Deployment Strategy of Highway RSUs for Vehicular Ad Hoc Networks Considering Accident Notification

Yufeng Chen[1], Yingkui Ma[1], Zhengtao Xiang[1(✉)], Lei Cai[2], Yu Zhang[1], and Hanwen Cao[1]

[1] School of Electrical and Information Engineering, Hubei University of Automotive Technology, Shiyan 442002, China
xztcyf@163.com
[2] Beijing GOTEC ITS Technology Co. Ltd., Beijing 100088, China

Abstract. In the highway scenario, the deployment of RSUs to improve the delivery delay of accident notification information is studied. In this paper, a theoretical analysis model is established by analyzing the relationship between the delivery delay of accident notification information and the deployment of RSUs in the Vehicular Ad Hoc Networks (VANETs). The model assumes that two adjacent RSUs are connected, and considers the impact of accident probability, vehicle node density, and speed on the delivery delay of accident notification information under different deployment distances. In addition, the model also considers secondary inter-cluster communication with vehicles in different driving directions from the accident vehicle, so as the accident notification information can be transmitted to the vehicle cluster with same direction of accident vehicle and closer to the RSUs. To validate the performance of our proposed model, this paper uses MATLAB to solve the model numerically. Compared with the existing model that assumes that two adjacent RSUs are not connected and the secondary inter-cluster communication are not considered, the delivery delay of the accident notification information of our proposed model can be reduced by 66% from the existing model.

Keywords: RSU deployment · VANETs · Accident notification information delivery delay · Secondary inter-cluster communication

1 Introduction

The rapid increase in road traffic accidents (RTAs) has caused massive property losses and casualties in different countries [1]. According to a study by the World Economic Forum in April 2016, the number of cars expected to double globally by 2040 will place more pressure on road transport infrastructure [2]. In addition, the World Health Organization (WHO) predicts that RTAs will become the seventh leading cause of death by 2030 [3]. In RTAs, the probability of an accident occurring within 100 km of a highway is about 4 times that of an ordinary road [4]. Since the highway is a linear fully enclosed road, if the

accident notification is not made to the rear vehicle in time after the initial accident, the rear vehicle will not brake and collided with the accident vehicle in time, resulting in a secondary accident. To reduce the probability of secondary road traffic safety accidents and ensure road traffic safety, Vehicle Ad hoc Networks (VANETs) have been developed around the world. Because the vehicle itself moves at a high speed, the topology of VANETs is highly dynamic, which leads to intermittent connectivity of the network, thus increasing the delay of accident information collection and transmission. To solve this problem, a roadside unit (RSU) is introduced into the VANETs. The deployment of RSU can improve the connectivity of the network, thereby greatly improving the real-time performance of accident information collection and transmission [5]. However, the single-unit cost and deployment cost of RSUs is extremely high [6], and it is impossible to deploy on a large scale to make the entire network reach a fully connected state. It is necessary to reasonably determine the deployment distance of RSUs.

We study the delay analysis of accident notification information transmission considering RSU deployment in intermittently connected VANETs. Considering the interconnection between two adjacent RSUs, we establish a theoretical analysis mathematical model to study the relationship between the average delay of the delivery of accident notification information transmission and the distance between RSU deployments.

The work done in this paper is as follows

(1) We studied the deployment of RSUs to improve the delivery delay of accident notification information in a highway scenario. We consider a direct connection between two adjacent RSUs and establish a theoretical analysis model by analyzing the relationship between the delivery delay of accident notification information in VANETs and the deployment distance of interconnected RSUs.
(2) We propose a secondary communication method between vehicle clusters. This method considers secondary inter-cluster communication with vehicles in different driving directions from the accident vehicle, so as the accident notification information can be transmitted to the vehicle cluster with same direction of accident vehicle and closer to the RSUs.
(3) We numerically solve the model using MATLAB and compare it with an existing model that assumes that two adjacent RSUs are not interconnected to determine the validity of our proposed model.

The organizational structure of this paper is as follows: Sect. 2 will introduce related work. Section 3 describes our network scenario. Section 4 will give the model of accident notification information transmission delay. In Sect. 5, we will simulate the theoretical model and analyze the numerical results. Section 6 is our conclusion.

2   Related Work

References [5, 7–14] studied the highway RSU deployment. Liang et al. [7] pointed out that measurement errors and inference errors should be considered in RSU deployment, defined RSU deployment as a bi-objective nonlinear binary integer programming problem, and proposed an ε-constraint solving method. Considering the proportion and

time threshold of vehicles, Silva et al. [8] proposed a Gamma deployment strategy to define the location and number of RSUs required to provide specific coverage. Ge et al. [9] used an improved K-means clustering algorithm to cluster vehicles and obtained the deployment distance of RSU by analyzing the relationship between RSU transmission range, vehicle density, vehicle connectivity rate, and average vehicle cluster length.

