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Multiple intersection selection routing protocol based on road section connectivity probability for urban VANETs

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ABSTRACT

An efficient routing protocol is of great significance to improve vehicular ad hoc networks (VANETs) performance. However, due to complex road conditions, intermittent connectivity among vehicles and rapid changes of network topology, how to design an efficient routing protocol in an urban environment to transmit the data packet to the destination remains a challenging problem. In this paper, we propose a multiple intersection selection based on road section connectivity probability routing protocol for vehicle–vehicle (V2V) communication in urban VANETs, which considers the vehicle distribution influenced by traffic lights. First, we present a method to calculate the road section connectivity probability of a two-way lane with traffic lights consideration. Then, we establish an optimization model to select the optimal road path from the source node to the destination node based on the road section connectivity probability. Furthermore, we analyze the relay node selection on the road section after the optimal road path is determined, which discusses the number of neighbor vehicles in the communication range of the vehicle carrying packets and jointly considers the position, speed and direction of vehicles. Simulation results demonstrate that our proposed routing protocol increases the packet delivery rate and reduces the end-to-end delay.

1. Introduction

Intelligent Transportation System (ITS) has the potential to provide new services, including traffic management, well-informed users/drivers and more coordinated and efficient use of transportation networks [1]. Vehicular ad hoc networks (VANETs) are a critical component to realize ITS, which has several applications, such as smart cities, infotainment, travel route recognition, travel time prediction and road accident avoidance [2]. Due to the rapid movement of vehicles and dynamic topology, vehicle-to-vehicle communication (V2V) of VANETs can disseminate information quickly and improve transportation efficiency. Therefore, research on V2V communication is crucial for the realization of intelligent transportation.

Efficient message dissemination can reduce the occurrence of road accidents in the urban, which depends on a reliable routing protocol [3]. However, due to complex road conditions, there are several problems in the routing design of V2V communication, such as multiple intersections, obstacles, vehicle speed limit, uneven distribution of vehicles caused by traffic lights and social spots [4]. In a routing protocol, it is indispensable for vehicles to select suitable road path for forwarding data packets. Road section connectivity probability is an important indicator and benchmark to select road path. Most routing protocols, such as improved greedy traffic-aware routing (GyTAR) protocol [5], enhanced GyTAR (E-GyTAR) protocol [6] and traffic flow-oriented routing (TFOR) protocol [7], used vehicle density of the road section and curve-metric distance to the destination to select one intersection at a time and selected next-hop node based on the position of vehicles. Vehicle density and distribution will be affected by traffic lights. In addition, selecting one intersection each time may cause the local optimal problem, which will lead to no next suitable intersection to be selected at next time. However, previous routing protocols did not consider the influence of traffic lights on vehicle density and vehicle distribution, which further affect road section connectivity probability. Besides, routing protocols for urban VANETs do not consider incorporate road section connectivity probability and data delivery delay into an optimization model to select the optimal road path for forwarding data packets.

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The contributions of this paper are as follows.

- First, we present a method to calculate road section connectivity probability on a two-way lane, which considers different traffic lights' operation at both ends of the road and assumes the vehicles are uneven distributed on the road section.
- Second, we establish an optimization model to select a road path from the source node to the destination node, which gives minimum of total delivery delay estimation as the objective. Furthermore, we propose the optimal road path algorithm based on the optimization model.
- Finally, we analyze how to select relay nodes at the intersection and road section after the optimal road path is determined. As for relay node selection on the road section, we jointly consider the position, speed and moving direction of vehicles on a two-way lane. Simulation results show that the proposed routing protocol has better performance in the average end-to-end delay and packet delivery ratio.

The remainder of this paper is organized as follows. In Section 2, we review the most related work in this field. In Section 3, we describe basic assumption and provide the details of the proposed routing protocol. In Section 4, we present simulation results via Simulation of Urban Mobility (SUMO) [8] and Network Simulator Version 2 (NS-2) [9]. In Section 5, we draw conclusions and ideas for future work.

