joint CDF of the packet delivery delay when $I = i$ as in (3),

$$\Pr(T \leq t, I = i) = \Pr(T \leq t | I = i) \Pr(I = i), \quad \forall i = 0, \ldots, N \tag{3}$$

we condition on the location of the packet generator vehicle and the distance between the packet generator vehicle and the packet carrier vehicles as in the following

$$\begin{aligned} &\Pr(T \leq t, I = i) = \\ &\int_0^a \int_0^\infty \ldots \int_0^\infty \Pr(T \leq t | I = i, D = \delta, X_1 = x_1, \ldots, X_N = x_N) \\ &\times \Pr(I = i | D = \delta, X_1 = x_1, \ldots, X_N = x_N) \\ &\times f(\delta, x_1, \ldots, x_N) dx_1 \ldots dx_N d\delta \end{aligned} \tag{4}$$

where D is a random variable representing the distance between the packet generator vehicle, A, (at the time when the packet is being sent) and the RSU as in Fig. 1, X_j, $j \in \{2, \ldots, N\}$, is a random variable that characterizes the inter-distance between approaching carrier vehicles, X_1 describes the distances between the generator vehicle A and the first approaching vehicle (e.g., B is the first approaching vehicle in Fig. 1 $j = 1$) and $f(\delta, x_1, \ldots, x_N)$ denotes the joint probability density function (PDF) of D and X_j (for all $j \in \{1, \ldots, N\}$).

The computation complexity of (4) depends on the spatial distribution of the vehicles and the distribution of the number of road junctions over the road segment. The objective of providing our mathematical framework is to help the ITS service provider to plan for the number of RSUs that can cover a road segment for a probabilistic satisfaction of the packet delivery delay in a worst case scenario. The framework depends on the off-line manipulation of the integral in (4) which can be done numerically by a computer with powerful hardware. This implies that there is no time or storage scaling limitations as there is no on-line computations needed.

The first term of the integrand in (4) is described by

$$\begin{aligned} &\Pr(T \leq t | I = j, D = \delta, X_1 = x_1, \ldots, X_N = x_N) = \\ &u\left(t - \min\left(\frac{a - \delta + \sum_{k=1}^{j} x_k}{V_b}, \frac{\delta}{V_f}\right)\right), \quad \forall \text{j} \in \{1, \ldots, N\} \end{aligned} \tag{5}$$

where $u(.)$ is the Heaviside unit step function, which is used as a result of conditioning the packet delivery delay CDF on all the random variables involved. The minimum function reflects the fact that the packet delivery delay is the minimum delivery time between the original copy of the packet and its multiple replicas in a case any or more than one of them reach the nearest RSU. The original packet carried by the generator vehicle arrives after a time of $\frac{\delta}{V_f}$, while the j^{th} replica arrives after $\frac{a-\delta+\sum_{k=1}^{j} x_k}{V_b}$ if its carrier vehicle does not exit the road. Thus, the unit step function term can be re-written as

$$\begin{aligned} &u\left(t - \min\left(\frac{a - \delta + \sum_{k=1}^{j} x_k}{V_b}, \frac{\delta}{V_f}\right)\right) \\ &= \begin{cases} u\left(t - \frac{\delta}{V_f}\right), \ 0 \leq \delta \leq \min\left(\frac{(a + \sum_{k=1}^{j} x_k)V_f}{V_b + V_f}, a\right); \\ u\left(t - \frac{a - \delta + \sum_{k=1}^{j} x_k}{V_b}\right), \ \min\left(\frac{(a + \sum_{k=1}^{j} x_k)V_f}{V_b + V_f}, a\right) \leq \delta \leq a. \end{cases} \end{aligned} \tag{6}$$

For the case where no replica is delivered to an RSU (i.e., $j = 0$), (5) becomes

$$\Pr(T \leq t | I = 0, D = \delta, X_1 = x_1, \ldots, X_N = x_N) = u\left(t - \frac{\delta}{V_f}\right) \tag{7}$$

as the packet will be held by its originator vehicle until it meets an RSU.

The probability that replica j will be successfully delivered to an RSU given that the carrier vehicle holding it is located at a distance of $a - \delta + \sum_{k=1}^{j} x_k$ from the nearest RSU, on its way at the time of receiving the packet, can be described as

$$\begin{aligned} &\Pr(I = j | D = \delta, X_1 = x_1, \ldots, X_N = x_N) \\ &= p_l(a - \delta + x_1) p_l(a - \delta + x_1 + x_2) \times \ldots \\ &\ldots \left(1 - p_l(a - \delta + \sum_{k=1}^{j} x_k)\right), \ \forall \text{j} \in \{1, \ldots, N\} \end{aligned} \tag{8}$$

[1] In this paper, we adopt using capital letters to express random variables.

where $p_l(y)$ denotes the probability that a carrier vehicle at distance y from the next RSU leaves the road from one of the available road junctions given the number of the available road junctions m within this distance over the road segment to the next RSU. Therefore, $p_l(y)$ depends on the exit probability p_c and the probability distribution of the number of road junctions over a distance y of the road as described by

$$p_l(y) = p_c G(y,1) + (p_c + p_c(1-p_c))\, G(y,2) + \cdots + \left(p_c + p_c(1-p_c) + \cdots + p_c(1-p_c)^{m-1}\right) G(y,m) \tag{9}$$

where $G(y,m)$ is probability of having m exits within the distance of y from the location of the carrier vehicle to the nearest RSU in its way. Here, $G(y,m)$ can be expressed as

$$G(y,m) = \Pr\left(W(s+y) - W(s) = m\right)$$

where $W(z)$ is a stationary counting process that characterizes the number of road junctions within a distance $[0,z]$.

On the other hand, the probability that all packet carrier vehicles carrying replicas exit the road before meeting an RSU is given by

$$\Pr(I=0|D=\delta, X_1=x_1,...,X_N=x_N) = p_l(a-\delta+x_1)p_l(a-\delta+x_1+x_2)...p_l(a-\delta+\sum_{j=1}^{N} x_j). \tag{10}$$

By manipulating the integral in (4) using (5)-(10), the cumulative distribution function (CDF) of the packet delivery delay can be obtained provided that the joint distribution $f(\delta, x_1, ..., x_N)$ and $G(y,m)$ are known. The mathematical framework (4)-(10) does not make special assumptions regarding the spatial processes of vehicles and road junctions on the road segment other than they are stationary processes. In Section IV-C, we select the Poisson distribution to check the applicability of our mathematical framework in a practical scenario since the time headway and the distance headway between vehicles in a low vehicle density case (vehicle density not larger than 12 vehicle/mile/lane [18]) have been shown to follow the exponential distribution as reported in [18] and [20]. Also, the usage of Poisson distribution leads to a closed-form expression for the packet delivery delay distribution, which can be accurately validated by computer simulations in Section V-A.