The above references only studied the setting of RSU deployment distance under normal traffic flow but did not consider the setting of RSU deployment distance in case of traffic accidents on the road. Sou et al. [10] analyzed and quantified the improvement of VANETs connectivity when deploying a limited number of RSUs, and studied the routing pros and cons of incident advertisement messaging in this enhanced VANETs environment. Wisitpongphan et al. [11] proposed a "store-carry-forward" strategy to study the accident notification message delivery delay using a statistical model extracted from measured data on the I-80 freeway in California. However, this strategy only considered the vehicle-to-vehicle message delivery delay but did not consider the vehicle-to-RSU delivery delay. Wang et al. [5, 12–14] further improved the model proposed by Wisitpongphan et al. [11], and proposed a new theoretical analysis model of the relationship between accident notification message delivery delay and RSU deployment distance, which assumes that two adjacent RSUs are not directly connected, and integrates the vehicle speed, vehicle density, accident location and two adjacent RSUs with different. The deployment distance between two adjacent RSUs is given by considering the relationship between vehicle speed, vehicle density, accident location, and different deployment distances of two adjacent RSUs. The experimental results show that the theoretical analysis model can be used to determine the maximum allowed deployment interval when two adjacent RSUs are not connected to each other. However, there is still room for further enhancement of the model as follows: 1) The model does not consider the direct connection between two adjacent RSUs; 2) In this model, only one inter-cluster communication is carried out, and the accident notification information is transmitted to the vehicle clusters in different driving directions of the accident vehicle. The secondary inter-cluster communication with vehicles in different driving directions is not considered, and the accident notification information is passed to the vehicle cluster in the same driving direction as the accident vehicle and closer to the RSU.

3   Network Scenarios

We stipulate that all vehicles are configured with the onboard unit (OBU), and global navigation satellite system (GNSS), and periodically broadcast beacon messages to surrounding vehicles. After receiving a neighbor beacon message, each vehicle must compare its GNSS information to determine whether it is traveling in the same direction as it is traveling. By constantly exchanging beacons, each vehicle maintains its list of lead, follow, and opposite one-hop neighbors. If vehicle nodes in the same driving direction can communicate in one or more hops, these vehicle nodes can be clustered into a cluster. A cluster that contains only one vehicle is called a single cluster, as shown in Fig. 1.

We consider a highway scene with sparse vehicle nodes, two RSUs are deployed at both ends of the road as shown in Fig. 1. Assume that the RSU located upstream of the eastbound vehicle is RSU1, which is at position 0. Assume that the RSU located downstream of the east-bound vehicle is RSU2, which is at position d. The RSU transmission

range is R_u, and the vehicle node transmission range is R_v. We assume that $R_u = R_v$. RSU1 and RSU2 are connected by cables, but the transmission range does not overlap each other, that is, $d \gg 2R_u$. Vehicle nodes traveling east and west randomly arrive at both ends of the road with the arrival rates of λ_e and λ_w, and the arrival distance obeys an exponential distribution [5]. Assuming that the speed of the vehicle is stochastic and obeys a truncated normal distribution [15], the average speeds of vehicle nodes traveling east and west are defined as v_e and v_w. If the accident vehicle is located in the transmission range of the two RSUs (i.e., $x \in [0, R_u]$ or $x \in [d - R_u, d]$), the accident vehicle can directly notify the accident information RSU. In this case, the time spent is far less than the "store-carry-forward" between vehicle nodes. The delay caused can be ignored. Therefore, we only consider the case where the accident information occurs in the blind area of the deployment of two RSUs (i.e., $x \in [R_u, d - R_u]$). When the accident occurs, the accident vehicle will select the appropriate forwarding node to forward the accident information until the event information is transmitted to RSU1 or RSU2. The average information delivery time required from the time of accident occurrence to the time when RSU1 or RSU2 receives accident information is defined as the average accident notification information delivery delay. In the highway scenario with sparse vehicle nodes, the probability of vehicle nodes competing for the channel at the MAC layer is very small, and the delay generated by channel competition in the MAC layer is also very low compared to the delay generated by "store-carry-forward", so it can be ignored. In addition, we ignore the delay in the transmission of accident notification information by cable between two adjacent RSUs.
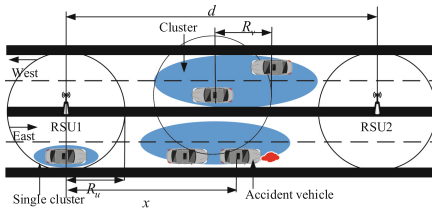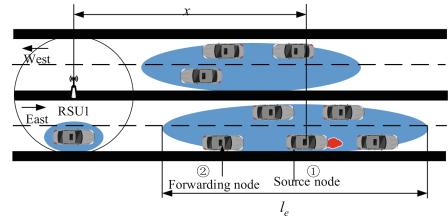

Fig. 1. Network scenario

Fig. 2. Node 2 becomes a forwarding node (Case 1)

4 Modeling of Information Delivery Delay

We assume that the accident occurred in a vehicle traveling eastward, the probability density function (PDF) of the distance x from the accident location to the RSU1 location is denoted as $f(x)$, and $f(x)$ obeys a uniform distribution. Due to the randomness of the accident location, the time required by the forwarding node to transmit the accident information to RSU1 or RSU2 is not equal. Since we assume that two adjacent RSUs are connected by cables, the average delivery delay of the accident notification information is taken as the short time required for the forwarding node to forward the accident notification information to RSU1 or RSU2. Based on the above considerations, the

average accident notification information delivery delay can be approximated by

$$T = \int_{R_u}^{d-R_u} \min\{T_{RSU1}, T_{RSU2}\} \cdot f(x) dx, \tag{1}$$

where T is the average accident notification information delivery delay, and T_{RSU1} and T_{RSU2} are the time required for the forwarding node to transmit the accident notification information to RSU1 and RSU2. T_{RSU1} and T_{RSU2} are analyzed separately below. The main symbol definitions used in this paper are shown in Table 1.

