

Delivery Delay Analysis for Roadside Unit Deployment in Intermittently Connected VANETs

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Abstract—This paper analyzes the information delivery delay for roadside unit deployment in an intermittently connected vehicular network. An analytical model is developed to describe the relationship between the average information delivery delay and the distance between two neighbor RSUs deployed along a road. The derived 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 analytical model is verified through simulation results. Given the delay requirement of some time-critical applications, this model can be used to estimate the maximum distance allowed between two neighbor RSUs, which can provide a reference basis for the deployment of RSUs in such scenarios.

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

I. INTRODUCTION

Vehicular Ad Hoc Networks (VANETs) have recently received a growing amount of attention from both industry and academia for a variety of potential applications in providing road safety and in-vehicle entertainment services. One of the important applications of a VANET is to collect road condition information by 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, etc. Due to its highly dynamic characteristic, the connectivity of a VANET is often intermittent, which would increase the delay for disseminating the collected information and thus affect the quality of service (QoS) provisioned to users. To address this problem, roadside units (RSUs) have been introduced 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 a RSU. However, road condition information in many applications is time critical. It is important to deliver such time-critical information to a RSU within a given time so that the RSU can help timely disseminate the information to the vehicles passing through it. For this purpose, two neighbor RSUs should not be deployed at a distance larger than a certain value. Therefore, it is interesting 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 analyze the information delivery delay for roadside unit deployment in an intermittently connected vehicular network. For this purpose, we derive an analytical model to describe the relationship between the average information delivery delay 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 analytical model. Simulation experiments are conducted to verify the effectiveness of the derived model.

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

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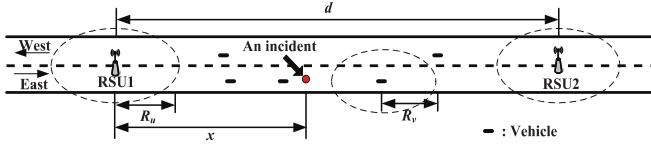


Fig. 1. Basic network scenario.

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 VANET 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 an analytical model for calculating the message delivery delay distribution on 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, the authors of [5] and [6] 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 vehicle to RSU. To the best of our knowledge, there is no work found in the literature that has studied 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 an analytical model to describe the relationship between the information delivery delay and the distance between two neighbor RSUs deployed along a road in an intermittently connected vehicular network.

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

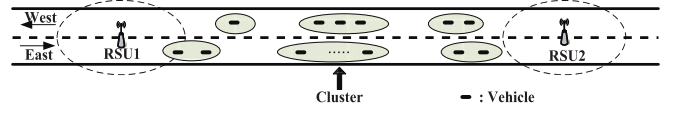


Fig. 2. Vehicle clusters on a road.

R_u . The communication radius of each vehicle is denoted by R_v . The two neighbor RSUs are deployed without any direct connection, i.e., $d \gg 2R_u$. We assume that the inter-vehicle spacings 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 speed 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 the same spacing and thus cannot communicate with each other. An incident occurs randomly at a location with a distance x from RSU1, i.e., $x \in [R_u, d - R_u]$. Once an incident occurs, the vehicle closest 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 information to the two neighbor RSUs directly or indirectly via other vehicles. A vehicle that can forward the collected information to a RSU is referred to as a forwarding node. We define the average information delivery delay as the time from the instant when an incident occurs to the instant when both the RSUs receive 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 a given delay requirement. Therefore, the problem considered in this paper is to develop an analytical model that describes the average information delivery delay and the distance between two neighbor RSUs deployed along a straight highway.

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

$$T = T_0 + T_S, \quad (1)$$

where T is the average delivery delay, T_0 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_S is the average time it takes for the source node to deliver the collected information from the occurring location of an incident to a RSU. Since we are considering a sparse highway scenario, both the network connectivity and the traffic load are low. In this case, the

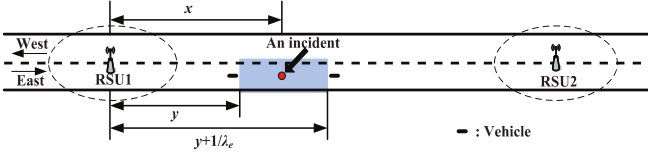


Fig. 3. Relative position of the source node and the location of an incident.

incident information can 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 the "store-carry-forward" mode. Therefore, in this paper, we will mainly consider the delivery delay caused by the "store-carry-forward" mode and ignore the direct transmission delay between a couple of source and destination nodes.