C. Exact Analysis for One Replica and Known Distributions

For simplicity, we address here the case of one replica and obtain a closed-form solution for the packet delivery delay CDF.

Initially, vehicles are assumed to be distributed on the road following a Poisson point process. We also assume that the number of cross roads within the road segment follows a Poisson distribution with a parameter λ_c. Practical values of λ_c can be obtained from [21], which provides measured statistics to the density of interchanges (road junctions) for some major cities in the United States. As a result, the vehicle will leave the road segment within a distance of y with probability $p_l(y)$, which can be manipulated using (9) to obtain

$$p_l(y) = 1 - e^{-\lambda_c p_c y}. \tag{11}$$

With one replica, the CDF of the packet delivery delay can be expressed as

$$\Pr(T \le t) = \Pr(T \le t, I=1) + \Pr(T \le t, I=0). \tag{12}$$

According to (4), we condition on the location of the packet generator vehicle and the distance between the packet generator vehicle and the nearest packet carrier vehicle as in the following

$$\Pr(T \le t, I=1) = \int_0^\infty \int_0^a \Pr(T \le t|I=1, D=\delta, X=x) \times \Pr(I=1|D=\delta, X=x) f(\delta,x)\, d\delta\, dx. \tag{13}$$

Note that the random variable D is uniformly distributed since the vehicle location is uniformly distributed over a. In addition, a packet can be sent randomly at any time. The random variable X is exponentially distributed since the vehicles form a Poisson point process. As a result, the joint PDF of D and X is given by

$$f(\delta,x) = \frac{1}{a}\left(N_1+N_2\right) e^{-(N_1+N_2)x}, \quad 0<\delta<a, x>0. \tag{14}$$

For the case $I=0$, an equation similar to (13) holds (by replacing $I=1$ with $I=0$ in (13)).

As described by (5), the first term inside the integration of (13) is given by

$$\Pr(T \le t|I=1, D=\delta, X=x) = u\left(t - \min\left(\frac{a-\delta+x}{V_b}, \frac{\delta}{V_f}\right)\right). \tag{15}$$

The unit step function in (15) can be defined according to (6), taking into account that the original packet arrives to the next RSU in the forward direction after a time of $\frac{\delta}{V_f}$, while the carrier vehicle holding the replica arrives to the next RSU in the backward direction after $\frac{a-\delta+x}{V_b}$ if the carrier vehicle does not exit the road.

The probability that the packet carrier vehicle will leave ($I=0$) or not exit ($I=1$) the road before delivering its packets to an RSU, given that the carrier vehicle is located at a distance of $a-d+x$ from the next RSU on its way, can be obtained as

$$\begin{aligned}\Pr(I=0|D=\delta, X=x) &= 1 - \Pr(I=1|D=\delta, X=x) \\ &= p_l(a-\delta+x).\end{aligned} \tag{16}$$

The detailed integration expressions for $\Pr(T \le t, I=1)$ and $\Pr(T \le t, I=1)$ are given in (17) and (18), respectively.

By using (12) and by evaluating the integrations in (17) and (18), we obtain the exact expressions for the packet delivery delay CDF as in (19).

D. Analysis of N replicas and Known Distributions

As it can be inferred from (4), the number of integrals depends on the number of replicas. Therefore, when the number of replicas is more than one, the complexity of manipulating a closed-form solution for the integration in (4) increases substantially.

In this section, we present an upper bound on the packet delivery delay CDF as in (2), which can be used to estimate

$$\begin{aligned}\Pr(T \le t, I=1) = &\int_0^\infty \tfrac{1}{a}(N_1+N_2)e^{-(N_1+N_2)x}\left[\int_0^{\min\left(\frac{(a+x)V_f}{V_b+V_f},a\right)} u\left(t-\tfrac{\delta}{V_f}\right)e^{-\lambda_c p_c(a-\delta+x)}\,d\delta\right]dx\\ &+\int_0^\infty \tfrac{1}{a}(N_1+N_2)e^{-(N_1+N_2)x}\left[\int_{\min\left(\frac{(a+x)V_f}{V_b+V_f},a\right)}^{a} u\left(t-\tfrac{a-\delta+x}{V_b}\right)e^{-\lambda_c p_c(a-\delta+x)}d\delta\right]dx.\end{aligned} \tag{17}$$

$$\Pr(T \le t, I=0) = \int_0^\infty\int_0^a u\left(t-\frac{\delta}{V_f}\right)\left(1-e^{-\lambda_c p_c(a-\delta+x)}\right)\frac{1}{a}(N_1+N_2)e^{-(N_1+N_2)x}\,d\delta\,dx. \tag{18}$$

$$\begin{aligned}\Pr(T \le t) = &\left[\left(\tfrac{V_f}{a}\right)t + K\left(1-e^{-tV_b(\lambda_c p_c+N)}\right)+\tfrac{e^{-tV_b(\lambda_c p_c+N)}}{a\lambda_c p_c}-\tfrac{e^{-t\lambda_c p_c V_b}}{a\lambda_c p_c}\right]u(t)\\ &+\left[\tfrac{e^{-tV_b\lambda_c p_c}}{a\lambda_c p_c}-K\left(e^{-\lambda_c p_c a}e^{t\lambda_c p_c V_f}-e^{-tV_b\lambda_c p_c}e^{-NV\left(t-\frac{a}{V}\right)}\right)-\tfrac{e^{-t\lambda_c p_c V_b}e^{-NV\left(t-\frac{a}{V}\right)}}{a\lambda_c p_c}\right]u\left(t-\tfrac{a}{V}\right)\\ &+\left[\begin{array}{l}1-\left(\frac{V_f}{a}\right)t-Ke^{-tV_b\lambda_c p_c}e^{-NV\left(t-\frac{a}{V}\right)}+\frac{e^{-t\lambda_c p_c V_b}e^{-NV\left(t-\frac{a}{V}\right)}}{a\lambda_c p_c}-\frac{e^{-tV_b(\lambda_c p_c+N)}}{a\lambda_c p_c}\\ -K\left(1-e^{-tV_b(\lambda_c p_c+N)}\right)+Ke^{-\lambda_c p_c a}e^{t\lambda_c p_c V_f}\end{array}\right]u\left(t-\tfrac{a}{V_f}\right)\\ &V=V_b+V_f,\ N=N_1+N_2,\ K=\tfrac{N}{ap_c\lambda_c(\lambda_c p_c+N)}.\end{aligned} \tag{19}$$

analytically an upper bound on T_{max} in (1) with low mathematical complexity.