Table 1. Main symbol definitions used in this paper.

Parameters	Values
l_e	The length of a cluster of eastbound vehicles
l_w	The length of a cluster of westbound vehicles
$E[l_e]$	The average l_e
$E[l_w]$	The average l_w
N_e	The number of vehicles in a cluster of eastbound vehicles
N_w	The number of vehicles in a cluster of westbound vehicles
$f_e(N_e)$	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 the two vehicles is in a cluster of eastbound
$E[d_v^w]$	The average distance between the two vehicles is in a cluster of westbound
$E[d_c^e]$	The average distance between two adjacent eastbound vehicle clusters
$E[d_c^w]$	The average distance between two adjacent westbound vehicle clusters

4.1 Analysis of T_{RSU1}

T_{RSU1} analysis is shown in Fig. 3. According to [14], we can assume that the accident vehicle is located in the middle of the vehicle cluster. Because the deployment location of RSU1 is located upstream of the accident vehicle, the accident vehicle selects the vehicle node (i.e., node 2) on the westernmost side of the vehicle cluster where it is located to be the forwarding node of the accident notification information. When node 2 is located in the transmission range of RSU1, node 2 forwards the accident notification information to RSU1. At this time, the delay caused by the direct forwarding of information is much smaller than that of storage carrying forwarding, which can be ignored. Therefore, it is only necessary to study the situation of node 2 outside the RSU1 transmission range (i.e., Case 1), as shown in Fig. 2. According to [12], we define the probability of this happening is defined as p_1.

$$p_1 = 1 - \left(1 - e^{-\lambda_e \cdot R_v}\right)^{k_1}, \tag{2}$$

where $k_1 = 2 \cdot (x - R_u + R_v)/E[d_v^e]$. According to [14], we have

$$E[d_v^e] = \frac{1}{\lambda_e} - \frac{R_v \cdot e^{-\lambda_e \cdot R_v}}{1 - e^{-\lambda_e \cdot R_v}}. \tag{3}$$

According to [11], we define the conditional expectation E_1 when half cluster length $l_e/2$ satisfies the condition $l_e/2 - R_v < x - R_u$.

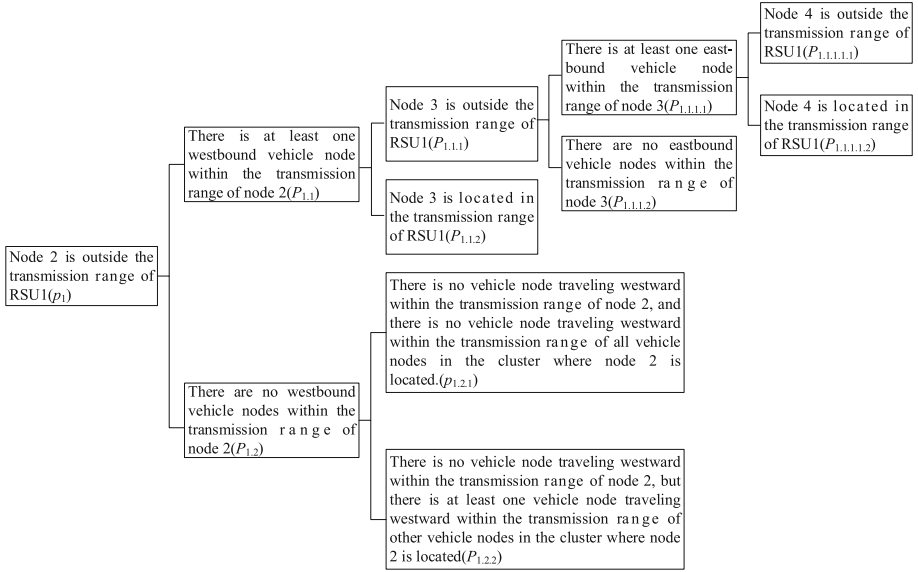$$E_1 = 0.5E[d_v^e] \cdot \frac{1 - (1 - p_1) \cdot \left(k_1 \cdot e^{-\lambda_e \cdot R_v} + 1\right)}{p_1 \cdot e^{-\lambda_e \cdot R_v}}. \tag{4}$$

Fig. 3. Analysis of T_{RSU1}

(1) Case 1.1

According to [12], we define the probability of this happening as $p_{1.1}$.

$$p_{1.1} = 1 - e^{-2\lambda_w \cdot R_v}. \tag{5}$$

At this time, the westmost vehicle node (i.e., node 3) in the vehicle cluster where the westbound vehicle node is located becomes the forwarding node of the accident notification information. When node 3 is located in the transmission range of RSU1, node 3 forwards the accident notification information to RSU1. At this time, the delay caused by the direct forwarding of information is much smaller than that of storage carrying forwarding, which can be ignored. Therefore, it is only necessary to study the

situation of node 3 outside the RSU1 transmission range (i.e., case 1.1.1), as shown in Fig. 4. According to [12], the probability of this happening can be calculated as

$$p_{1.1.1} = 1 - (1 - e^{-\lambda_w \cdot R_v})^{k_{1.1.1}}, \tag{6}$$

where $k_{1.1.1} = 2 \cdot (x - E_1 + R_v)/E[d_v^w]$. According to [14], $E[d_v^w]$ can be calculated as

$$E[d_v^w] = \frac{1}{\lambda_w} - \frac{R_v \cdot e^{-\lambda_w \cdot R_v}}{1 - e^{-\lambda_w \cdot R_v}}. \tag{7}$$

For this case, Wang et al. [5, 12–14] did not continue processing, but chose node 3 to continue carrying the accident notification information to RSU1. We propose a method for secondary communication between vehicle clusters. This method uses node 3 to transmit the accident notification information to the vehicle cluster in the same driving direction as the accident vehicle and closer to RSU1 so that the accident notification information can be transmitted faster to RSU1.