Let $f(x)$ denote the probability density function of the distance x . We can obtain the expectation of the distance x as follows

$$E[L] = \int_{R_u}^{d-R_u} x f(x) dx, f(x)(R_u \leq x \leq d - R_u). \quad (2)$$

Next we analyze T_0 and T_S , respectively. Without loss of generality, we assume that when an incident occurs an eastbound vehicle is closest to the occurring location of the incident and thus will first arrive at the occurring location of the incident. This vehicle is called source node hereafter.

2.1 Analysis of T_0

According to the property of an exponential distribution, the average inter-vehicle spacing of eastbound vehicles is $1/\lambda_e$. Let y denote that the location of the vehicle closest to the occurring location of an incident. Obviously, we have $R_u - 1/\lambda_e \leq y \leq d - R_u - 1/\lambda_e$, as illustrated in Fig. 3. Let $f'(x)$ 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 vehicle closest to the occurring location of an incident to arrive at the occurring location of the incident can be calculated as

$$T_0 = \frac{1}{v_e} \cdot \left(\int_y^{y+1/\lambda_e} x \cdot f'(x) dx - y \right). \quad (3)$$

2.2 Analysis of T_S

As explained earlier, T_S is the average time for the collected information to be delivered from the occurring location of an incident to a 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

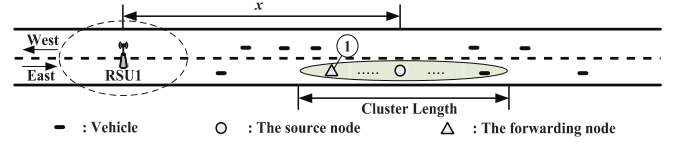


Fig. 4. The forwarding node is out of the communication radius of RSU1.

information to both RSU1 and RSU2. Since it takes a 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 in that case both RSU1 and RSU2 can receive the information. Therefore, we have

$$T_S = \int_{R_u}^{d-R_u} \max\{T_{RSU1}, T_{RSU2}\} \cdot f(x) dx, \quad (4)$$

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 T_{RSU1} and T_{RSU2} , respectively. The notations used in the analysis are explained 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 ;

$E[S_{intra_e}]$: the average distance between two vehicles within an eastbound cluster;

$E[S_{intra_w}]$: the average distance between two vehicles within a westbound cluster;

$E[S_{inter_e}]$: 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;

$E[S_{inter_w}]$: 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.

2.2.1 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. 4. 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

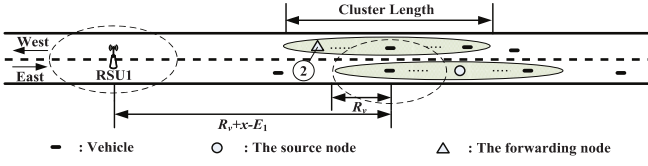


Fig. 5. The westbound cluster is out of the communication radius of RSU1.

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 1 in Fig. 4.

If node 1 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 1 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

$$p_1 = \Pr \{L_e/2 - R_v < x - R_u\}. \quad (5)$$

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

$$E[S_{intra_e}] = \frac{1}{\lambda_e} - \frac{R_v \cdot e^{-\lambda_e R_v}}{1 - e^{-\lambda_e R_v}}, \quad (6)$$

and the PMF of N_e is

$$f_e(N_e) = e^{-\lambda_e R_v} (1 - e^{-\lambda_e R_v})^{N_e - 1}. \quad (7)$$

Obviously, given $E[S_{intra_e}]$ and N_e , we can obtain

$$\begin{aligned} p_1 &= \Pr \left\{ \frac{L_e}{2} - R_v < x - R_u \right\} \\ &= \Pr \left\{ \frac{N_e \cdot E[S_{intra_e}]}{2} < x - R_u + R_v \right\}, \quad (8) \\ &= 1 - (1 - e^{-\lambda_e R_v})^{k_1} \end{aligned}$$

where $k_1 = 2 \cdot (x - R_u + R_v) / E[S_{intra_e}]$.