Let V^C be the set of carrier vehicles moving on the road segment under study while holding packet replicas to the next RSU in the backward direction. Consider the case where a generator vehicle sends only two packet replicas to two carrier vehicles. The packet delivery delay CDF can be presented as

$$\Pr(T \le t) = \Pr\left(\min\left(\min\left(T_f, T_1\right), T_2\right) \le t\right) \tag{20}$$

where T_f is the delay experienced by the original packet in reaching the next RSU in the forward direction ($T_f = \frac{D}{V_f}$), T_1 and T_2 are the delays experienced by the first replica and second replicas in reaching the next RSU in the backward direction, respectively, with

$$T_1 = \frac{a-D+X_1}{V_b}, \quad T_2 = \frac{a-D+X_1+X_2}{V_b}.$$

The right-hand side of (20) can be expressed as

$$\begin{aligned}&\Pr\left(\min\left(\min\left(T_f, T_1\right), T_2\right) \le t\right) =\\ &\left\{\begin{array}{l}\Pr\left(\min\left(T_f, T_1\right) \le t\right),\ \mathrm{v_{c1}} \in \mathrm{V^C}, \mathrm{v_{c2}} \notin \mathrm{V^C}\\ \Pr\left(\min\left(T_f, T_2\right) \le t\right),\ \mathrm{v_{c1}} \notin \mathrm{V^C}, \mathrm{v_{c2}} \in \mathrm{V^C}\end{array}\right\}\end{aligned} \tag{21}$$

where $\mathrm{v_{cj}}$ denotes the carrier vehicle holding the j^{th} replica. In the first case of (21), $\mathrm{v_{c2}}$ leaves the road segment under study without delivering the packet replica it holds. Similarly, in the second case, $\mathrm{v_{c1}}$ leaves the road without meeting the next RSU.

In fact, $\Pr\left(\min\left(T_f, T_1\right) \le t\right)$ can be represented by the same expression as in (19) when the vehicle distribution over the road segment follows a Poisson point process and the number of cross roads follows the Poisson distribution as in Section IV-C.

For the upper bound we seek, the term $\Pr\left(\min\left(T_f, T_2\right) \le t\right)$ in (21) can also be expressed by (19) after changing the vehicle density in the first lane to be $\frac{N_1}{2}$ instead of N_1 since

$$\Pr(\mathrm{X_1+X_2 \le x}) \le \Pr(\min(\mathrm{X_1, X_2}) \le \mathrm{x}/2) = 1 - e^{-\left(\frac{N_1}{2}+N_2\right)x} \tag{22}$$

which implies that the packet delivery process of the second replica is similar to the case of a single replica but with less vehicle density in the first lane. This leads to

$$\begin{aligned}&\Pr\left(\min\left(\min\left(D_f, D_1\right), D_2\right) \le t\right) \le\\ &\quad\Pr\left(\mathrm{v_{c1}} \in \mathrm{V^C}, \mathrm{v_{c2}} \notin \mathrm{V^C}\right)\Pr\left(\min\left(T_f, T_1\right) \le t\right)\\ &\quad+\Pr\left(\mathrm{v_{c1}} \notin \mathrm{V^C}, \mathrm{v_{c2}} \in \mathrm{V^C}\right)\Pr\left(\min\left(T_f, T_2\right) \le t\right)\end{aligned} \tag{23}$$

The rest of the terms in the right hand side of (23) are given by (24) and (25). In essence, the mathematical approach that is used to obtain the upper bound in (23) is not limited to the case of two replicas. It can be directly applied to any number of replicas by using a similar argument to (21) and changing (23) accordingly. Apparently, (23) can be used to obtain an upper bound on maximum packet delivery delay T_{max} in (1) for a certain RSU separation distance a. We compare the analytical results of estimating T_{max} analytically for different number of replicas with computer simulations in Section V-C.

V. Simulation Results and Discussion

In this section, we first validate our analysis using computer simulations. Subsequently, we use our analytical model to study the effect of varying system parameters on the required RSU density, under the constraint of satisfying the packet delivery delay requirement probabilistically. We also investigate the effect of transmitting multiple replicas of the same packet on packet delivery delay.

A. Model Validation

The ns-2 simulator is used for simulations in order to validate our analysis. We implement the mobility model mentioned in Section III inside the ns-2 mobility scenario generator. In this mobility model, vehicles are forced to move

$$\Pr\left(\mathrm{v_{c1}} \in \mathrm{V^C}, \mathrm{v_{c2}} \notin \mathrm{V^C}\right) = \left(1 - \int_0^a \int_0^\delta p_l(a-\delta+x_1)(N_1+N_2)e^{-(N_1+N_2)x_1} dx_1 d\delta\right) \times \left(\int_0^a \int_0^\delta \int_0^\delta p_l(a-\delta+x_1+x_2)(N_1+N_2)e^{-(N_1+N_2)x_1} N_2 e^{-N_2 x_2} dx_1 dx_2 d\delta\right). \tag{24}$$

$$\Pr\left(\mathrm{v_{c1}} \notin \mathrm{V^C}, \mathrm{v_{c2}} \in \mathrm{V^C}\right) = \left(\int_0^a \int_0^\delta p_l(a-\delta+x_1)(N_1+N_2)e^{-(N_1+N_2)x_1} dx_1 d\delta\right) \times \left(1 - \int_0^a \int_0^\delta \int_0^\delta p_l(a-\delta+x_1+x_2)(N_1+N_2)e^{-(N_1+N_2)x_1} N_2 e^{-N_2 x_2} dx_1 dx_2 d\delta\right). \tag{25}$$