1) Case 1.1.1.1

   We define the probability of this happening as $p_{1.1.1.1}$.

$$p_{1.1.1.1} = 1 - e^{-2\lambda_e \cdot R_v}. \tag{8}$$

   At this time, the vehicle node (i.e., node 4) on the westernmost side of the vehicle cluster where the eastward traveling vehicle node is located becomes the forwarding node of the accident notification information. When node 4 is located in the transmission range of RSU1, node 4 forwards the accident notification information to RSU1. At this time, the delay caused by the direct forwarding of information is much smaller than that of storage carrying forwarding, which can be ignored. Therefore, it is only necessary to study the situation of node 4 outside the RSU1 transmission range (i.e., Case 1.1.1.1.1), as shown in Fig. 5. At this time, the length of the vehicle cluster where node 4 is located satisfies the following conditions:

$$l_e - 2R_v < x - E_1 - E[d_c^e] + R_v.$$

   We define the probability of this happening as $p_{1.1.1.1.1}$.

$$p_{1.1.1.1.1} = \Pr\{l_e < x - E_1 - E[d_c^e] + 3R_v\}. \tag{9}$$

   According to [14], $E[d_c^e]$ can be calculated by

$$E[d_c^e] = R_v + \lambda_e^{-1}, \tag{10}$$

and according to [12], the PMF of N_e:

$$f_e(N_e) = e^{-\lambda_e \cdot R_v} \cdot (1 - e^{-\lambda_e \cdot R_v})^{N_e - 1}. \tag{11}$$

   Therefore, the vehicle cluster length l_e can be approximated by the equation. Given the probability mass function obeyed by $E[d_v^e]$, $E[d_c^e]$ and N_e, $p_{1.1.1.1.1}$ can be calculated as

$$p_{1.1.1.1.1} = \Pr\{l_e < x - E_1 - E[d_c^e] + 3R_v\}$$

$$= \Pr\{N_e \cdot E[d_v^e] < x - E_1 - E[d_c^e] + 3R_v\}$$

$$= \Pr\{N_e < \frac{x - E_1 - E[d_c^e] + 3R_v}{E[d_v^e]}\}$$

$$= \Pr\{N_e < k_{1.1.1.1.1}\} = \sum_{n_e=1}^{k_{1.1.1.1.1}} f_e(N_e)$$

$$= 1 - (1 - e^{-\lambda_e \cdot R_v})^{k_{1.1.1.1.1}}, \tag{12}$$

where $k_{1.1.1.1.1} = (x - E_1 - E[d_c^e] + 3R_v)/E[d_v^e]$.

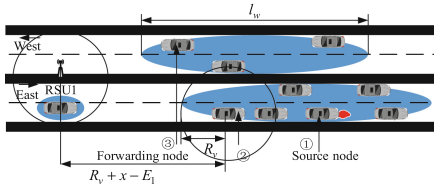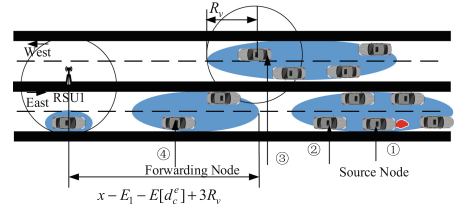**Fig. 4.** Node 3 becomes a forwarding node (Case 1.1.1)

Fig. 5. Node 4 becomes a forwarding node (Case 1.1.1.1.1)

At this time, the deployment position of RSU1 is located upstream of node 4. Node 4 cannot carry the accident notification information to RSU1, and the accident notification information will continue to be carried by node 3 to RSU1. According to [12], the accident notification information delivery delay can be approximated by

$$T_{1.1.1.1.1} = (x - R_u - E_1 + 2R_v - E\left[\frac{l_w}{2} | \frac{l_w}{2} < x - E_1 + R_v\right]/2)/v_w, \tag{13}$$

where $E\left[\frac{l_w}{2} | \frac{l_w}{2} < x - E_1 + R_v\right] = 0.5E[d_v^w] \cdot \frac{1-(1-p_{1.1.1})\cdot(k_{1.1.1}\cdot e^{-\lambda_w \cdot R_v}+1)}{p_{1.1.1}\cdot e^{-\lambda_w \cdot R_v}}$.

2) Case 1.1.1.2

We define the probability of this happening as $p_{1.1.1.2}$.

$$p_{1.1.1.2} = 1 - p_{1.1.1.1}. \tag{14}$$

At this time, the accident notification information needs to be stored and carried by node 3 and passed to the RSU1. The calculation expression of the delay $T_{1.1.1.2}$ required for the transmission of the accident notification information is the same as that of $T_{1.1.1.1.1}$.

