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Delivery Delay Analysis for Roadside Unit Deployment in Vehicular Ad Hoc Networks with Intermittent Connectivity

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Abstract

This paper studies the information delivery delay analysis for roadside unit deployment in a vehicular ad hoc network (VANET) with intermittent connectivity. A mathematical model is developed to describe the relationship between the average delay for delivering road condition information and the distance between two neighbor RSUs deployed along a road. The derived mathematical model considers a straight highway scenario where two RSUs are deployed at a distance without any direct connection and vehicles are sparsely distributed on the road with road condition information randomly generated between the two neighbor RSUs. Moreover, the model takes into account the vehicle speed, the vehicle density, the likelihood of an incident, and the distance between two RSUs. The effectiveness of the derived mathematical model is verified through simulation results. Given the information delivery delay constraint of a time-critical application, this model can be used to estimate the maximum distance allowed between two neighbor RSUs, which can provide a reference for the deployment of RSUs in such scenarios.

Keywords—delay analysis; information delivery; roadside unit; VANET

I . Introduction

Vehicular Ad Hoc Networks (VANETs) promise a variety of potential applications in providing road safety and in-vehicle entertainment services. One of the important VANET applications is to collect road condition information via vehicles and disseminate the collected information to all vehicles in the network in order to help avoid traffic jams, reduce car accidents, and save fuel consumption. Due to its highly dynamic characteristic, a VANET is often of intermittent connectivity, which would increase the delay for disseminating collected road condition information and thus affect the quality of service (QoS) provisioned to users. To address this problem, roadside units (RSUs) can be deployed in a VANET to improve the network connectivity, and help disseminate

road condition information. Obviously, the more densely the RSUs are deployed, the better the network connectivity can be obtained. However, deploying RSUs is costly. It is impractical to deploy RSUs in a dense scale, in particular, in those remote areas. This means that two neighbor RSUs can be deployed along a road without any direct connection, which would increase the delay for disseminating road condition information collected outside the coverage of an RSU. For many applications, however, road condition information is time critical. It is important to deliver such time-critical information to an RSU within a delay constraint so that the RSU can help timely disseminate the information to the vehicles passing through it. To this end, two neighbor RSUs should not be deployed at a distance larger than a certain value. Therefore, it is helpful to find out and analyze the relationship between the information delivery delay and the distance between two neighbor RSUs deployed along a road, which is the motivation for this work.

In this paper, we study the information delivery delay analysis for roadside unit deployment in a VANET with intermittent connectivity. We derive a mathematical model to describe the relationship between the average delay for delivering road condition information and the distance between two neighbor RSUs deployed along a road. We consider a straight highway scenario where two RSUs are deployed at a distance without any direct connection and vehicles are sparsely distributed on the road with road condition information randomly generated between the two neighbor RSUs. Moreover, we take into account the vehicle speed, the vehicle density, the likelihood of an incident, and the distance between two RSUs in the mathematical model. Simulation experiments are conducted to verify the effectiveness of the derived mathematical model and investigate the impacts of different parameters on the average information delivery delay.

The remainder of the paper is organized as follows. Section II reviews related work in the literature. Section III derives the mathematical model and analyzes the information delivery delay. Section IV presents simulation results to verify the effectiveness of the mathematical model. Section V concludes this paper.

II . Related work

Delay analysis for sparse VANETs has been studied in the literature [1-8]. In [1-4], Khabbaz et al. proposed several information release mechanisms to achieve a delay-minimal information delivery in the context of an intermittent roadside network. However, all of them considered how to send the information to passing vehicles, rather than send the information to RSUs by passing vehicles. In [5], Abdrabou et al. studied the multi-hop packet delivery delay in a low-density network scenario, where an end-to-end path is not available between a vehicle and the nearest RSU, in order to obtain the maximum distance between RSUs that stochastically limits the worst-case packet delivery delay to a certain bound. However, this work only considers the scenario where vehicles move in

one direction. In [6], Abdrabou et al. presented a mathematical model for calculating the message delivery delay distribution on a two-lane road, where vehicles in one direction can carry messages for the vehicles in the other direction and have the freedom to leave the road from randomly distributed road junctions with a certain probability. However, they considered the infrastructure-based RSUs, where the RSUs are connected through fiber or broadband wireless links. In [7], Wisitpongphan et al. proposed a model for analyzing the packet delivery delay between disconnected vehicles. Based on [7], Reis et al. proposed a model for analyzing the average time taken to propagate a packet to disconnected nodes when considering both scenarios of connected and disconnected RSUs in [8]. The results show significant delay improvement with RSU deployment, particularly in multi-cluster communication scenarios. However, both of them only considered the information delivery delay from vehicle to vehicle without considering the delivery delay between a vehicle and an RSU. To the best of our knowledge, there is no work found in the literature that studies the delay analysis of delivering road condition information to non-connected RSUs by passing vehicles for RSU deployment.

III. Modeling and Analysis of Delivery Delay

In this section, we derive a mathematical model to describe the relationship between the information delivery delay and the distance between two neighbor RSUs deployed along a road.

1. Network Scenario and Problem Description

We consider a straight road segment between two neighbor RSUs on a sparse highway with two lanes in opposite directions, and low connectivity and traffic load, as illustrated in Fig. 1. The distance between RSU1 and RSU2 is denoted by d . The communication radius of each RSU is denoted by R_u . The communication radius of each vehicle is denoted by R_v . We assume that $R_u \geq R_v$. The two neighbor RSUs are deployed without any direct connection, i.e., $d \gg 2R_u$. The inter-vehicle spacing of westbound vehicles and eastbound vehicles are exponentially distributed with λ_e and λ_w [7], respectively, where λ_e and λ_w are the average arrival rates of the westbound vehicles and eastbound vehicles, respectively. All vehicles moving in one direction have the same speed with v_e and v_w as the speeds for the eastbound vehicles and westbound vehicles, respectively. The vehicles that move in the same direction and can communicate with one another in one hop or multiple hops form a cluster, as shown in Fig. 2. As all vehicles moving in one direction have the same speed, all clusters in the same direction will keep their respective spacing and thus cannot communicate with each other. An incident occurs randomly at a location with a distance x from RSU1, i.e., $x \in [0, d]$. Once an incident occurs, the closest vehicle to the occurring location of the incident will first arrive at the location and collect the incident information. This vehicle is referred to as a source node, which will deliver the collected information to the two neighbor RSUs directly or indirectly

via other vehicles. A vehicle that can forward the collected information to an RSU is referred to as a forwarding node. We define the average information delivery delay as the average time from the instant when an incident occurs to the instant when both the RSUs have received the incident information. Since this delay depends on the distance between the two neighbor RSUs, it is interesting to find out the relationship between the distance and the delay, which would be helpful to RSU deployment in order to meet the delay constraint of an application. Therefore, the problem considered in this paper is to develop a mathematical model that describes the average information delivery delay and the distance between two neighbor RSUs deployed along a straight highway.

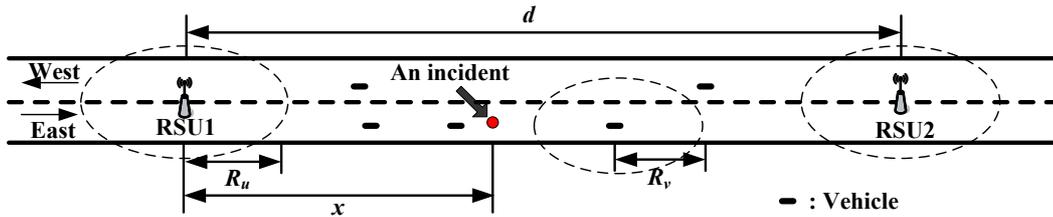


Fig.1 Basic network scenario.