TABLE I
SYSTEM PARAMETERS

System Parameter	Value
Road Segment Length (a)	$5km$
N_1	5 vehicle/km
N_2	5 vehicle/km
Exit Probability p_c	0.3
Road junction Density λ_c	0.002 m^{-1}
V_f	$25m/s$
V_b	$30m/s$

with a constant speed over a two-lane straight line along a road segment of fixed length. The spatial distribution of the vehicles over the road segment follows Poisson point process. One RSU is placed at each end of the road segment. Vehicles in the first lane are moving in the forward direction, while in the second lane vehicles are moving in the opposite direction as in Fig. 1. Only vehicles on the first lane are active data traffic sources, while the vehicles in the other lane receive the packets from the vehicles on the first lane, store them, and then send them all to the RSU at the end of the road segment when the transmission range allows. IEEE 802.11 is used as the medium access control (MAC) protocol for the single channel system in the simulator as the draft standard IEEE 802.11p [19] is proposed to support ITS applications. IEEE 802.11p mainly takes into account the issues related to fast mobility of vehicles when connecting to RSUs. For instance, IEEE 802.11p uses a small channel bandwidth (only 10 MHz) to suit the fast mobility physical layer issues such as large delay spread. In addition, IEEE 802.11p allows a vehicle to start exchanging data with an RSU once the transmission range allows without the need to wait for the completion of the authentication and association procedures. This feature accommodates fast vehicles that stay within the transmission range of an RSU for a short time. Moreover, the main access mechanism of IEEE 802.11 (RTS-CTS-DATA-ACK) is kept unchanged since IEEE 802.11p MAC layer is inherited from IEEE 802.11e enhanced distributed channel access (EDCA) with modifications to some parameters. This makes the current ns-2 implementation of the MAC layer of IEEE 802.11 suitable for this research to accurately simulate IEEE 802.11p as well. In this work, the ns-2 implementation of the physical layer of IEEE 802.11a is used after changing its parameters to the physical layer parameters of the IEEE 802.11p as both depend on the orthogonal frequency division multiplexing (OFDM) technology [19].

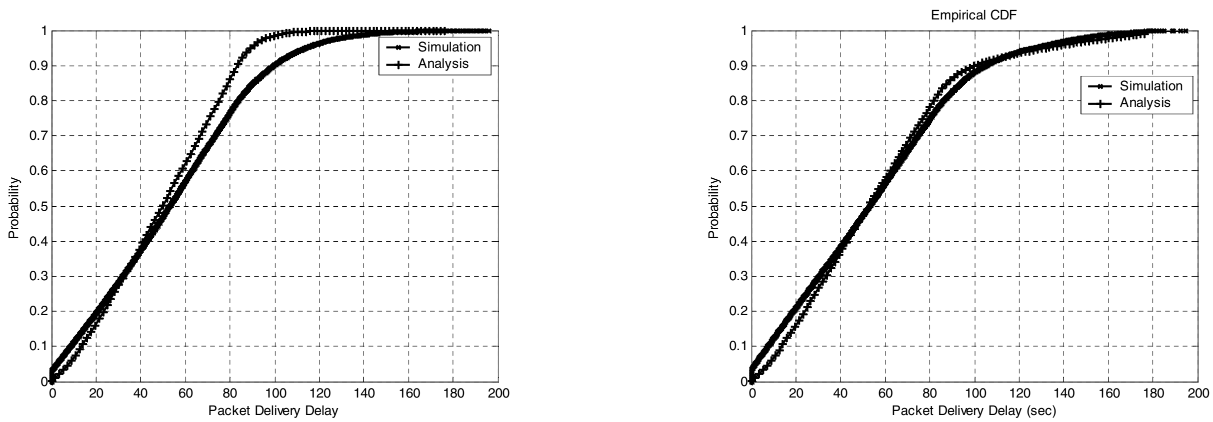
Data traffic is generated by constant bit rate sources with a very low rate as compared to the channel data rate, which guarantees that the contact time between two vehicles is sufficient for packet exchange. Table I gives the key system parameter values used in the analysis and simulations unless otherwise specified. Here, we assume that generator vehicles send only one replica of each packet to the carrier vehicles they meet, while keeping the original packet until they meet the next RSU.

Fig. 2 shows the cumulative distribution function of the packet delay probability distribution (with the delay values approximated to the nearest integer) obtained from the simulator and the analytical results obtained from (19) for two exit probability values, namely, $p_c = 0$ and $p_c = 0.3$. The simulated cumulative distribution function is obtained using 600 runs, where each run represents $200s$ of system time. Fig. 2 demonstrates that there is a close match between the analysis and the simulation results, indicating that our analysis is accurate in characterizing the packet delivery delay distribution. The small gap between the simulation and the analytical results arises mainly from the assumptions that we have used to minimize the mathematical complexity of our analytical framework. For instance, we abstract the operation procedure of IEEE 802.11 MAC layer while the detailed implementation of IEEE 802.11 MAC protocol is incorporated in the ns-2 simulator. Also, in the analysis, we assume that there is no contribution of the vehicles in the same lane in delivering packets to RSUs as the vehicles move with the same speed, while this may occasionally happen due to the random location of these vehicles.

B. RSU Density and System Parameters

In this section, we study the effect of varying key system parameters such as exit probability, road junction density, vehicle density, and vehicle speed on the required RSU density. Indeed, the separation distance a between two adjacent RSUs translates directly to the RSU density. Here, we solve (1) for the case of one replica to get analytically the value of a, which satisfies $T_{max} = 30s$ and $\epsilon = 5\%$ for different values of key system parameters.

Fig. 3 shows the effect of changing the exit probability on the RSU density with different road junction densities. It is observed that, as the exit probability increases, the maximum RSU separation distance for satisfying T_{max} and ϵ decreases significantly. This is expected as, when carrier vehicles have



(a) Packet Delivery Delay CDF ($p_c = 0$)   (b) Packet Delivery Delay CDF ($p_c = 0.3$)

Fig. 2. Packet delivery delay CDF (analysis and simulation).

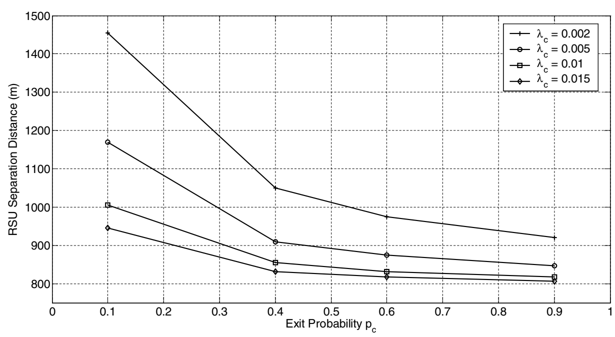


Fig. 3. The maximal RSU separation distance with different exit probabilities and road junction densities.