Let E_1 denote the conditional expectation of $L_e/2$ under condition $L_e/2 < x - R_u + R_v$. We can obtain

$$\begin{aligned} E_1 &= E \left[\frac{L_e}{2} \mid \frac{L_e}{2} < x - R_u + R_v \right] \\ &= \frac{E[S_{intra_e}]}{2} \cdot \frac{1 - (1 - e^{-\lambda_e R_v})^{k_1} \cdot (1 + k_1 e^{-\lambda_e R_v})}{[1 - (1 - e^{-\lambda_e R_v})^{k_1}] e^{-\lambda_e R_v}}. \quad (9) \end{aligned}$$

For further analysis, we divide this case into two sub-cases:

- Case 1.0: There are one or more westbound vehicles within the coverage of node 1.
- Case 1.1: There is no westbound vehicle in the coverage of node 1.

Case 1.0

Case 1.0 happens when there is at least one westbound vehicle within the communication radius of node 1. Let p_{10}

denote the probability that Case 1.0 happens. Thus, we have

$$p_{10} = 1 - \frac{(2R_v \lambda_w)^0}{0!} e^{-2R_v \lambda_w} = 1 - e^{-2R_v \lambda_w}. \quad (10)$$

In this case, the first vehicle of the corresponding westbound cluster becomes a forwarding node, which is denoted by node 2, as shown in Fig. 5. If node 2 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 2 is out of the communication radius of RSU1, i.e., the length of the westbound cluster satisfies the following condition:

$$\frac{L_w}{2} < R_v + x - E_1.$$

In this case, node 2 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_{100} denote the probability that this case happens. Thus, we have

$$p_{100} = \Pr \left\{ \frac{L_w}{2} < R_v + x - E_1 \right\}. \quad (11)$$

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

$$E[S_{intra_w}] = \frac{1}{\lambda_w} - \frac{R_v \cdot e^{-\lambda_w R_v}}{1 - e^{-\lambda_w R_v}}, \quad (12)$$

and the PMF of N_w is

$$f_w(N_w) = e^{-\lambda_w R_v} (1 - e^{-\lambda_w R_v})^{N_w - 1}. \quad (13)$$

Obviously, given $E[S_{intra_w}]$ and N_w , we can obtain

$$\begin{aligned} p_{100} &= \Pr \left\{ \frac{L_w}{2} < R_v + x - E_1 \right\} \\ &= \Pr \left\{ \frac{N_w \cdot E[S_{intra_w}]}{2} < R_v + x - E_1 \right\}, \quad (14) \\ &= 1 - (1 - e^{-\lambda_w R_v})^{k_{100}} \end{aligned}$$

where $k_{100} = 2(R_v + x - E_1) / E[S_{intra_w}]$.

Therefore, the delivery delay for node 2 to forward the incident information to RSU1 can be approximately calculated as

$$T_{100} = \frac{R_v + x - E_1 - 0.5E \left[\frac{L_w}{2} \mid \frac{L_w}{2} < R_v + x - E_1 \right]}{v_w}, \quad (15)$$

where

$$\begin{aligned} &E \left[\frac{L_w}{2} \mid \frac{L_w}{2} < R_v + x - E_1 \right] \\ &= 0.5E[S_{intra_w}] \cdot E[N_w | N_w < k_{100}] \\ &= 0.5E[S_{intra_w}] \cdot \frac{1 - (k_{100} e^{-\lambda_w R_v} + 1)(1 - e^{-\lambda_w R_v})^{k_{100}}}{[1 - (1 - e^{-\lambda_w R_v})^{k_{100}}] e^{-\lambda_w R_v}}. \end{aligned}$$

Case 1.1

Case 1.1 happens when there is no westbound vehicle within the communication radius of node 1. The probability that case 1.1 happens can be calculated as

$$p_{11} = 1 - p_{10}. \quad (16)$$

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

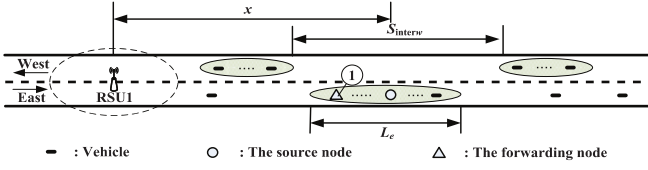


Fig. 6. Case 1.1.0.