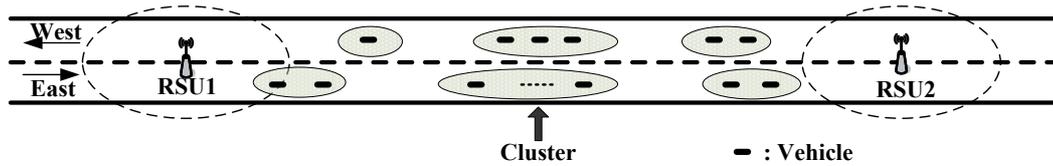


Fig.2 Vehicle clusters on a road.

2. Modeling and Analysis of Delivery Delay

Considering the basic network scenario shown in Fig. 1, the average information delivery delay can be calculated as

$$T = T_0 + T_S, \tag{1}$$

where T is the average delivery delay, T_0 is the average time it takes for the closest vehicle to the occurring location of an incident (i.e., the source node) to arrive at the occurring location of the incident, and T_S is the average time it takes for the source node to deliver the collected information from the occurring location of an incident to an RSU. Since we are considering a sparse highway scenario, both the network connectivity and the traffic load are low. In this case, the incident information will be delivered from the source node to the destination node via one or multiple vehicles in a “store-carry-forward” manner, and the delivery delay is typically on the order of seconds or even minutes [7]. For this reason, if the destination node of the collected information is within the transmission radius of the source node, the delay caused by direct transmission between the two nodes would be much smaller than the delivery delay caused by “store-carry-forward”. Therefore, we will mainly consider the

delivery delay caused by “store-carry-forward” and ignore the direct transmission delay between a couple of source and destination nodes in the analytical model.

Let $f(x)$ denote the probability density function of the distance x . The expectation of x can be calculated as follows

$$E[X] = \int_0^d x \cdot f(x) dx, f(x)(0 \leq x \leq d). \quad (2)$$

As explained earlier, T_S is the average time for the collected information to be delivered from the occurring location of an incident to an RSU. Obviously, T_S depends on the distance between the two neighbor RSUs. When a source node has collected the incident information, it will deliver the collected information to both RSU1 and RSU2. Since it takes different time for the source node to deliver the information to RSU1 and RSU2, respectively, we take the longer one in calculating T_S because only after T_S both RSU1 and RSU2 can receive the information. Therefore, we have

$$T_S = \int_0^d \max\{T_{RSU1}, T_{RSU2}\} \cdot f(x) dx, \quad (3)$$

where T_{RSU1} and T_{RSU2} represents the delay for the collected information to be delivered from the occurring location of the incident to RSU1 and RSU2, respectively.

Next we analyze the average information delivery delay T in the following three cases:

- Case 2.1: The incident occurs at a location where $x \in [0, R_v]$;
- Case 2.2: The incident occurs at a location where $x \in [R_v, d - R_v]$;
- Case 2.3: The incident occurs at a location where $x \in [d - R_v, d]$.

Without loss of generality, we assume that when an incident occurs, an eastbound vehicle is the closest to the occurring location of the incident and will first arrive at the occurring location of the incident. This vehicle is called source node hereafter. The notations used in the analysis are defined as follows:

n_e : The size of an eastbound cluster, i.e., the number of vehicles in an eastbound cluster;

n_w : The size of a westbound cluster, i.e., the number of vehicles in a westbound cluster;

l_e : The length of an eastbound cluster, i.e., the distance between the first vehicle and the last vehicle in an eastbound cluster;

l_w : The length of a westbound cluster, i.e., the distance between the first vehicle and the last vehicle in a westbound cluster;

$E[l_e]$: The average length of an eastbound cluster;

$E[l_w]$: The average length of a westbound cluster;

$f_e(n_e)$: The probability mass function (PMF) of N_e ;

$f_w(n_w)$: The probability mass function (PMF) of N_w ;

$E[d_v^e]$: The average distance between two vehicles within an eastbound cluster;

$E[d_v^w]$: The average distance between two vehicles within a westbound cluster;

$E[d_c^e]$: The average distance between two neighbor eastbound clusters, i.e., the expected distance between the last vehicle of an eastbound cluster and the first vehicle of the following eastbound cluster;

$E[d_c^w]$: The average distance between two neighbor westbound clusters, i.e., the expected distance between the last vehicle of a westbound cluster and the first vehicle of the following westbound cluster.

2.1 Case 2.1: The incident occurs at $x \in [0, R_v]$

In Case 2.1, the incident occurs within the communication radius of RSU1. After the source node detects the incident, it can transmit the information to RSU1 directly. Thus, the time it takes for the source node to directly forward the incident information to RSU1 can be ignored. Let $f_1(x)$ denote the conditional probability density function of the distance x in $[0, R_v]$. Then, the average information delivery delay can be written as follows

$$T_1 = T_{01} + T_{S1}, \quad (4)$$

where T_{01} is the average time it takes for the vehicle closest to the occurring location of an incident (i.e., the source node) to arrive at the occurring location of the incident, and T_{S1} is the average time it takes for the source node to deliver the collected information from the occurring location of the incident to RSU2. Next we analyze T_{01} and T_{S1} , respectively.

2.1.1 Analysis of T_{01}

According to the property of an exponential distribution, the average time that it takes for the eastern vehicle node to arrive at the left end point of interval $[0, R_v]$ is $1/(\lambda_e v_e)$. Thus, T_{01} can be calculated as

$$T_{01} = 1/v_e \cdot \int_0^{R_v} x \cdot f_1(x) dx + 1/(\lambda_e v_e). \quad (5)$$

2.1.2 Analysis of T_{S1}

Like [7], we assume that the source node is statistically located in the center of its cluster. As we assumed that the source node is an eastbound vehicle, the forwarding direction of the incident information to RSU2 is the same as the moving direction of the source node. Since the direct transmission delay can be ignored, the incident information can be delivered to the first vehicle in the cluster without any delay. In this case, the first vehicle

becomes a forwarding node, which is denoted by node 1, as shown in Fig. 3. If node 1 is in the communication radius of RSU2, the information can be transmitted to RSU2 directly. Thus, we only need to consider the case where node 1 is out of the communication radius of RSU2. This case happens if the length of the eastbound cluster satisfies the following condition:

$$l_e/2 - R_v < d - x - R_u,$$

and the probability that this case happens is given by

$$p_{212} = \Pr\{l_e/2 - R_v < d - x - R_u\}. \quad (6)$$

According to [7], the average distance between two vehicles in an eastbound cluster can be calculated as

$$E[d_v^e] = 1/\lambda_e - R_v \cdot e^{-\lambda_e R_v} / (1 - e^{-\lambda_e R_v}), \quad (7)$$

and the PMF of n_e is

$$f_e(n_e) = e^{-\lambda_e R_v} (1 - e^{-\lambda_e R_v})^{n_e - 1}. \quad (8)$$

Obviously, given $E[d_v^e]$ and n_e , we can obtain

$$p_{212} = \Pr\{l_e/2 - R_v < d - x - R_u\} = 1 - (1 - e^{-\lambda_e R_v})^{k_{212}}, \quad (9)$$

where $k_{212} = 2(d - x - R_u + R_v) / E[d_v^e]$.