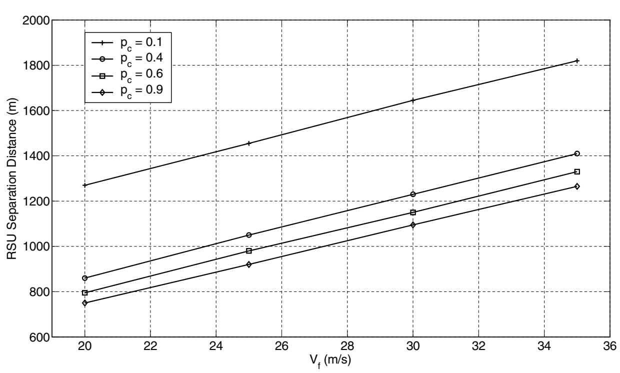


Fig. 4. The maximal RSU separation distance with different exit probabilities and vehicle speeds in the forward direction V_f.

more tendency to exit the road, it is more likely that a packet will reach an RSU carried only by its generator. As depicted also in Fig. 3, the decrease in the RSU separation distance is faster at a smaller value of p_c ($p_c < 0.4$) while it becomes much slower with large values of road junction densities since the vehicles have more tendency to exit with the availability of large number of road junctions. Certainly, a high leaving probability increases the number of RSUs required to cover a road for certain packet delivery delay requirements.

Fig. 4 shows the variation of the RSU separation distance

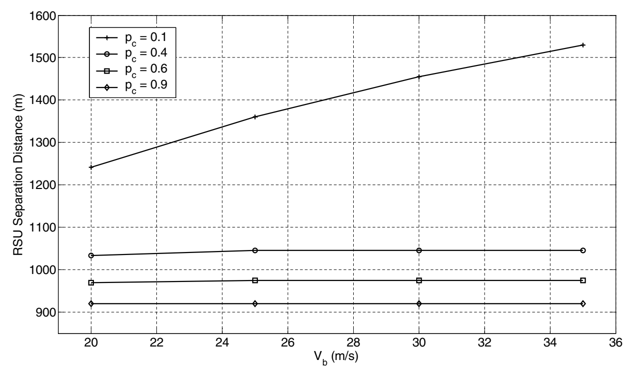


Fig. 5. The maximal RSU separation distance with different exit probabilities and vehicle speeds in the backward direction V_b.

with different vehicle speeds in the forward direction V_f and different exit probabilities, for $N_1 = N_2$. It can be clearly seen that, as V_f increases, the RSU separation distance increases linearly. Indeed, as the generator vehicles move faster, the speed of delivering the original packet to the next RSU increases, which has a direct impact on shortening the time that a generator vehicle will take to meet a carrier vehicle or the next RSU. This translates directly to a decrease in the packet delivery delay for the same RSU separation distance or alternatively an increase in the RSU separation distance for the same maximum delay. The effect of the exit probability on the RSU separation distance is also evident from the result.

Fig. 5 illustrates the effect of varying vehicle speed in the backward direction V_b and the exit probability on the RSU separation distance. It is clear that, when V_b increases, the RSU separation distance increases for the small p_c value. However, when p_c tends to be larger, changing V_b does not constitute a significant impact on the RSU separation distance for same p_c. The reason is that we address a low vehicle density scenario. When p_c becomes high, the number of carrier vehicles that do not exit the road before meeting the next RSU becomes fairly small with a large probability. Consequently, changing the speed of carrier vehicles do not have a significant impact on the RSU separation distance when carrier vehicles tend to

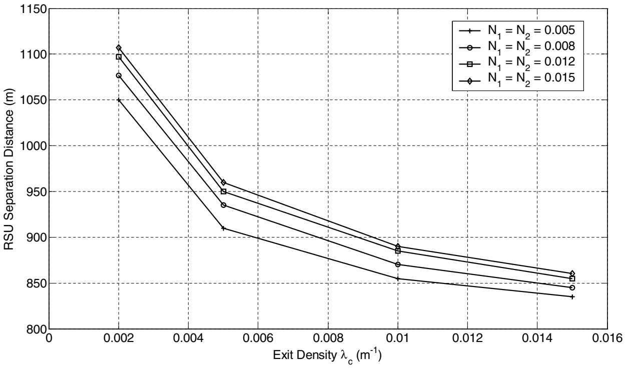


Fig. 6. The maximal RSU separation distance with different road junction and vehicle densities.

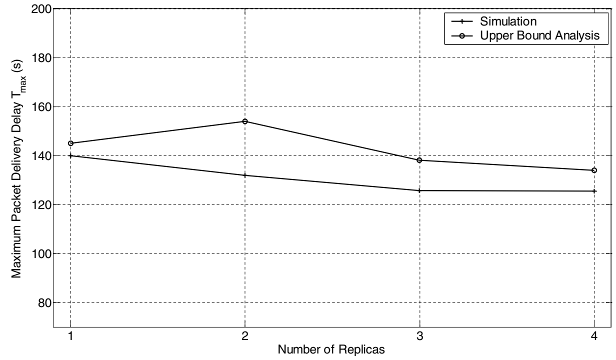


Fig. 7. Maximum packet delivery delay versus the number of replicas.

TABLE II

AVERAGE NUMBER OF RECEIVED PACKETS BY AN RSU AND THE NUMBER OF REPLICAS.

Number of Replicas	1	2	3	4	5
Average Number of Packets	435.6	593.8	748.6	901.6	1051.4

exit the road with a high probability.