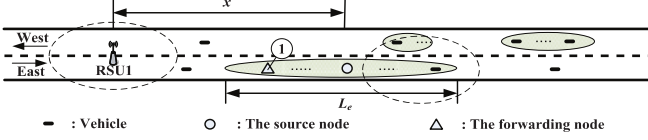


Fig. 7. Case 1.1.1.

- Case 1.1.0: There is no westbound vehicle within the communication radius of node 1 and there is no westbound vehicle within the communication range of other nodes in the same cluster, as shown in Fig. 6.
- Case 1.1.1: There is no westbound vehicle within the communication radius of node 1 but there is one or more westbound vehicles within the communication range of a node other than node 1 in the same cluster, as shown in Fig. 7.

Next we analyze Case 1.1.0 and Case 1.1.1, respectively.

Case 1.1.0

In Case 1.1.0, there is no westbound vehicle in the entire coverage of the eastbound cluster, as shown in Fig. 6. This case happens when the length of the eastbound cluster satisfies the following condition:

$$L_e < E[S_{interw}] - 2R_v,$$

and the probability that Case 1.1.0 happens is given by

$$p_{110} = \Pr \{L_e < E[S_{interw}] - 2R_v\}. \quad (17)$$

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

$$E[S_{interw}] = R_v + \frac{1}{\lambda_w}. \quad (18)$$

Obviously, given $E[S_{interw}]$ and $E[S_{intrae}]$, we can obtain

$$p_{110} = \Pr \{L_e < E[S_{interw}] - 2R_v\} = 1 - (1 - e^{-\lambda_e R_v})^{k_{110}}, \quad (19)$$

where $k_{110} = (E[S_{interw}] - 2R_v)/E[S_{intrae}]$.

In this case, node 1 will store and carry the information until it meets a westbound vehicle, when it will transmit the information to the westbound vehicle, which will further forward the information to RSU1. Since the westbound vehicle closest to node 1 is at least $x + E[S_{interw}]$ away from RSU1, the delivery delay can be approximately calculated as

$$T_{110} = \frac{x + 0.5E[S_{interw}]}{v_w}. \quad (20)$$

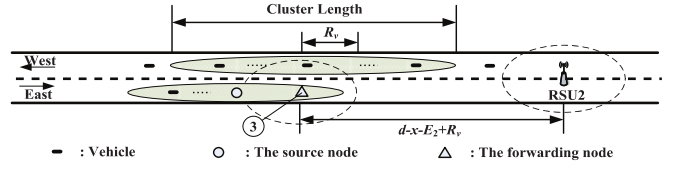


Fig. 8. The westbound cluster is out of the communication radius of RSU2.

Case 1.1.1

In Case 1.1.1, there is one or more westbound vehicles within the communication range of a node other than node 1 in the eastbound cluster. Obviously, this case happens with probability

$$p_{111} = 1 - p_{110}. \quad (21)$$

In this case, node 1 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

$$E[L_e] = \left(\frac{1}{e^{-\lambda_e R_v}} - 1 \right) \cdot \left(\frac{1}{\lambda_e} - \frac{R_v \cdot e^{-\lambda_e R_v}}{1 - e^{-\lambda_e R_v}} \right). \quad (22)$$

Since the westbound vehicle closest to node 1 is at most $x + 0.5E[L_e]$ away from RSU1, the delivery delay can be approximately calculated as

$$T_{111} = \frac{x + 0.5E[L_e]}{v_w}. \quad (23)$$

Considering all the above cases, we have

$$T_{RSU1} = [p_{10} \cdot p_{100} \cdot T_{100} + p_{11} \cdot (p_{111} \cdot T_{111} + p_{110} \cdot T_{110})] \cdot p_1. \quad (24)$$