2. Related work

There have been existing works on routing protocol design to address these special problems in urban VANETs, such as traffic lights, intersections, uneven distribution of vehicles, obstacles. Mezher et al. [10] adopted city map information to select the next-hop, which pointed out that buildings will block the signal. The bidirectional roadways and the operation of traffic lights can affect the data delivery delay and the delivery rate of VANETs in the urban environment [11].

At present, there are many routing protocols to solve the problem of selecting the next intersection when the data packet arrives at an intersection. Jerbi et al. [5] proposed a greedy traffic-aware routing (GyTAR) protocol, which assumes the vehicles on the road section is evenly distributed and calculates road section connectivity by using the length of road and the number of vehicles. When the packet arrives at an intersection, the forwarding vehicle calculates the score of candidate intersections according to road section connectivity and the distance to the destination and selects the intersection with the highest score. Bilal et al. [12] proposed the directional geographic source routing (DGSR) protocol, which uses the Dijkstra Algorithm to establish a shortest path from source to destination. The shortest path consists of ordered intersections and the packet from the source vehicle along the sequence of intersections to arrive at the destination. To eliminate the dependence of route on vehicle density, Zahedi et al. [13] proposed a connected junction-based routing (CJBR) protocol in VANETs for city scenarios, which considers the number of RSU on the road to select the best intersection. A novel position-based routing protocol called dynamic multiple junction selection routing (DMJSR) protocol for the city environment was studied in [14], which selected two junctions based on vehicular density on the road and the curve-metric distance to the destination. However, these intersection-based routing protocols do not consider the influence of current traffic conditions on vehicle distribution on a two-way lane, which further affect the road section connectivity probability.

The routing performance can be improved by considering current traffic status in the road network. Ding et al. [15] considered the influence of traffic lights on vehicular distribution on the road section in urban VANETs, which assumes the number of vehicles driving on bidirectional roadways is the same and calculates the whole road section connectivity according to vehicular distribution and density to select road sections. A greedy traffic light and queue aware routing (GTLQR) protocol [16] jointly considered the uneven vehicular distribution caused by traffic lights and network congestion caused by high traffic demand during peak hours based on [15]. Besides, GTLQR used vehicular density on the road, channel quality, relative distance and queue delay to select the next intersection and next-hop vehicle. Sun et al. [17] proposed an intersection-based distributed routing (IDR) strategy for V2V communication in the urban environment, which adopts fuzzy logic to analyze routing path connectivity based on the traffic conditions between intersections. Nonetheless, these routing protocols selected one intersection at a time and did not include the path selection mechanism from the source node to the destination node based on road section connectivity probability.

The poor quality of nodes will cause data packets loss and routing redundancy [18]. Therefore, how to select the best relay node becomes a key challenge of a reliable routing protocol design. Tu et al. [19] present a geographical routing protocol namely Greedy Perimeter Stateless Routing Motion Vector (GPRS-MV), which selects the next forwarder node by predicting the future location of source and direct neighbor vehicular nodes. Distance and signal quality aware routing protocol (DSQR) [20] focused on optimal Mid-region selection within communication range of source node and the calculation of neighbor nodes link quality. These studies [5,6] have used one-hop neighbor information to select next-hop vehicle based on vehicular speed. Some studies [7,14] have suggested that employing a greedy forwarding technique to forward the data packet according to vehicular position and direction can minimize the hop count and reduce the end-to-end delay compared to that based on vehicular speed. But, neither of these works jointly consider the position, speed and direction of vehicles on a two-way lane to improve link quality in forwarding mechanism.

In this paper, a multiple intersection selection routing protocol based on road section connectivity probability in VANETs is proposed for an urban environment. The routing protocol consists of two components, which include the path selection and the relay node selection. As for the path selection, we establish an optimization model for path selection, which is based on connectivity probability of each road section. After an optimal path is determined, we analyze the relay node selection at the intersection and between intersections. For the forwarding in each road section of the determined path, we jointly consider position, speed and moving direction of vehicles on a two-way lane. The details are further discussed in the following sections.