The relation between the road junction density and the RSU density for various vehicle density values is illustrated in Fig. 6. It can be observed that the required maximum RSU separation distance significantly decreases when the road junction density increases. This is anticipated as, for the same road segment, when we decrease the available number of road junctions, the expected number of carrier vehicles that exit the road decreases (for the same exit probability p_c). This implies an increasing role of packet carrier vehicles in delivering packets to the RSU, which translates directly to a higher probability of a small packet delivery delay (or a larger a for the same T_{max} and ϵ). Fig. 6 also shows that the required RSU density increases as the vehicle density decreases for the same road junction density. A low vehicle density reduces meeting opportunities between the generator and carrier vehicles for a certain a, which gives less favor to packet transfer on the backward direction, and in turn increases the probability of a long delay. In addition, we can infer from Fig. 6 that the impact of varying vehicle density on the RSU density decreases as the road junction density increases. The explanation for this relates to an increase in the number of carrier vehicles, which tend to leave the road when the road junction density increases for the same value of exit probability. This implies that the larger the vehicle density, the larger the number of carrier vehicles likely leaving the road, which leads to a non-significant impact of the vehicle density on the RSU separation distance.

C. Multiple Replicas and the Packet Delivery Delay

Next, we investigate the effect of sending multiple replicas by a generator vehicle on the packet delivery delay via computer simulations. Fig. 7 is obtained using the following values of system parameters: $\lambda_c = 0.004$, $p_c = 0.7$, $N_1 = N_2 = 5$ vehicle/km, and $\epsilon = 0.05$, while the other system parameters are kept the same as in Table I. It is observed that the maximum packet delivery delay (T_{max}) decreases with an increasing number of replicas. This is anticipated since sending more replicas by the generator vehicle boosts the chances that one or more carrier vehicles will meet the next RSU and send a replica to it before the delay bound. In addition, Fig. 7 also shows a comparison between the simulation results and the computed T_{max} using the upper bound derivation approach in Section IV-D. The upper bound provides a conservative estimate to T_{max}, approximately 10% above the simulation results, for a given value of the RSU separation distance a.

Furthermore, we study the effect of increasing the number of replicas on the average number of packets received by an RSU. Table II indicates that the average number of packets received by an RSU increases almost linearly when the number of replicas increases. This is expected as we assume all carrier vehicles have the same exit probability. On the other hand, it is clearly observed, from Fig. 7, that the packet delivery delay does not decrease monotonically when the number of replicas increases. Instead, it almost approaches some asymptotic value. In fact, when the number of replicas increases, a generator vehicle may not find a sufficient number of carrier vehicles to send replicas to before meeting the next RSU. This, in turn, leads to an unnoticeable impact on the packet delivery delay if the number of replica is kept increasing above some value (5 replicas in Fig. 8).

Moreover, we have studied the relation between the vehicle density and the smallest number of replicas that can have a significant impact on the packet delivery delay. Fig. 8 shows the number of replicas versus the maximum packet delivery delay T_{max} for two different vehicle densities; namely, 1 vehicle/kilometer and 0.5 vehicle/kilometer. As depicted in Fig. 8, it is evident that for the case of 1 vehicle/kilometer, the decreasing trend of the packet delivery delay stabilizes asymptotically at 5 replicas, while it stabilizes at 4 replicas for the case of 0.5 vehicle/kilometer. Apparently, this indicates that the number of replicas with a significant influence on the packet delivery delay is heavily dependent on the vehicle density. In addition, increasing the number of replicas for a given vehicle density, beyond a certain limit, adds no benefit to reducing the packet delivery delay. On contrary, it loads the RSUs and the ITS telecommunication infrastructure with an unnecessary number of packet replicas as Table II indicates.

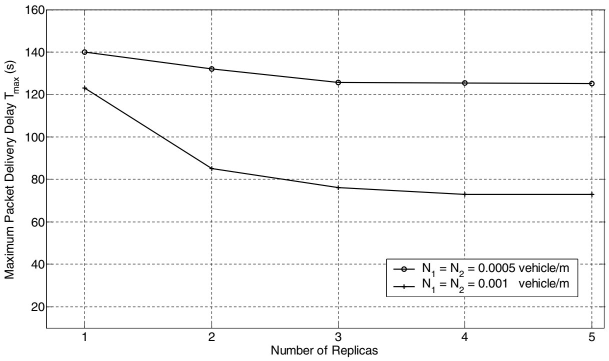


Fig. 8. Effect of vehicle density on the number of replicas required to reduce packet delay.

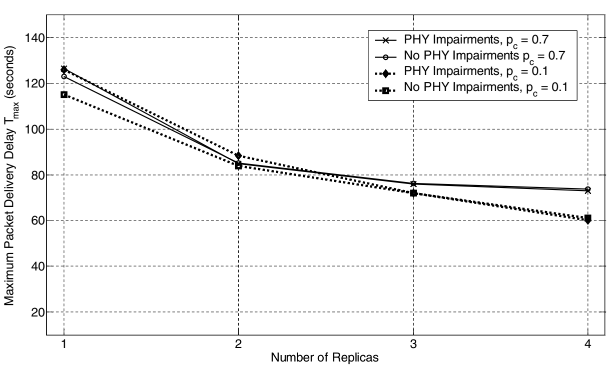


Fig. 9. Maximum packet delivery delay (T_{max}) versus the number of replicas with the existence of physical layer impairments.

D. Effect of Physical Channel Impairments

For the sake of completeness, we address how the physical channel impairments affect the packet delivery delay. Inside the ns-2 simulator, we use the vehicle-to-vehicle physical channel model as developed in [17]. In this model, the large scale path loss is characterized by a dual-slope piecewise linear model [22]. The model is empirical with parameters obtained from hardware measurements over a vehicle-to-vehicle wireless channel in a suburban environment. The model is extended in [23] for a vehicle-to-vehicle highway scenario. The small scale fading is modeled using a correlated-distance varying Nakagami-m distribution whose severity (the value of m) changes based on the time-varying distance between the sender and the receiver [22]. In addition, the model takes into account the temporal correlation of fading by a mobile-to-mobile time-variant power spectrum that depends on the ratio between the speeds of the sender and the receiver as introduced in [24].

Fig. 9 illustrates the influences of physical channel on the packet delivery delay. For a low exit probability (such as $p_c = 0.1$), the physical channel impairments cause an increase in the packet delivery delay as compared to a free space path model (no physical channel impairments). Fig. 9 also shows that, with increasing the number of replicas, the physical layer effect becomes insignificant. The reason is that the impact of physical channel errors on the packet delivery delay is equivalent to the impact of increasing the exit probability. This stems from the fact that a packet replica will not reach an RSU due to channel errors. When the exit probability is large ($p_c = 0.7$), the effect of the physical layer impairments is slightly noticed (mainly for the case of one replica) since carrier vehicles exit the road anyway with a large probability and increasing the number of replicas overcomes channel errors.