(2) Case 1.2

We define the probability of this happening as $p_{1.2}$.
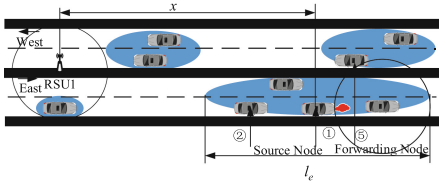
$$p_{1.2} = 1 - p_{1.1}. \tag{15}$$

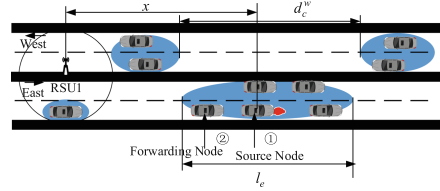**Fig. 6.** Node 5 becomes a forwarding node (Case 1.2.1)

Fig. 7. Node 2 becomes a forwarding node (Case 1.2.2)

1) Case 1.2.1

Case 1.2.1 is shown in Fig. 6. According to [12], we define the probability of this happening as $p_{1.2.1}$.

$$p_{1.2.1} = (1 - e^{-\lambda_e \cdot R_v})^{k_{1.2.1}}, \tag{16}$$

where $k_{1.2.1} = (E[d_c^w] - 2R_v)/E[d_v^e]$.

At this time, node 2 directly transmits the accident notification information to the vehicle node (i.e., node 5) traveling westward, and the delay caused by the direct transmission of the accident notification information is negligible. Node 5 becomes a new forwarding node and transmits the accident notification information to RSU1. According to [5], the distance between node 5 and RSU1 is at most $x + 0.5E[l_e]$. Therefore, the accident notification information delivery delay is approximated by:

$$T_{1.2.1} = (x + E[l_e]/2)/v_w. \tag{17}$$

According to [14], we have

$$E[l_e] = (e^{\lambda_e \cdot R_v} - 1) \cdot \left(\frac{1}{\lambda} - \frac{R_v \cdot e^{-\lambda_e \cdot R_v}}{1 - e^{-\lambda_e \cdot R_v}} \right). \tag{18}$$

2) Case 1.2.2

Case 1.2.2 as shown in Fig. 7. We define the probability of this happening as $p_{1.2.2}$.

$$p_{1.2.2} = 1 - p_{1.2.1}. \tag{19}$$

At this time, the accident notification information will be stored and carried by node 2 until the vehicle node traveling westward is encountered, and the accident notification information will be forwarded to the vehicle node traveling westward. The vehicle node traveling westward becomes a new forwarding node and transmits the accident notification information to RSU1. Among the vehicle nodes traveling westward, the vehicle node closest to node 2 may become a new forwarding node, and the distance between this node and RSU1 is at least $x + 0.5E[d_c^w]$. According to [12], the accident notification information delivery delay is approximated by:

$$T_{1.2.2} = (x + E[d_c^w]/2)/v_w. \tag{20}$$

In summary, we have

$$T_{RSU1} = p_1 \cdot [p_{1.1} \cdot p_{1.1.1} \cdot (p_{1.1.1.1} \cdot p_{1.1.1.1.1} \cdot T_{1.1.1.1.1} + p_{1.1.1.2} \cdot T_{1.1.1.2})$$
$$+ p_{1.2} \cdot (p_{1.2.1} \cdot T_{1.2.1} + p_{1.2.2} \cdot T_{1.2.2})]. \tag{21}$$

4.2 Analysis of T_{RSU2}

T_{RSU2} analysis is shown in Fig. 8. Because the deployment location of RSU1 is located downstream of the accident vehicle, the accident vehicle can directly forward the accident notification information to the vehicle node (i.e., node 6) on the easternmost side of the vehicle cluster to become the forwarding node of the accident notification information. When node 6 is located in the transmission range of RSU2, the accident notification information will be forwarded from node 6 to RSU2. At this time, the delay caused by the direct forwarding of information is much smaller than that of storage carrying forwarding, which can be ignored. Therefore, it is only necessary to study the case where node 6 is outside the RSU2 transmission range (i.e., Case 2), as shown in Fig. 9. At this time, the length of the vehicle cluster where node 6 is located satisfies the following conditions:

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

According to [12], we define the probability of this happening as p_2.

$$p_2 = 1 - (1 - e^{-\lambda_e \cdot R_v})^{k_2}, \tag{22}$$

where $k_2 = 2 \cdot (d - x - R_u + R_v)/E[d_v^e]$.

We define the conditional expectation E_2 when half cluster length $l_e/2$ satisfies the condition $l_e/2 < d - x - R_u + R_v$.

$$E_2 = E[d_v^e] \cdot E[N_e|N_e < k_2]/2, \tag{23}$$

where $E[N_e|N_e < k_2] = \frac{1-(1-p_2)\cdot(k_2 \cdot e^{-\lambda_e \cdot R_v}+1)}{p_2 \cdot e^{-\lambda_e \cdot R_v}}.$
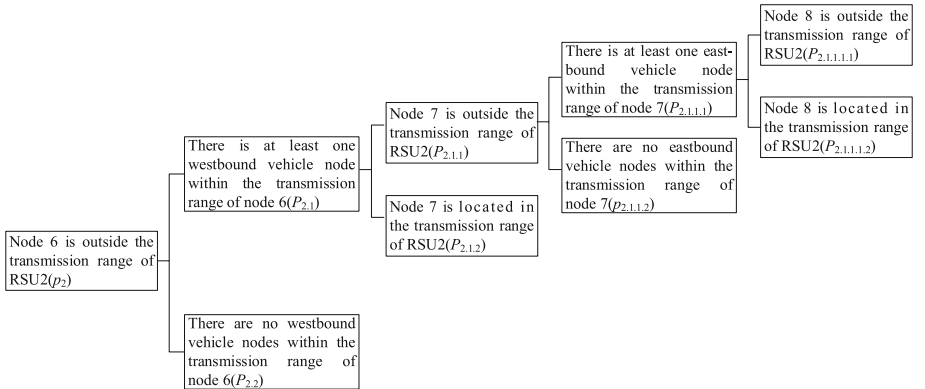