Let E_{212} denote the conditional expectation of $l_e/2$ under condition $l_e/2 < d - x - R_u + R_v$. We can obtain

$$E_{212} = E[l_e/2 | l_e/2 < d - x - R_u + R_v] = 0.5E[d_v^e]E[n_e | n_e < k_{212}], \quad (10)$$

where

$$E[n_e | n_e < k_{212}] = [1 - (k_{212} + 1)(1 - e^{-\lambda_e R_v})^{k_{212}} + k_{212}(1 - e^{-\lambda_e R_v})^{k_{212} + 1}] / \{[1 - (1 - e^{-\lambda_e R_v})^{k_{212}}]e^{-\lambda_e R_v}\}.$$

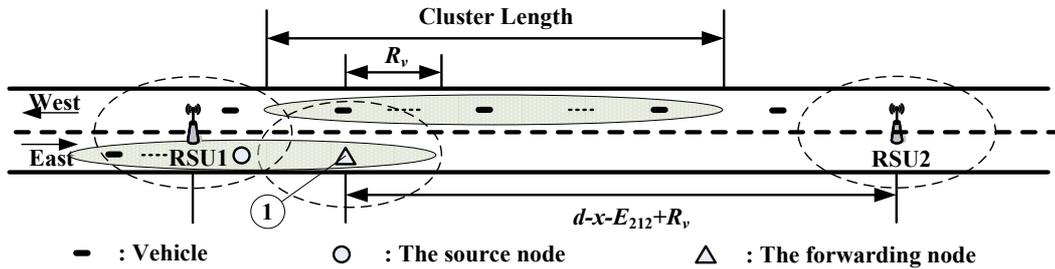


Fig.3 The westbound cluster is out of the communication radius of RSU2.

Further, this case can be divided into the following two sub-cases:

- Case 2.1.2.0: There are one or more westbound vehicles in the coverage of node 1.
- Case 2.1.2.1: There is no westbound vehicle in the coverage of node 1.

Case 2.1.2.0

Case 2.1.2.0 happens when there is at least one westbound vehicle within the communication radius of node 1.

Let p_{2120} denote the probability that Case 2.1.2.0 happens. Thus, we have

$$p_{2120} = 1 - e^{-2\lambda_w R_v}. \quad (11)$$

In this case, if the last vehicle of the westbound cluster is within the communication radius of RSU2, the information can be transmitted to RSU2 directly and the direct transmission delay can be ignored. However, if the last vehicle of the westbound cluster is out of the communication radius of RSU2, i.e., the length of the westbound cluster satisfies the following condition:

$$l_w/2 < d - x - E_{212} + R_v,$$

information will be forwarded to RSU2 by node 1. The probability of this case is given by

$$p_{21200} = \Pr\{l_w/2 < d - x - E_{212} + R_v\}. \quad (12)$$

According to [7], the average distance between two vehicles in a westbound cluster can be calculated as

$$E[d_v^w] = 1/\lambda_w - R_v \cdot e^{-\lambda_w R_v} / (1 - e^{-\lambda_w R_v}), \quad (13)$$

and the PMF of n_w is

$$f_w(n_w) = e^{-\lambda_w R_v} (1 - e^{-\lambda_w R_v})^{n_w - 1}. \quad (14)$$

Obviously, given $E[d_v^w]$ and n_w , we can obtain

$$p_{21200} = \Pr\{l_w/2 < d - x - E_{212} + R_v\} = 1 - (1 - e^{-\lambda_w R_v})^{k_{21200}}, \quad (15)$$

where $k_{21200} = 2(d - x - E_{212} + R_v) / E[d_v^w]$. Therefore, the delivery delay can be calculated as

$$T_{21200} = (d - x - R_u - E_{212} + R_v) / v_e. \quad (16)$$

Case 2.1.2.1

Case 2.1.2.1 happens when there is no westbound vehicle within the communication radius of node 3. The probability that Case 2.1.2.1 happens can be calculated as

$$p_{2121} = 1 - p_{2120}. \quad (17)$$

In this case, the information will be forwarded to RSU2 by node 1. Thus, the delivery delay T_{2121} equals to T_{21200} .

Considering all the above cases, we have

$$T_{S1} = p_{212} \cdot (p_{2120} \cdot p_{21200} \cdot T_{21200} + p_{2121} \cdot T_{2121}). \quad (18)$$

2.2 Case 2.2: The incident occurs at $x \in [R_v, d - R_v]$

Let $f_2(x)$ denote the conditional probability density function of the distance x in $[R_v, d - R_v]$. The average

information delivery delay can be given as

$$T_2 = T_{02} + T_{S2}, \quad (19)$$

where T_{02} is the average time that it takes for the source node to arrive at the occurring location of the incident, and T_{S2} is the average time it takes for the source node to deliver the collected information from the occurring location of the incident to both of the neighboring RSUs. Since it takes a different time to deliver the information to RSU1 and RSU2, we need to calculate T_{RSU1} and T_{RSU2} , and take the longer one in calculating T_{S2} . Next we analyze T_{02} and T_{S2} , respectively.

2.2.1 Analysis of T_{02}

According to the property of an exponential distribution, the average inter-vehicle spacing of eastbound vehicles is $1/\lambda_e$. Let y denote the distance between RSU1 and the vehicle closest to the occurring location of an incident. Obviously, we have $x - 1/\lambda_e \leq y \leq x$, as illustrated in Fig. 4. Let $f_2'(x)$ denote the conditional probability density function of the distance x in $[y, y+1/\lambda_e]$. Thus, the average time that it takes for the closest vehicle to the occurring location of an incident to arrive at the occurring location of the incident can be calculated as

$$T_{02} = \left[\int_y^{y+1/\lambda_e} x \cdot f_2'(x) dx - y \right] / v_e. \quad (20)$$

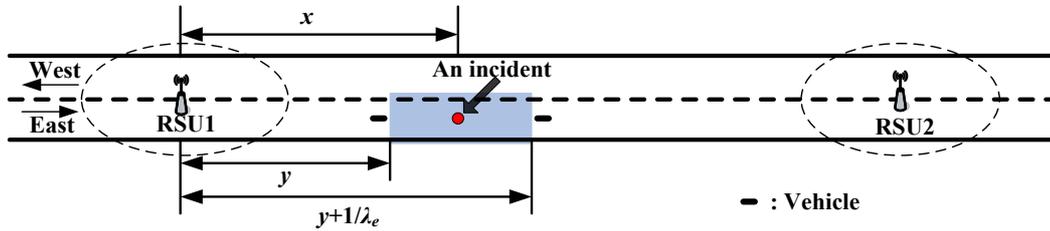


Fig.4 Relative position of the source node and the location of an incident.

2.2.2 Analysis of T_{S2}

As discussed earlier, T_{S2} is the longest one in T_{RSU1} and T_{RSU2} . Next we first analyze T_{RSU1} and T_{RSU2} , respectively.

2.2.2.1 Analysis of T_{RSU1}

Like [7], we assume that the source node is statistically located in the center of its cluster, as shown in Fig. 5. As we assumed that the source node is an eastbound vehicle, the delivery direction of the incident information to RSU1 is opposite to the moving direction of the source node. Since the direct transmission delay is ignored, the incident information can be delivered to the last vehicle in the cluster without any delay. In this case, this vehicle becomes a forwarding node, which is denoted by node 2 in Fig. 5.