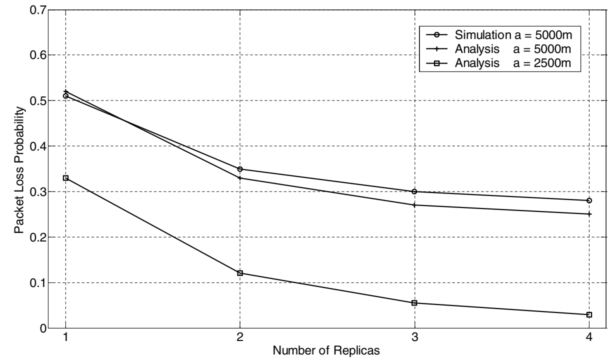


Fig. 10. Packet loss probability versus the number of replicas.

E. Discussion

The packet delivery reliability of the scheme introduced in this work depends on the ability of a packet generator vehicle to store its packets until it meets the next RSU. We control the separation distance between adjacent RSUs (or RSU density) to limit the packet delivery delay probabilistically.

However, if we are concerned with packet delivery delay without taking into account packet delivery reliability, another limitation imposed on the RSU density is the packet loss probability (PLP). The PLP is a measure of the probability of discarding packets by their holding vehicles when they exit the road to an uncovered area. Consider a modified packet delivery scheme where a generator vehicle sends multiple replicas to different carrier vehicles without storing the original packet for delivery to the next RSU in the forward direction.

The packet loss probability, in a case that N replicas have been sent by the packet originator vehicle is given by

$$PLP = \int_0^a \int_0^\delta \cdots \int_0^\delta \prod_{j=1}^{N} p_l \left(a - \delta + \sum_{k=1}^{j} x_k \right) \times \prod_{k=1}^{N} f_k(x_k) dx_1 \cdots dx_k d\delta \qquad \forall \text{j} \in \{1, ..., N\} \quad (26)$$

where $f_k(.)$ is the probability distribution function of X_k, $k \in \{1, \ldots, j\}$.

Fig. 10 shows the analytical results of calculating the integration in (26) numerically for two different values of a and a small value of p_c (0.1). The figure also depicts a comparison with the simulation results for the case of $a = 5000$m. It is observed that, even with a small value of p_c, the PLP reaches a value of around 50% for the case of a single replica and decreases to around 20% for 4 replicas when $a = 5000$m.

While for $a = 2500$m, the PLP decreases to 30% for a single replica and is reduced to around 3% for the case of 4 replicas. Consequently, we can infer from Fig. 10 that as a increases, the packet loss probability increases. Thus, a small a (or a large RSU density) is required to achieve a small, and hence acceptable, packet loss probability. This implies that a scheme with a reliable packet delivery is invetiable.

Given the recent advances in the capacity of memory chips, vehicles are able to store a fairly large amount of packets in their buffers before meeting an RSU. Therefore, in comparison with a scheme that does not offer a reliable packet delivery, storing one copy of every packet in a generator vehicle does not represent a disadvantage for our scheme; further, this leads to a smaller required RSU density.

VI. Conclusion

In this paper, we present a study of the relation between the packet delivery delay and the RSU density for vehicle-to-RSU communication in sparse vehicular sensor networks. We investigate the case where vehicles moving in one direction send their packets to vehicles traveling in the opposite direction in order to deliver the packets to the nearest RSU. We consider the scheme for a reliable packet delivery, in which a packet generator vehicle attempts to send multiple copies of each of its packets to carrier vehicles moving in the opposite direction. The original packet is carried by its originator vehicle on its way to the next RSU, and the copies are carried by the carrier vehicles to the nearest RSU in the opposite direction. An exact packet delivery delay distribution for the case of one replica is derived. The analysis offers a mathematical tool for RSU deployment given the key system parameters (such as vehicle exit probability, vehicle speed, road junction density, and vehicle density) with a probabilistic requirement of packet delivery delay. Simulation results validate the accuracy of our mathematical model. Furthermore, extensive computer simulations are conducted in order to study the influence of varying the number of replicas on packet delivery delay in the existence of a realistic vehicle-to-vehicle physical channel model. An analytical comparison with another scheme where the originating vehicle does not retain a copy of the transmitted packets till meeting the next RSU (i.e., no packet delivery guarantee) shows that our proposed scheme provides a fully reliable packet delivery while reducing the maximum packet delivery delay.

References

[1] A. Abdrabou, B. Liang, and W. Zhuang, "Delay analysis for a reliable message delivery in sparse vehicular ad hoc networks," in *Proc. 2010 IEEE Globecom*.

[2] Ten-Year National Program Plan and Research Agenda for Intelligent Transportation Systems in the United States, ITS Amer., U.S. Dept. Transp., Washington, DC, Oct. 2001.

[3] J. Gozalvez, M. Sepulcre, and R. Bauza, "IEEE 802.11p vehicle to infrastructure communications in urban environments," *IEEE Commun. Mag.*, vol. 50, no. 5, pp. 176–183, May 2012.

[4] S. Sou and O. Tonguz, "Enhancing VANET connectivity through roadside units on highways," *IEEE Trans. Veh. Technol.*, vol. 60, no. 8, pp. 3586–3602, Oct. 2011.

[5] X. Li, W. Shu, M. Li, H. Huang, P. Luo, and M. Wu, "Performance evaluation of vehicle-based mobile sensor networks for traffic monitoring," *IEEE Trans. Veh. Technol.*, vol. 58, no. 4, pp. 1647–1653, 2009.

[6] K. Lim and Y. Ko, "Multi-hop data harvesting in vehicular sensor networks," *IET Commun.*, vol. 4, no. 7, pp. 768–775, 2010.

[7] A. Abdrabou and W. Zhuang, "Probabilistic delay control and road side unit placement for vehicular ad hoc networks with disrupted connectivity," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 1, pp. 129–139, Jan. 2011.

[8] U. Lee, E. Magistretti, M. Gerla, P. Bellavista, and A. Corradi, "Dissemination and harvesting of urban data using vehicular sensing platforms," *IEEE Trans. Veh. Technol.*, vol. 58, no. 2, pp. 882–901, 2009.

[9] IEEE, "5.9 GHz Dedicated Short Range Communications (DSRC)." Available: http://grouper.ieee.org/groups/scc32/dsrc/

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

[11] A. Agarwal, D. Starobinski, and T. Little, "Analytical model for message propagation in delay tolerant vehicular ad hoc networks," in *Proc. 2008 IEEE VTC – Spring*, pp. 3067–3071.