Fig. 8. Analysis of $TRSU2$

(1) Case 2.1

According to [12], we define the probability of this happening as $p_{2.1}$.

$$p_{2.1} = 1 - e^{-2\lambda_w \cdot R_v}. \tag{24}$$

When case 2.1 occurs, the easternmost vehicle node of the vehicle cluster where the westward traveling vehicle node is located in the transmission range of node 6 (i.e., node 7) is the forwarding node of the accident notification information. When node 7 is located in the transmission range of RSU2, the accident notification information will be forwarded from node 7 to RSU2. At this time, the delay caused by the direct forwarding of information is much smaller than that of storage carrying forwarding, which can be ignored. Therefore, it is only necessary to study the case where node 7 is outside the RSU2 transmission range (i.e., Case 2.1.1), as shown in Fig. 10. Denote the probability of occurrence of case 2.1.1 as $p_{2.1.1}$, according to [12], we have

$$p_{2.1.1} = 1 - (1 - e^{-\lambda_w \cdot R_v})^{k_{2.1.1}}, \tag{25}$$

where $k_{2.1.1} = 2 \cdot (d - x - E_2 + R_v)/E[d_v^w]$.

For this case, Wang et al. [5, 12–14] did not continue processing, but selected node 6 to continue carrying the accident notification information to RSU2. We propose a secondary communication method between vehicle clusters. The method first determines whether there is a vehicle node traveling eastward located in the transmission range of node 7. If it exists, the accident notification information is transmitted to the easternmost vehicle node of the vehicle cluster where the node is located, so that it transmits the accident notification information to RSU2. If it does not exist, the selected node 6 will continue to carry the accident notification information to the RSU2.
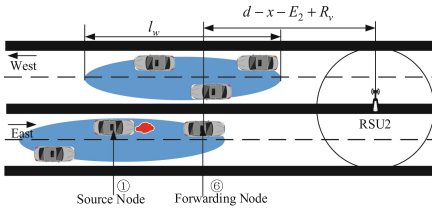

Fig. 9. Node 6 becomes a forwarding node (Case 2)
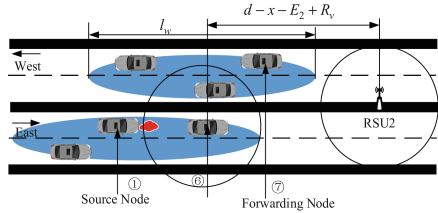

Fig. 10. Node 7 becomes a forwarding node (Case 2.1.1)

1) Case 2.1.1.1

We define the probability of this happening as $p_{2.1.1.1}$.

$$p_{2.1.1.1} = 1 - e^{-2\lambda_e \cdot R_v}. \tag{26}$$

At this time, the vehicle node on the easternmost side of the vehicle cluster where the eastbound vehicle node located in the transmission range of node 7 is located (i.e.,

node 8) is the forwarding node of the accident notification information. When node 8 is located in the transmission range of RSU2, the accident notification information will be forwarded from node 8 to RSU2. At this time, the delay caused by the direct forwarding of information is much smaller than that of storage carrying forwarding, which can be ignored. Therefore, it is only necessary to study the case where node 8 is outside the RSU2 transmission range (i.e., Case 2.1.1.1.1), as shown in Fig. 11. This occurs when the length of the eastbound vehicle cluster where node 8 is located satisfies the following conditions:

$$l_e < d - x - E_2 - E[d_c^e] + R_V + 2R_v.$$

With the Eq. (13), we define the probability of this happening as $p_{2.1.1.1.1}$.

$$p_{2.1.1.1.1} = 1 - (1 - e^{-\lambda_e \cdot R_v})^{k_{2.1.1.1.1}}, \tag{27}$$

where $k_{2.1.1.1.1} = (d - x - E_2 - E[d_c^e] + 3R_v)/E[d_v^e]$.

We define the conditional expectation E_3 when cluster length l_e satisfies the condition $l_e - R_v < d - x - E_2 - E[d_c^e] - R_u$.

$$
\begin{aligned}
E_3 &= E[l_e | l_e < d - x - E_2 - E[d_c^e] - R_u + 3R_v] \\
&= E[d_v^e] \cdot E[N_e | N_e < k_{2.1.1.1.1}],
\end{aligned} \tag{28}
$$

where
$$
\begin{aligned}
E[N_e | N_e < k_{2.1.1.1.1}] &= \sum N_e \cdot f_e(N_e | N_e < k_{2.1.1.1.1}) \\
&= \sum_{N_e=1}^{k_{2.1.1.1.1}} N_e \cdot \frac{f_e(N_e)}{\Pr\{N_e < k_{2.1.1.1.1}\}} \\
&= \frac{1 - (1 - p_{2.1.1.1.1}) \cdot (k_{2.1.1.1.1} \cdot e^{-\lambda_e R_v} + 1)}{p_{2.1.1.1.1} \cdot e^{-\lambda_e R_v}}
\end{aligned}
$$