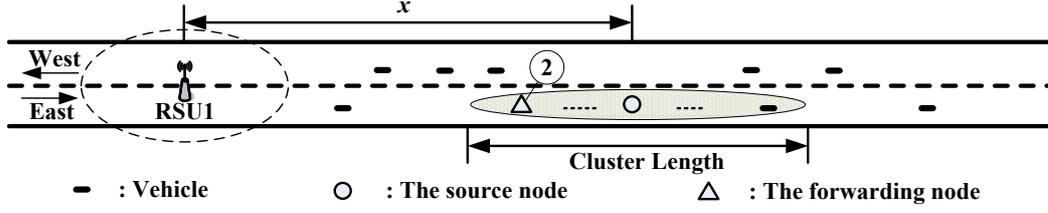


Fig.5 The forwarding node is out of the communication radius of RSU1.

If node 2 is within the communication radius of RSU1, the information can be directly transmitted to RSU1. Since the direct transmission delay can be ignored, we only need to analyze the case where node 2 is out of the communication radius of RSU1. In this case, the forwarding node can take advantage of the westbound vehicles to forward the information to RSU1.

This case happens if the length of the eastbound cluster satisfies the following condition:

$$l_e/2 - R_v < x - R_u,$$

and the probability that this case happens is given by

$$p_{2221} = \Pr\{l_e/2 - R_v < x - R_u\}. \quad (21)$$

Similar to Eq. (9), we can obtain

$$p_{2221} = \Pr\{l_e/2 - R_v < x - R_u\} = 1 - (1 - e^{-\lambda_e R_v})^{k_{2221}}, \quad (22)$$

where $k_{2221} = 2(x - R_u + R_v)/E[d_v^e]$.

Let E_{2221} denote the conditional expectation of $l_e/2$ under condition $l_e/2 - R_v < x - R_u$. We can obtain

$$\begin{aligned} E_{2221} &= E[l_e/2 | l_e/2 < x - R_u + R_v] \\ &= 0.5E[d_v^e] \cdot [1 - (1 - e^{-\lambda_e R_v})^{k_{2221}} \cdot (k_{2221} e^{-\lambda_e R_v} + 1)] / \{[1 - (1 - e^{-\lambda_e R_v})^{k_{2221}}] e^{-\lambda_e R_v}\}. \end{aligned} \quad (23)$$

Further, we divide this case into two sub-cases:

- Case 2.2.2.1.0: There are one or more westbound vehicles within the coverage of node 2.
- Case 2.2.2.1.1: There is no westbound vehicle in the coverage of node 2.

Case 2.2.2.1.0

Case 2.2.2.1.0 happens when there is at least one westbound vehicle within the communication radius of node 2. Let p_{22210} denote the probability that Case 2.2.2.1.0 happens. Thus, we have

$$p_{22210} = 1 - e^{-2\lambda_w R_v}. \quad (24)$$

In this case, the first vehicle of the corresponding westbound cluster becomes a forwarding node, which is denoted by node 3, as shown in Fig. 6. If node 3 is within the communication radius of RSU1, the information can be directly transmitted to RSU1 and the direct transmission delay can be ignored. Thus, we only need to analyze that

the case where node 3 is out of the communication radius of RSU1, i.e., the length of the westbound cluster satisfies the following condition:

$$l_w/2 < x - E_{2221} + R_v.$$

In this case, node 3 will store and carry the information until it enters the communication radius of RSU1, when it will transmit the information to RSU1 directly.

Let p_{222100} denote the probability that this case happens. Thus, we have

$$p_{222100} = \Pr\{l_w/2 < x - E_{2221} + R_v\}. \quad (25)$$

Similar to Eq.(15), we can obtain

$$p_{222100} = \Pr\{l_w/2 < x - E_{2221} + R_v\} = 1 - (1 - e^{-\lambda_w R_v})^{k_{222100}}, \quad (26)$$

where $k_{222100} = 2(x - E_{2221} + R_v) / E[d_v^w]$.

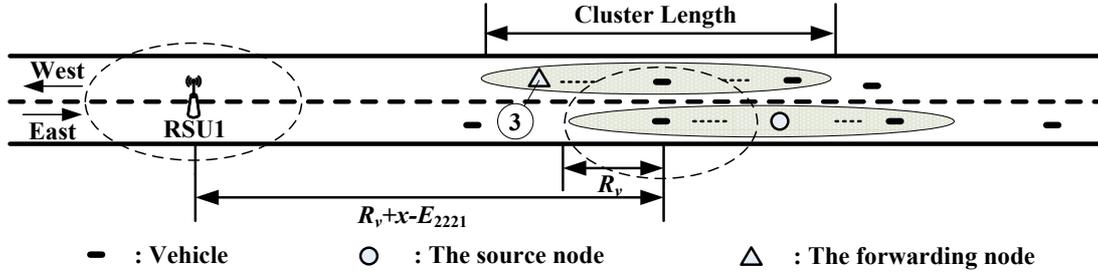


Fig.6 The westbound cluster is out of the communication radius of RSU1.

Therefore, the delivery delay for node 3 to forward the incident information to RSU1 can be approximately calculated as

$$T_{222100} = (x - R_u - E_{2221} + 2R_v - 0.5E[l_w/2 | l_w/2 < x + R_v - E_{2221}]) / v_w, \quad (27)$$

where

$$\begin{aligned} & E[l_w/2 | l_w/2 < x + R_v - E_{2221}] \\ &= 0.5E[d_v^w] \cdot [1 - (1 - e^{-\lambda_w R_v})^{k_{222100}} \cdot (k_{222100} e^{-\lambda_w R_v} + 1)] / \{[1 - (1 - e^{-\lambda_w R_v})^{k_{222100}}] e^{-\lambda_w R_v}\}. \end{aligned}$$

Case 2.2.2.1.1

Case 2.2.2.1.1 happens when there is no westbound vehicle within the communication radius of node 1. The probability that case 2.2.2.1.1 happens can be calculated as

$$p_{22211} = 1 - p_{22210}. \quad (28)$$

This case can be further divided into the following two sub-cases:

- Case 2.2.2.1.1.0: There is no westbound vehicle within the communication radius of node 2 and there is no westbound vehicle within the communication range of other nodes in the same cluster either, as shown in

Fig. 7.

- Case 2.2.2.1.1.1: There is no westbound vehicle within the communication radius of node 2 but there is one or more westbound vehicles within the communication range of a node other than node 2 in the same cluster, as shown in Fig. 8.

Next we analyze Case 2.2.2.1.1.0 and Case 2.2.2.1.1.1, respectively.

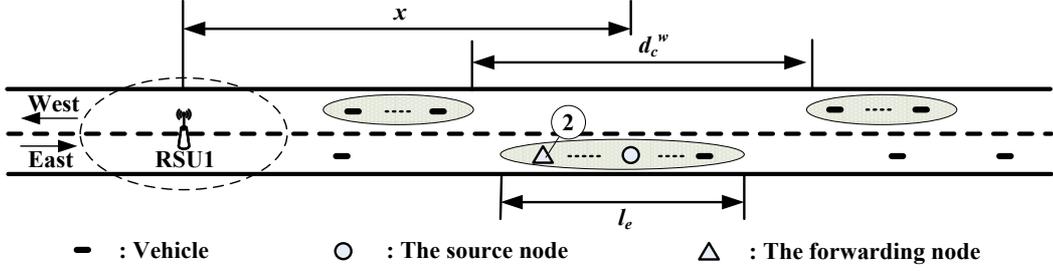


Fig.7 Case 2.2.2.1.1.0.