3. Routing protocol design

In this section, we define some basic assumptions and provide the details of our proposed protocol. The descriptions of notations used in the following are shown in Table 1.

For better analysis, we make the following basic assumptions:

- Vehicle–vehicle communication is used to forward the data packet without considering roadside units.
- Each vehicle is equipped with global positioning system (GPS) and an embedded digital road map to determine the position of its neighboring intersections.
- Each vehicle is equipped with on-board units (OBU), which are used to send, forward, and receive data packets between a vehicle and its neighbor vehicles.
- All vehicles have the same communication radius and can obtain neighbor vehicles' information (such as position, speed, direction, acceleration) from periodically transmitted Hello packet.
- The number of vehicles on a road section can be obtained by deploying traffic sensors beside intersections or a distributed traffic density estimation mechanism used by all vehicles [21].
- The knowledge of the destination's position is ensured by means of grid's location service (GLS) [22].

Table 1
Summary of the main mathematical notations.

Notation	Description
T_θ^R	total time of red light of part θ segment
T_θ^r	remaining time of red light of part θ segment
Δd	average distance between two neighbor vehicles
$\bar{l}_v$	average length of vehicle
N_θ	total number of vehicles on part θ segment
N_θ^g	number of vehicle gathered on part θ segment
N_θ^r	number of mobile vehicle on part θ segment
len_θ	length of waiting queue on part θ segment
$\overline{v_{ij}}$	average speed of vehicles on road section ij
ρ	vehicle density on the road section
P_b	probability of a broken link between two vehicles
Con_{ij}	road section ij connectivity probability
τ_{ij}	data delivery delay of road section ij
L_{ij}	length of road section ij
λ	connectivity probability threshold
A	set of road section in the road network
N_I	set of intersection in the road network
$d_{i,d}$	distance from vehicle i to destination vehicle d
IC	instability coefficient of a vehicle
W	the width of an intersection
R	the range of wireless communication

3.1. Road section connectivity probability

Due to the dynamic topology and different vehicle density on road sections, VANETs will suffer from repetitive network partitioning and the link is broken, which makes it difficult to exchange messages among vehicles. Therefore, road section connectivity probability is an effective indicator of Internet of Vehicles (IoV) and its applications. We adopt a two-way single lane model and calculate the road section connectivity probability considering vehicle density based on traffic lights' operation. In the urban environment, because traffic lights' operation and the numbers of vehicles moving towards different directions along a two-way lane are different, the vehicle density on the two-way lane is different and should be analyzed separately.

There are three different states of traffic lights at two intersections. As shown in Fig. 1(a), when the traffic light is red on both sides of the road section, vehicles near the intersection slow down or even stop. There will have two waiting queues near two intersections and fewer vehicles in the middle area. As shown in Fig. 1(b), when one side of the traffic light is red and the other side of the traffic light is green, vehicles will gather on one side of the two-way lane. As shown in Fig. 1(c) when the traffic light is green on both sides of the road section, the distribution of vehicles on the road is more uniform, and vehicular speed is stable.

Based on the above analysis, we divide the road section into two parts based on moving direction to calculate vehicle density. The length of the waiting queue near the intersection can be calculated as follows:

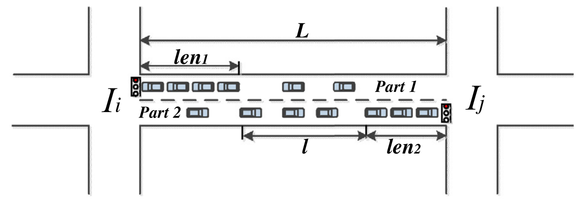
$$T_\theta^{R-r} = \begin{cases} T_\theta^R - T_\theta^r, & \text{it is red light,} \\ 0, & \text{it is green light .} \end{cases} \tag{1}$$