In this case, the delivery delay required to deliver the accident notification information to the RSU2 can be calculated by:

$$T_{2.1.1.1.1} = (d - x - E_2 - E_3 - E[d_c^e] - R_u + 3R_v)/v_e. \tag{29}$$

2) Case 2.1.1.2

In case 2.1.1.2, the accident notification information needs to be stored and carried by node 6 and passed to the RSU2. We define the probability of this happening as $p_{2.1.1.2}$.

$$p_{2.1.1.2} = 1 - p_{2.1.1.1}. \tag{30}$$

At this time, the accident notification information delivery delay is approximated by:

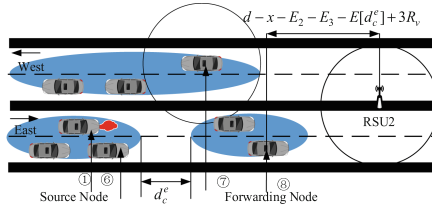$$T_{2.1.1.2} = \frac{d - x - R_u - E_2 + R_v}{v_e}. \tag{31}$$

Fig. 11. Node 8 becomes a forwarding node (Case 2.1.1.1.1)

(2) Case 2.2

According to [12], we define the probability of this happening as $p_{2.2}$.

$$p_{2.2} = 1 - p_{2.1}. \tag{32}$$

At this time, node 6 will continue to store and carry accident notification information until the accident notification information is transmitted to the RSU2. The calculation expression of the delay $T_{2.2}$ required for the transmission of the accident notification information is the same as that of $T_{2.1.1.2}$.

In summary, we have

$$T_{RSU2} = p_2 \cdot [p_{2.1} \cdot p_{2.1.1}(\cdot p_{2.1.1.1} \cdot p_{2.1.1.1.1} \cdot T_{2.1.1.1.1} + p_{2.1.1.2} \cdot T_{2.1.1.2}) + p_{2.2} \cdot T_{2.2}]. \tag{33}$$

5   Numerical Analysis

To validate the accuracy and validity of the theoretical analysis model derived in the previous section, we use MATLAB to calculate and analyze the numerical results. Parameter settings are shown in Table 2.

Figure 12 shows the effects of different deployment distances of RSU and different speeds of vehicle nodes on the transmission delay of accident notification information. It can be concluded from Fig. 12: First, under the same RSU deployment distance, with the increase of the average speed of the vehicle node, the delivery delay of the accident notification information decreases. The reason is: that as the average speed of the vehicle node increases, the forwarding node can forward the accident notification information to the RSU in a shorter time. Secondly, with the increase of RSU deployment distance, the delay of accident notification information transmission increases under the same vehicle node speed. The reason is: that as the deployment distance of the two RSUs increases, the distance between the accident vehicle and the two RSUs increases, which causes the forwarding node carrying the accident notification information to take longer to enter the transmission range of the RSUs, which in turn leads to the accident notification. The increase in information delivery delay. Finally, comparing Fig. 12(a), (b), and (c), we find that with the increase in vehicle node arrival rate, the delay of accident notification information delivery decreases. The reason is: that as the arrival rate of vehicles increases, the density of vehicle nodes on the road increases, the length of the formed vehicle cluster
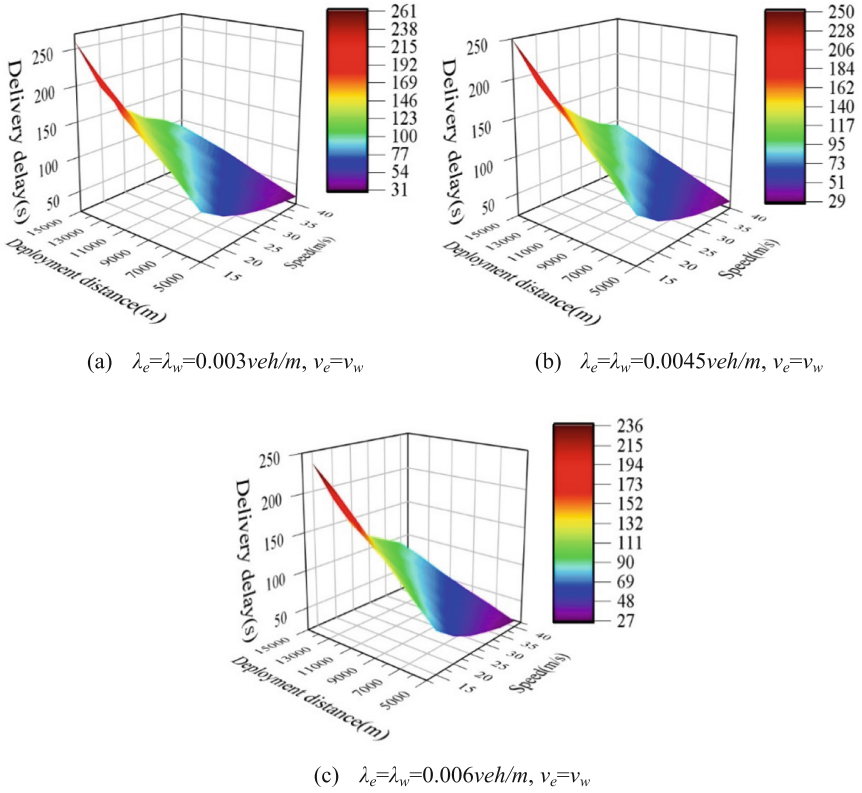
(a) $\lambda_e=\lambda_w=0.003veh/m$, $v_e=v_w$ (b) $\lambda_e=\lambda_w=0.0045veh/m$, $v_e=v_w$

(c) $\lambda_e=\lambda_w=0.006veh/m$, $v_e=v_w$

Fig. 12. Effects of different deployment distances of RSU and different speeds of vehicle nodes on the transmission delay of accident notification information

Table 2. Parameter settings.