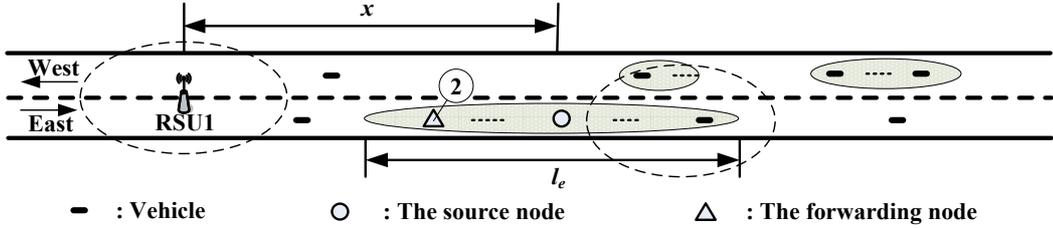


Fig.8 Case 2.2.2.1.1.1.

Case 2.2.2.1.1.0

In Case 2.2.2.1.1.0, there is no westbound vehicle in the entire coverage of the eastbound cluster, as shown in Fig. 7. This case happens when the length of the eastbound cluster satisfies the following condition:

$$l_e < E[d_c^w] - 2R_v,$$

and the probability that Case 2.2.2.1.1.0 happens is given by

$$p_{222110} = \Pr\{l_e < E[d_c^w] - 2R_v\}. \quad (29)$$

According to [7], the average distance between two neighbor eastbound clusters is

$$E[d_c^w] = R_v + 1/\lambda_w. \quad (30)$$

Obviously, given $E[d_c^w]$ and $E[d_v^e]$, we can obtain

$$p_{222110} = \Pr\{l_e < E[d_c^w] - 2R_v\} = 1 - (1 - e^{-\lambda_e R_v})^{k_{222110}}, \quad (31)$$

where $k_{222110} = (E[d_c^w] - 2R_v) / E[d_v^e]$.

In this case, node 2 will store and carry the information until it meets a westbound vehicle, when it will

forward the information to the westbound vehicle, which will further forward the information to RSU1. Since the westbound vehicle closest to node 2 is at least $x + 0.5E[d_c^w]$ away from RSU1, the delivery delay can be approximately calculated as

$$T_{222110} = (x + 0.5E[d_c^w])/v_w. \quad (32)$$

Case 2.2.2.1.1.1

In Case 2.2.2.1.1.1, there is one or more westbound vehicles within the communication range of a node other than node 2 in the eastbound cluster. Obviously, this case happens with probability

$$p_{222111} = 1 - p_{222110}. \quad (33)$$

In this case, node 2 will directly transmit the information to a westbound node, which will further forward the information to RSU1. According to [7], the average length of an eastbound cluster is

$$E[l_e] = (e^{\lambda_e R_v} - 1) \cdot [1/\lambda_e - R_v \cdot e^{-\lambda_e R_v} / (1 - e^{-\lambda_e R_v})]. \quad (34)$$

Since the closest westbound vehicle to node 2 is at most $x + 0.5E[l_e]$ away from RSU1, the delivery delay can be approximately calculated as

$$T_{222111} = (x + 0.5E[l_e])/v_w. \quad (35)$$

Considering all the above cases, we have

$$T_{RSU1} = [p_{22210} \cdot p_{222100} \cdot T_{222100} + p_{22211} \cdot (p_{222111} \cdot T_{222111} + p_{222110} \cdot T_{222110})] \cdot p_{2221}. \quad (36)$$

2.2.2.2 Analysis of T_{RSU2}

Similar to the analysis of T_{RSU1} , we assume that the source node is statistically located in the center of its cluster. As we assumed that the source node is an eastbound vehicle, the forwarding direction of the incident information to RSU2 is the same as the moving direction of the source node. Since the direct transmission delay can be ignored, the incident information can be delivered to the first vehicle in the cluster without any delay. In this case, the first vehicle becomes a forwarding node, which is denoted by node 4, as shown in Fig. 9. If node 4 is in the communication radius of RSU2, the information can be transmitted to RSU2 directly. Thus, we only need to consider the case where node 4 is out of the communication radius of RSU2. This case happens if the length of the eastbound cluster satisfies the following condition:

$$l_e/2 - R_v < d - x - R_u,$$

and the probability that this case happens is given by

$$p_{2222} = \Pr\{l_e/2 - R_v < d - x - R_u\}. \quad (37)$$

Similar to Eq.(9), p_{2222} can be calculated as follows

$$p_{2222} = \Pr\{l_e/2 - R_v < d - x - R_u\} = 1 - (1 - e^{-\lambda_e R_v})^{k_{2222}}, \quad (38)$$

where $k_{2222} = 2(d - x - R_u + R_v) / E[d_v^e]$.

Let E_{2222} denote the conditional expectation of $l_e/2$ under condition $l_e/2 < d - x - R_u + R_v$. We can obtain

$$E_{2222} = E[l_e/2 | l_e/2 < d - x - R_u + R_v] = 0.5E[d_v^e]E[n_e | n_e < k_{2222}], \quad (39)$$

where $E[n_e | n_e < k_{2222}] = [1 - (k_{2222} + 1)(1 - e^{-\lambda_e R_v})^{k_{2222}} + k_{2222}(1 - e^{-\lambda_e R_v})^{k_{2222}+1}] / \{[1 - (1 - e^{-\lambda_e R_v})^{k_{2222}}]e^{-\lambda_e R_v}\}$.

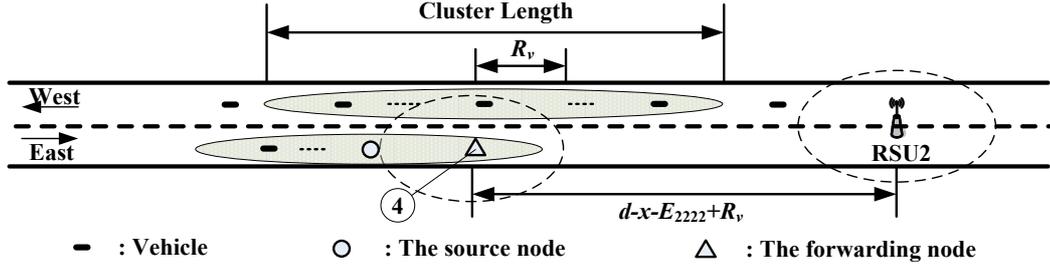


Fig.9 The westbound cluster is out of the communication radius of RSU2.

Similarly to the analysis of T_{RSU1} , this case can further be divided into two sub-cases.

- Case 2.2.2.2.0: There are one or more westbound vehicles in the coverage of node 4.
- Case 2.2.2.2.1: There is no westbound vehicle in the coverage of node 4.