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 3 as shown in Fig. 8. If node 3 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 3 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 of this case is given by

$$p_2 = \Pr \left\{ \frac{L_e}{2} - R_v < d - x - R_u \right\}. \quad (25)$$

Similar to Eq. (8), p_2 can be calculated as follows

$$p_2 = \Pr \left\{ \frac{L_e}{2} < d - x - R_u + R_v \right\} = 1 - (1 - e^{-\lambda_e R_v})^{k_2}, \quad (26)$$

where $k_2 = 2(d - x - R_u + R_v)/E[S_{\text{intra}_e}]$.

Let E_2 denote the conditional expectation of $L_e/2$ under condition $L_e/2 < d - x - R_u + R_v$. We can obtain

$$\begin{aligned} E_2 &= E \left[\frac{L_e}{2} \mid \frac{L_e}{2} < d - x - R_u + R_v \right], \\ &= 0.5 E[S_{\text{intra}_e}] E[N_e | N_e < k_2], \end{aligned} \quad (27)$$

where

$$E[N_e | N_e < k_2] = \frac{1 - (k_2 + 1)(1 - e^{-\lambda_e R_v})^{k_2} + k_2(1 - e^{-\lambda_e R_v})^{k_2 + 1}}{[1 - (1 - e^{-\lambda_e R_v})^{k_2}]e^{-\lambda_e R_v}}.$$

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

- Case 2.0: There are one or more westbound vehicles in the coverage of node 3.
- Case 2.1: There is no westbound vehicle in the coverage of node 3.

Case 2.0

Case 2.0 happens when there is at least one westbound vehicle within the communication radius of node 3. Let p_{20} denote the probability that Case 2.0 happens. Thus, we have

$$p_{20} = 1 - e^{-2\lambda_w R_v}. \quad (28)$$

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:

$$L_w/2 < d - x - E_2 + R_v,$$

the information will be forwarded to RSU2 by node 3. the probability of this case is given by

$$p_{200} = \Pr \left\{ \frac{L_w}{2} < d - x - E_2 + R_v \right\}. \quad (29)$$

Similar to Eq. (14), we can obtain

$$p_{200} = \Pr \left\{ \frac{L_w}{2} < d - x - E_2 + R_v \right\} = 1 - (1 - e^{-\lambda_w R_v})^{k_{200}}, \quad (30)$$

where $k_{200} = 2(d - x - E_2 + R_v)/E[S_{\text{intra}_w}]$. Therefore, the delivery delay can be calculated as

$$T_{200} = \frac{d - x - E_2}{v_e}. \quad (31)$$

Case 2.1

Case 2.1 happens when there is no westbound vehicle within the communication radius of node 3. The probability that Case 2.1 happens can be calculated as

$$p_{21} = 1 - p_{20}. \quad (32)$$

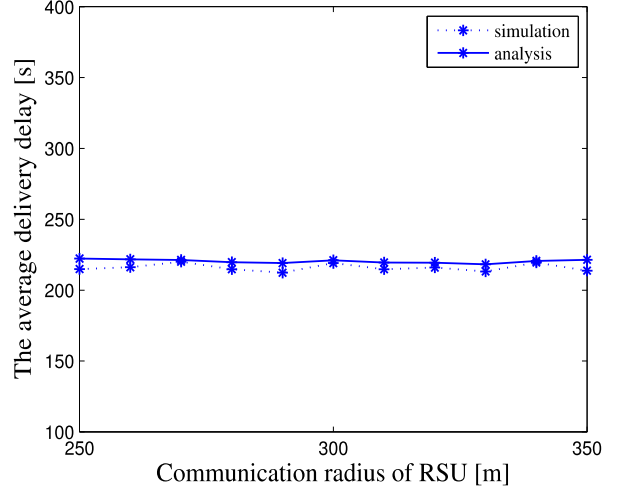


Fig. 9. Impact of the R_u on the average delivery delay ($d = 10000$, $R_v = 250$, $v_w = 30$, $v_e = 40$, $\lambda_w = \lambda_e = 0.0030$).