Parameters	Values
RSU deployment distance d	5000, 7000, 9000, 11000, 13000, 15000 m
RSU transmission range R_u	250 m
Vehicle transmission range R_v	250 m
Eastbound vehicle arrival rate λ_e	0.003, 0.0045, 0.006 veh/m
Westbound vehicle arrival rate λ_w	0.003, 0.0045, 0.006 veh/m
Eastbound vehicle speed v_e	15, 20, 25, 30, 35, 40 m/s
Westbound vehicle speed v_w	15, 20, 25, 30, 35, 40 m/s
Number of iterations	1000

increases. The accident vehicle can choose a vehicle that is far away from it but closer to the RSU as a forwarding node.

In [12] and [14], it is assumed that there is no direct connection between two adjacent RSUs. Considering the vehicle speed, vehicle density, accident location, and different deployment intervals of two RSUs, a theoretical analysis model of the relationship between the delivery delay of accident notification information and the deployment interval of RSUs is proposed, which can be used to determine the maximum allowable deployment interval when two adjacent RSUs are not connected to each other. The model in this paper considers the direct connection between two adjacent RSUs and considers the secondary inter-cluster communication between the vehicles with the help of the accident vehicle to transmit the accident notification information to the vehicle cluster which is in the same direction as the accident vehicle and closer to the RSU. To verify the validity and effectiveness of the theoretical analysis proposed model, we compared it with Ref. [12] and Ref. [14], as shown in Fig. 13. It can be concluded from Fig. 13 that the transmission delay of the accident notification information in the model proposed in this paper can be reduced by more than 66% compared with Refs. [12] and [14]. The reason is that under the model proposed in this paper, the forwarding node only needs to transmit the accident information to an RSU nearest to the accident location, which will greatly reduce the transmission delay of the accident notification information. Under the model proposed in [12] and [14], the forwarding node needs to transmit the accident information to the remote RSU which is the farthest away from the accident site while transmitting the accident information to the nearest RSU, which will greatly increase the delivery delay of the accident notification information. In addition, the secondary inter-cluster communication method designed in this paper can also make the accident notification information transmitted to the RSU faster.
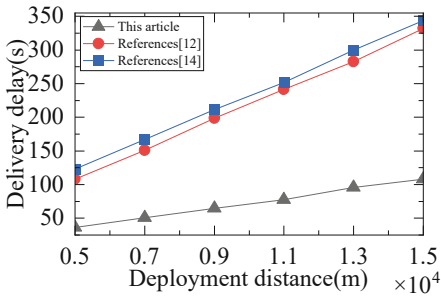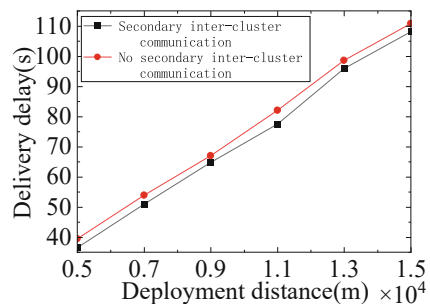
$(\lambda_e=\lambda_w=0.003veh/m, v_e=40m/s, v_w=30m/s)$

Fig. 13. Compared with references 12 and 14

$(\lambda_e=\lambda_w=0.003veh/m, v_e=40m/s, v_w=30m/s)$

Fig. 14. Secondary inter-cluster transmission verification

To further verify the effectiveness of the secondary inter-cluster communication method designed in this paper, we design a comparative experiment considering the secondary inter-cluster transmission and not considering the secondary inter-cluster transmission, as shown in Fig. 14. It can be concluded from Fig. 14 that the delivery delay of accident notification information considering the secondary inter-cluster communication mode is significantly lower than that without considering the secondary inter-cluster transmission. The reason is that under the same conditions, the secondary transmission

between clusters can transmit the accident notification information to a vehicle cluster farther away from the accident vehicle but closer to the RSU, which will significantly reduce the transmission delay of the accident notification information.

6   Conclusion

In this paper, in the highway scene with sparse vehicle nodes, RSU is deployed to improve the transmission delay of accident notification information. A theoretical analysis model is established by analyzing the relationship between the transmission delay of accident notification information and the RSU deployment distance in the VANETs environment. An inter-cluster transmission method is proposed to transmit the accident notification information to the vehicle cluster in the same driving direction and closer to the RSUs through the vehicle cluster in the opposite direction. Compared with the existing model that assumes that two adjacent RSUs are not connected and the secondary inter-cluster communication is not considered, the transmission delay of the accident notification information of our proposed model can be reduced by 66% compared with the existing model. In the future, we will implement the proposed model in the vehicular simulation environment to verify the effectiveness of our model in VANETs.

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