Case 2.2.2.2.0

Case 2.2.2.2.0 happens when there is at least one westbound vehicle within the communication radius of node

4. Let p_{22220} denote the probability that Case 2.2.2.2.0 happens. Thus, we have

$$p_{22220} = 1 - e^{-2\lambda_w R_v}. \quad (40)$$

In this case, if the last vehicle of the westbound cluster is within the communication radius of RSU2, the information can be transmitted to RSU2 directly and the direct transmission delay can be ignored. However, if the last vehicle of the westbound cluster is out of the communication radius of RSU2, i.e., the length of the westbound cluster satisfies the following condition:

$$l_w/2 < d - x - E_{2222} + R_v,$$

the information will be forwarded to RSU2 by node 4. The probability of this case is given by

$$p_{222200} = \Pr\{l_w/2 < d - x - E_{2222} + R_v\}. \quad (41)$$

Similar to Eq.(15), we can obtain

$$p_{222200} = \Pr\{l_w/2 < d - x - E_{2222} + R_v\} = 1 - (1 - e^{-\lambda_w R_v})^{k_{222200}}, \quad (42)$$

where $k_{222200} = 2(d - x - E_{2222} + R_v) / E[d_v^w]$. Therefore, the delivery delay can be calculated as

$$T_{222200} = (d - x - R_u - E_{2222} + R_v) / v_e. \quad (43)$$

Case 2.2.2.2.1

Case 2.2.2.2.1 happens when there is no westbound vehicle within the communication radius of node 4. The probability that Case 2.2.2.2.1 happens can be calculated as

$$p_{22221} = 1 - p_{22220}. \quad (44)$$

In this case, the information will be forwarded to RSU2 by node 4. Thus, the delivery delay T_{22221} equals to T_{222200} .

Considering all the above cases, we have

$$T_{RSU2} = p_{2222} \cdot (p_{22220} \cdot p_{222200} \cdot T_{222200} + p_{22221} \cdot T_{22221}). \quad (45)$$

$$T_{S2} = \max\{T_{RSU1}, T_{RSU2}\}. \quad (46)$$

2.3 Case 2.3: The incident occurs at $x \in [d - R_v, d]$

In Case 2.3, the incident occurs within the communication radius of RSU2. After the source node collects the information, it can transmit the incident information to RSU2 directly. Thus, the time it takes for the source node to directly forward the incident information to RSU2 can be ignored. Let $f_3(x)$ denote the conditional probability density function of the distance x in $[d - R_v, d]$. Then, the average information delivery delay can be written as follows

$$T_3 = T_{03} + T_{S3}, \quad (47)$$

where T_{03} is the average time that it takes for the source node to arrive at the occurring location of the incident information, and T_{S3} is the average time that it takes for the source node to deliver the incident information to RSU1. Next we analyze T_{03} and T_{S3} , respectively.

2.3.1 Analysis of T_{03}

Similar to the analysis of T_{01} , T_{03} can be calculated as

$$T_{03} = 1/v_e \cdot \left(\int_{d-R_v}^d x \cdot f_3(x) dx - d + R_v \right) + 1/(\lambda_e v_e). \quad (48)$$

2.3.2 Analysis of T_{S3}

Similar to the analysis of T_{RSU1} , we assume that the source node is statistically located in the center of its cluster, as shown in Fig. 10. As we assumed that the source node is an eastbound vehicle, the delivery direction of the incident information to RSU1 is opposite to the moving direction of the source node. Since the direct transmission delay is ignored, the incident information can be delivered to the last vehicle in the cluster without any delay. In this case, this vehicle becomes a forwarding node, which is denoted by node 5 in Fig. 10. If node 5 is

in the communication radius of RSU1, the information can be transmitted to RSU1 directly. Thus, we only need to consider the case where node 5 is out of the communication radius of RSU1. This case happens if the length of the eastbound cluster satisfies the following condition:

$$l_e/2 - R_v < x - R_u,$$

and the probability that this case happens is given by

$$p_{232} = \Pr\{l_e/2 - R_v < x - R_u\}. \quad (49)$$

Similar to Eq.(9), we can obtain

$$p_{232} = \Pr\{l_e/2 - R_v < x - R_u\} = 1 - (1 - e^{-\lambda_e R_v})^{k_{232}}, \quad (50)$$

where $k_{232} = 2(x - R_u + R_v) / E[d_v^e]$.

Let E_{232} denote the conditional expectation of $l_e/2$ under condition $l_e/2 < x - R_u + R_v$. We can obtain

$$\begin{aligned} E_{232} &= E[l_e/2 | l_e/2 < x - R_u + R_v] \\ &= 0.5E[d_v^e] \cdot [1 - (k_{232} + 1)(1 - e^{-\lambda_e R_v})^{k_{232}} + k_{232}(1 - e^{-\lambda_e R_v})^{k_{232} + 1}] / \{[1 - (1 - e^{-\lambda_e R_v})^{k_{232}}]e^{-\lambda_e R_v}\}. \end{aligned} \quad (51)$$

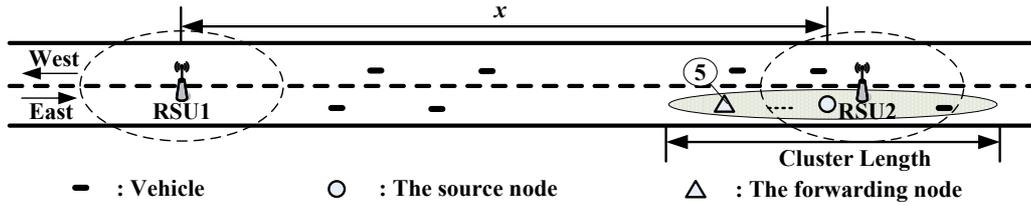


Fig.10 The eastbound forwarding node is out of the communication radius of RSU1

Further, we divide this case into two sub-cases:

- Case 2.3.2.0: There are one or more westbound vehicles within the coverage of node 5.
- Case 2.3.2.1: There is no westbound vehicle in the coverage of node 5.

Case 2.3.2.0

Case 2.3.2.0 happens when there is at least one westbound vehicle within the communication radius of node 5.

Let p_{2320} denote the probability that Case 2.3.2.0 happens. Thus, we have

$$p_{2320} = 1 - e^{-2\lambda_v R_v}. \quad (52)$$

In this case, the first vehicle of the corresponding westbound cluster becomes a forwarding node, which is denoted by node 6, as shown in Fig. 11. If node 6 is within the communication radius of RSU1, the information can be directly transmitted to RSU1 and the direct transmission delay can be ignored. Thus, we only need to analyze that the case where node 6 is out of the communication range of RSU1, i.e., the length of the westbound cluster satisfies the following condition:

$$l_w/2 < x - E_{232} + R_v.$$

In this case, node 6 will store and carry the information until it enters the communication radius of RSU1, when it will transmit the information to RSU1 directly.

Let p_{23200} denote the probability that this case happens. Thus, we have

$$p_{23200} = \Pr\{l_w/2 < x - E_{232} + R_v\}. \quad (53)$$

Similar to Eq.(15), we can obtain

$$p_{23200} = \Pr\{l_w/2 < x - E_{232} + R_v\} = 1 - (1 - e^{-\lambda_w R_v})^{k_{23200}}, \quad (54)$$

where $k_{23200} = 2(x - E_{232} + R_v)/E[d_v^w]$.