[12] S. Panichpapiboon and W. Pattara-atikom, "Connectivity requirements for self-organizing traffic information," *IEEE Trans. Veh. Technol.*, vol 57, no. 6, pp. 3333–3340, Nov. 2008.

[13] R. Groenevelt, P. Nain, and G. Koole, "The message delay in mobile ad hoc networks," *ACM Perform. Eval.*, vol. 62, no. 1–4, pp. 210–228, May 2005.

[14] H. Wu, R. M. Fujimoto, G. F. Riley, and M. Hunter, "Spatial propagation of information in vehicular networks," *IEEE Trans. Veh. Technol.*, vol. 58, pp. 420–431, Jan. 2009.

[15] S. Yousefi, E. Altman, R. Elazouzi, and M. Fathy, "Improving connectivity in vehicular ad hoc networks: an analytical study," *Computer Commun.*, vol. 31, pp. 1653–1659, 2008.

[16] C. Lochert, B. Scheuermann, M. Caliskan, and M. Mauve, "The feasibility of information dissemination in vehicular ad-hoc networks," in *Proc. 2007 WONS*, pp. 92–99.

[17] G. Dib, "Vehicle-to-vehicle channel simulation in a network simulator," M.Sc. thesis, The Information Networking Institute, Carnegie Mellon University, Apr. 2009.

[18] A. D. May, *Traffic Flow Fundamentals*. Prentice Hall, 1990.

[19] Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments, IEEE 802.11p published standard, IEEE, July 2010.

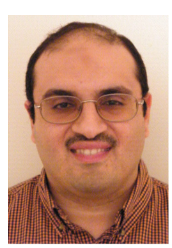
[20] N. Wisitpongphan, F. Bai, P. Mudalige, V. Sadekar, and O. Tonguz, "Routing in sparse vehicular ad hoc networks," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 8, pp. 1538–1556, Oct. 2007.

[21] S. Boyles, A. Voruganti, and S. Waller, "Quantifying distributions of freeway operational metrics," *Transp. Lett.: Int. J. Transp. Research 3*, no. 1, pp. 21–36, 2011.

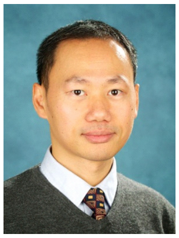
[22] L. Cheng, B. Henty, D. Stancil, F. Bai, and P. Mudalige, "Mobile vehicle-to-vehicle narrow-band channel measurement and characterization of the 5.9 GHz dedicated short range communcation (DSRC) frequency band," *IEEE J. Sel. Areas Commun.*, vol. 25, pp. 1501–1516, Oct. 2007.

[23] L. Cheng, B. Henty, F. Bai, and D. Stancil, "Highway and rural propagation channel modeling for vehicle-to-vehicle communications at 5.9 GHz," in *Proc. 2008 IEEE Antennas Propag. Soc. Int. Symp.*, pp. 1–4.

[24] A. S. Akki and F. Haber, "A statistical model of the mobile-to-mobile land communication channel," *IEEE Trans. Veh. Technol.*, vol. 35, no. 1, pp. 2–7, Feb. 1986.



Atef Abdrabou (M'09) received the Ph.D. degree in electrical engineering from the University of Waterloo, Waterloo, ON, Canada, in 2008. In 2010, he joined the Department of Electrical Engineering, United Arab Emirates University, Al-Ain, Abu Dhabi, UAE, where he is an Assistant Professor. His research interests include smart grid communications, network resource management, quality-of-service provisioning, and information dissemination in self-organizing wireless networks. Dr. Abdrabou is a co-recipient of the Best Paper Award of IEEE WCNC 2010. In 2009, he received the National Science and Engineering Research Council of Canada (NSERC) postdoctoral fellowship for academic excellence, research potential, communication, and leadership abilities. He is an Associate Editor of the *Journal of Circuits, Systems, and Computers*.



Ben Liang received honors-simultaneous B.Sc. (valedictorian) and M.Sc. degrees in electrical engineering from Polytechnic University, Brooklyn, New York, in 1997 and the Ph.D. degree in electrical engineering with a computer science minor from Cornell University in Ithaca, New York, in 2001. In the 2001–2002 academic year, he was a visiting lecturer and post-doctoral research associate at Cornell University. He joined the Department of Electrical and Computer Engineering at the University of Toronto in 2002, where he is now a Professor. His current research interests are in mobile networking and multimedia systems. He received an Intel Foundation Graduate Fellowship in 2000 and an Ontario MRI Early Researcher Award (ERA) in 2007. He was a co-author of the Best Paper Award at the IFIP Networking Conference in 2005. He is an editor for the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS and an associate editor for the *Wiley Security and Communication Networks* journal. He serves on the organizational and technical committees of a number of conferences each year. He is a senior member of IEEE and a member of ACM and Tau Beta Pi.

Weihua Zhuang (M'93-SM'01-F'08) has been with the Department of Electrical and Computer Engineering, University of Waterloo, Canada, since 1993, where she is a Professor and a Tier I Canada Research Chair in Wireless Communication Networks. Her current research focuses on resource allocation and QoS provisioning in wireless networks and smart grid. She is a co-recipient of the Best Paper Awards from IEEE Globecom 2012, the IEEE International Conference on Communications (ICC) 2007 and 2012, the IEEE Multimedia Communications Technical Committee in 2011, the IEEE Vehicular Technology Conference (VTC) Fall 2010, the IEEE Wireless Communications and Networking Conference (WCNC) 2007 and 2010, and the International Conference on Heterogeneous Networking for Quality, Reliability, Security and Robustness (QShine) 2007 and 2008. She received the Outstanding Performance Award four times since 2005 from the University of Waterloo, and the Premiers Research Excellence Award in 2001 from the Ontario Government. Dr. Zhuang was the Editor-in-Chief of the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY (2007–2013), the Technical Program Symposia Chair of IEEE Globecom 2011, and an IEEE Communications Society Distinguished Lecturer (2008–2011). She is a Fellow of the IEEE, a Fellow of the Canadian Academy of Engineering (CAE), a Fellow of the Engineering Institute of Canada (EIC), and an elected member of the Board of Governors of the IEEE Vehicular Technology Society (2012–2014).