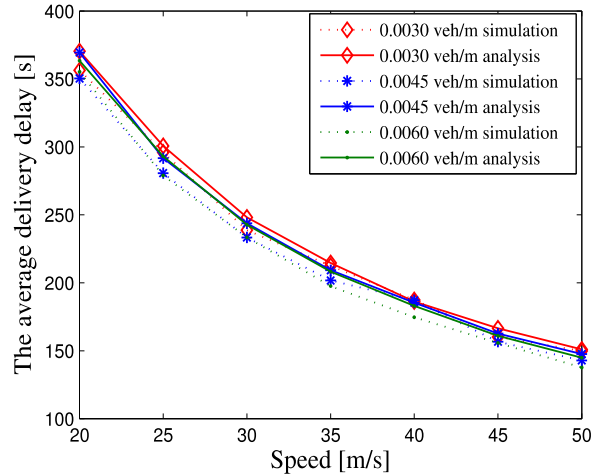


Fig. 10. Average delivery delay vs traffic arrival rate ($d = 10000$, $v_w = v_e$, $R_u = 250$, $R_v = 250$, $\lambda_w = \lambda_e$).

In this case, the information will be forwarded to RSU2 by node 3. Thus, the delivery delay T_{21} equals to T_{200} .

Considering all the above cases, we have

$$T_{RSU2} = p_2 \cdot (p_{20} \cdot p_{200} \cdot T_{200} + p_{21} \cdot T_{21}). \quad (33)$$

IV. SIMULATION RESULTS AND DISCUSSION

In this section, we verify the effectiveness of the analytical 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

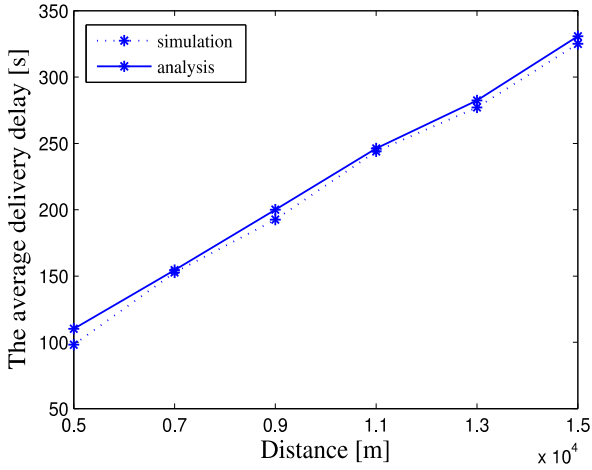


Fig. 11. Average delivery delay vs distance between RSUs ($v_e = 40$, $v_w = 30$, $R_u = 250$, $R_v = 250$, $\lambda_w = \lambda_e = 0.0030$).

assume that the location of an incident is uniformly distributed in the range of $[R_u, d - R_u]$, and the transmission radius of a vehicle is 250m, i.e., $R_v = 250$ m, which follows the US Federal Communications Commission (FCC) regulations. Each simulation result is an average over 1000 simulations.

Fig. 9 shows the impact of the communication radius of a RSU on the average delivery delay. It is seen that the simulation results are very close to the analytical results, which means the analytical model is effective. Moreover, the communication radius of a RSU has little impact on the average delivery delay. This is because the incident information is delivered from vehicle to RSU, not RSU to vehicle, and thus the communication radius of a vehicle has a larger impact on the delivery delay. Therefore, without loss of generality, we assume $R_u = 250$ m in the following simulation experiments.

Fig. 10 shows the average delivery delay under different traffic arrival rates and vehicle speeds. It is seen that the 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 a RSU more rapidly and thus more significantly reduce the average delivery delay.

Fig. 11 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 the distance between two neighbor RSUs increasing, the average delivery delay increases. Therefore, the analytical 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.

V. CONCLUSION

In this paper, we developed an analytical 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 analytical 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 requirement of some time-critical applications, this model can be used to estimate the maximum distance allowed between two neighbor RSUs, which can provide a reference basis for the deployment of RSUs in such scenarios.

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