Therefore, the delivery delay for node 6 to forward the incident information to RSU1 can be approximately calculated as

$$T_{23200} = (R_v + x - E_{232} - 0.5E[l_w/2 | l_w/2 < x - E_{232} + R_v])/v_w, \quad (55)$$

where

$$\begin{aligned} & E[l_w/2 | l_w/2 < x - E_{232} + R_v] \\ &= 0.5E[d_v^w] \cdot [1 - (k_{23200} + 1)(1 - e^{-\lambda_w R_v})^{k_{23200}} + k_{23200}(1 - e^{-\lambda_w R_v})^{k_{23200} + 1}] / \{[1 - (1 - e^{-\lambda_w R_v})^{k_{23200}}]e^{-\lambda_w R_v}\} \end{aligned}$$

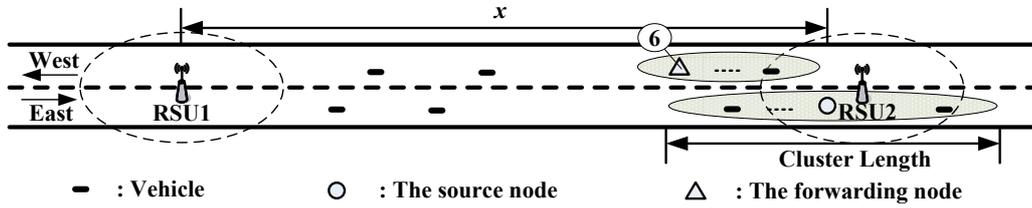


Fig.11 The westbound forwarding node is out of the communication radius of RSU1.

Case 2.3.2.1

Case 2.3.2.1 happens when there is no westbound vehicle within the communication radius of node 5. The probability that case 2.3.2.1 happens can be calculated as

$$p_{2321} = 1 - p_{2320}. \quad (56)$$

In this case, RSU2 should store and deliver the incident information to the upcoming western vehicles which will forward the incident information to RSU1. Then, the delivery delay can be approximately calculated as follows

$$T_{2321} = (d - R_v)/v_w + 1/(\lambda_w v_w). \quad (57)$$

Considering all the above cases, we have

$$T_{S3} = (p_{2320} \cdot p_{23200} \cdot T_{23200} + p_{2321} \cdot T_{2321}) \cdot p_{232}. \quad (58)$$

The average information delivery delay can be calculated as follows

$$T = \int_0^{R_v} T_1 \cdot f_1(x) dx + \int_{R_v}^{d-R_v} T_2 \cdot f_2(x) dx + \int_{d-R_v}^d T_3 \cdot f_3(x) dx. \quad (59)$$

IV Simulation Results and Discussion

In this section, we verify the effectiveness of the mathematical model derived in Section III through simulation results and investigate the impacts of different parameters on the average delivery delay, respectively. The simulation experiments were conducted using MATLAB. In the simulation experiments, we assumed that the location of an incident is uniformly distributed in interval $[0, d]$, and the transmission radius of a vehicle is 250m, i.e., $R_v=250m$, which follows the US Federal Communications Commission (FCC) regulations. Each simulation result is an average over 1000 simulations.

Fig. 12 shows the impact of the communication radius of an RSU on the average delivery delay. It is seen that the simulation results are very close to the analytical results, which means the mathematical model is effective. Moreover, the communication radius of an RSU has little impact on the average delivery delay. This is because the incident information is delivered from a vehicle to an RSU, not an RSU to a vehicle, and thus the communication radius of a vehicle has a larger impact on the delivery delay. Therefore, without loss of generality, we assume $R_v=250m$ in the following simulation experiments.

Fig. 13 - Fig. 15 show the average delivery delay under different traffic loads. Fig. 16 - Fig. 18 show the average delivery delay under different vehicle speeds. It is seen that simulation results are very close to the analytical results. On the other hand, the average delivery delay decreases with the increase of the vehicle speed and the increase of the traffic arrival rate, respectively. Moreover, the impact of the vehicle speed on the average delivery delay is much larger than that of the traffic arrival rate. This is because that a sparse network with a low traffic arrival rate has a small probability to form a large cluster which can help reduce the delivery delay. A higher speed may enable a forwarding node to enter the communication range of an RSU more rapidly and thus more significantly reduce the average delivery delay.

Fig. 19 shows the average delivery delay under different distances between two neighbor RSUs. It is seen that the simulation results are very close to the analytical results. Moreover, with an increasing distance between two neighbor RSUs, the average delivery delay decreases. Therefore, the mathematical model can be used to estimate the average delivery delay given a distance between two neighbor RSUs, which can provide a reference basis for RSU deployment in order to meet the delay requirement of some applications.

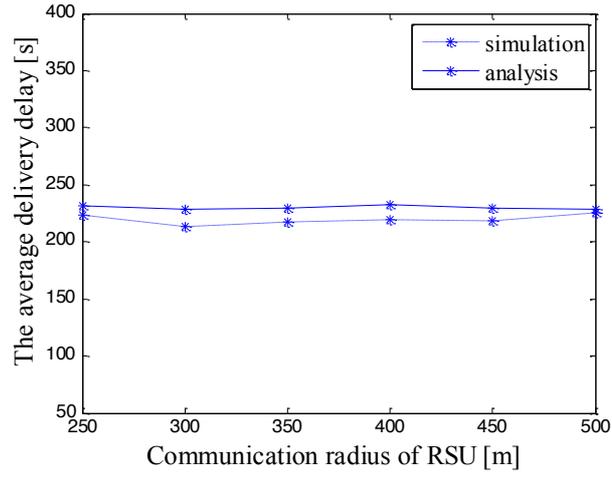


Fig. 12. Impact of R_u on the average delivery delay
 ($d=10000\text{m}$, $R_v=250\text{m}$, $v_w=30\text{m/s}$, $v_e=40\text{m/s}$, $\lambda_w=\lambda_e=0.0030\text{veh/m}$).

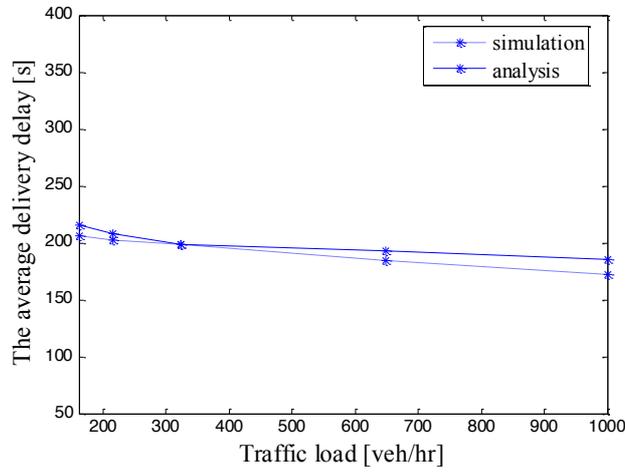


Fig. 13. Average delivery delay vs traffic load
 ($d=10000\text{m}$, $R_u=R_v=250\text{m}$, $v_w=v_e=40\text{m/s}$, $\lambda_w=\lambda_e$).

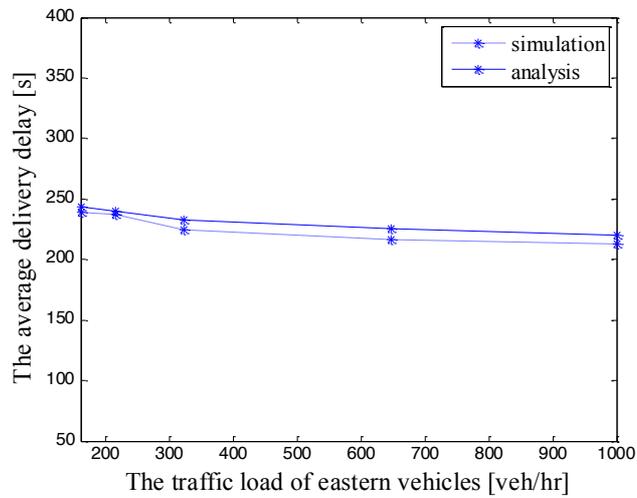


Fig. 14. Average delivery delay vs traffic load of eastern vehicles
 ($d=10000\text{m}$, $R_u=R_v=250\text{m}$, $v_w=30\text{m/s}$, $v_e=40\text{m/s}$, $\lambda_w=0.003\text{veh/m}$).

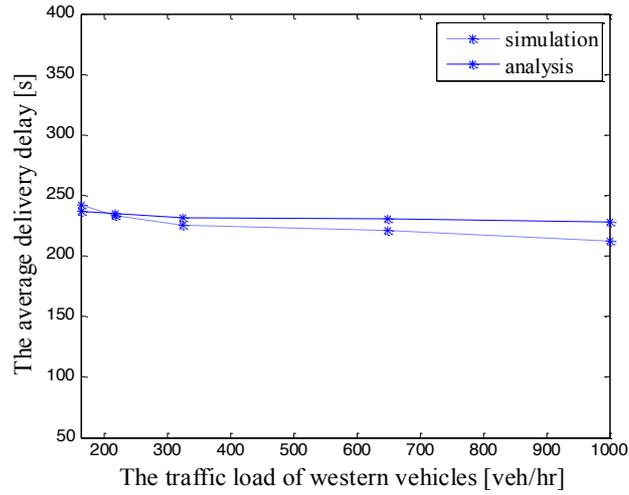


Fig. 15. Average delivery delay vs traffic load of western vehicles
 ($d=10000\text{m}$, $R_u=R_v=250\text{m}$, $v_w=30\text{m/s}$, $v_e=40\text{m/s}$, $\lambda_e=0.003\text{veh/m}$).

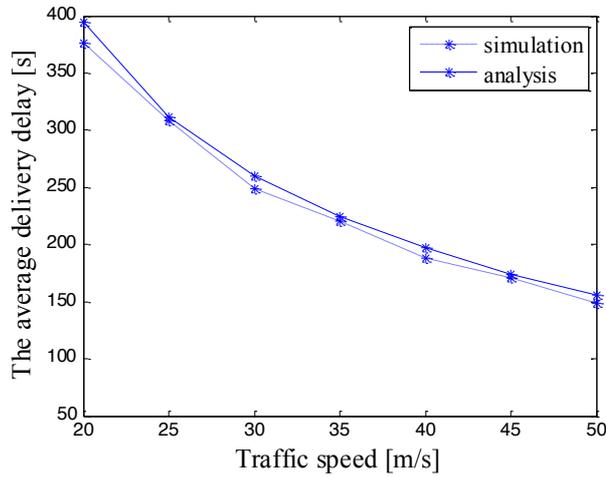


Fig. 16. Average delivery delay vs traffic speed
 ($d=10000\text{m}$, $R_u=R_v=250\text{m}$, $v_w=v_e$, $\lambda_w=\lambda_e=0.003\text{veh/m}$).

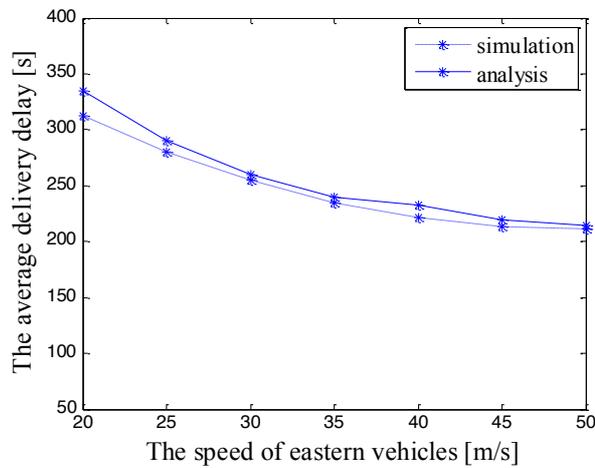


Fig. 17. Average delivery delay vs the speed of eastern vehicles
 ($d=10000\text{m}$, $R_u=R_v=250\text{m}$, $v_w=30\text{m/s}$, $\lambda_w=\lambda_e=0.003\text{veh/m}$).

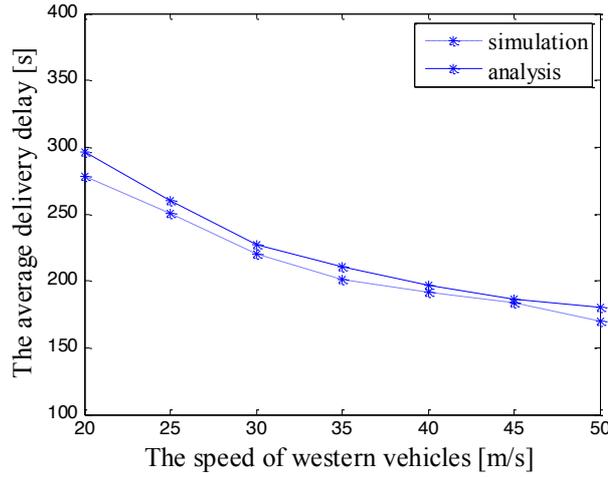


Fig. 18. Average delivery delay vs the speed of eastern vehicles
 $(d=10000\text{m}, R_u=R_v=250\text{m}, v_e=40\text{m/s}, \lambda_w=\lambda_e=0.003\text{veh/m})$.

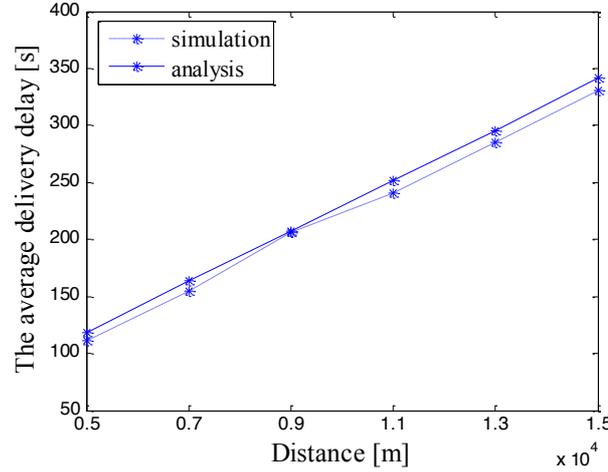


Fig. 19. Average delivery delay vs distance between RSUs
 $(R_u=R_v=250\text{m}, v_w=30\text{m/s}, v_e=40\text{m/s}, \lambda_w=\lambda_e=0.003\text{veh/m})$.

V. Conclusion

In this paper, we developed a mathematical model for analyzing information delivery delay in a straight highway scenario where two RSUs are deployed at a distance without any direct connection and vehicles are sparsely distributed with road condition information randomly generated between the two neighbor RSUs. The mathematical model takes into account the vehicle speed, the vehicle density, the likelihood of an incident, and the distance between two RSUs, and its effectiveness is verified through simulation results. Given the delay constraint of time-critical applications, this model can be used to estimate the maximum distance allowed between two neighbor RSUs, which can provide a reference for the deployment of RSUs in such scenarios.

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BIOGRAPHY



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