Here T_θ^R is the total time of red light, T_θ^r is the remaining time of red light and $\theta = \{1, 2\}$. Then the number of vehicles gathered is calculated as:

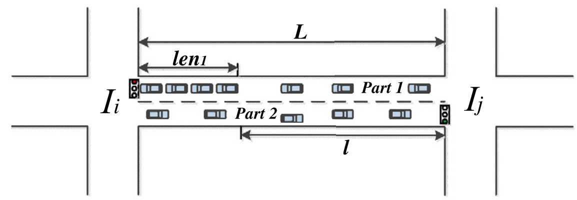
$$N_\theta^g = \frac{\overline{v_{ij}} T_\theta^{R-r}}{L} \times N_\theta, \tag{2}$$

$\overline{v_{ij}}$ is the average speed of vehicles on the road section, which is estimated based on the number of vehicles on the road section using traffic sensors and the maximum speed limit of the road section. L is the total length of the road section, and N_θ denotes the total number of vehicles on part θ segment of the road section, respectively. The remaining number of vehicles driving smoothly on the road section can be calculated as $N_\theta^r = N_\theta - N_\theta^g$. Then the length of the waiting queue gathered near the intersection is calculated as:

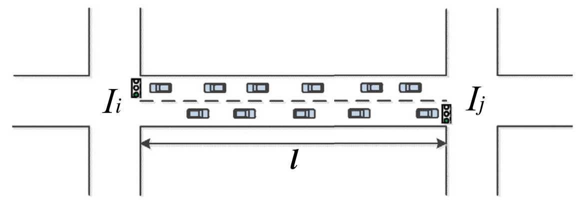
$$len_\theta = \left(\bar{l}_v + \Delta d\right) \times N_\theta^g, \tag{3}$$



(a)



(b)



(c)

Fig. 1. Illustration of the effect of traffic lights on vehicle distribution. (a) Traffic lights are red. (b) Traffic lights are asynchronous. (c) Traffic lights are green.

where $\bar{l}_v$ denotes the average length of vehicles, Δd represents the average distance between two neighbor vehicles in the waiting queue and N_θ^g is the number of vehicles gathered. Therefore, considering traffic lights, the vehicle density on the road section can be calculated as follow:

$$\rho = \sum_{\theta=1}^{2} \frac{N_\theta^r}{L - len_\theta}, \tag{4}$$

where N_θ^r is the number of vehicles driving smoothly on the road section, L is the total length of the road section and len_θ is the length of the waiting vehicle queue near the intersection.

Based on the analysis of the different states of traffic lights at both ends of the road, vehicle density on road has been calculated based on Eq. (4). Then, the probability of k vehicles are driving on a road segment of length r follows a Poisson distribution as [23] : $f(k,r) = \frac{(\rho r)^k}{k!} e^{-\rho r}$. Therefore, the probability that the distance between two adjacent vehicles smaller than x on the road follows exponential distribution as [23]:

$$F(x) = P\{X \le x\} = 1 - f(0,x) = 1 - e^{-\rho x}, x > 0. \tag{5}$$

A link is defined as broken if the inter-vehicle distance is larger than R, as shown in Fig. 2. According to Eq. (5), the probability P_b that a link between two consecutive vehicles is broken can be calculated as:

$$P_b = 1 - F(R) = e^{-\rho R}, \tag{6}$$

where R is the communication range of vehicle and ρ is the density of mobile vehicles on the road section.

There are multiple broken links on the road section due to the rapid movement of vehicles. $N^r = N_1^r + N_2^r$ denotes the number of vehicles normally driving on the road section ij. The connectivity probability of the road section ij can be given by

$$Con_{ij} = \left(1 - P_b\right)^{N^r - 1}, \tag{7}$$

where P_b is the probability of broken link between two vehicles and $N^r - 1$ is the number of connected links on the road section.

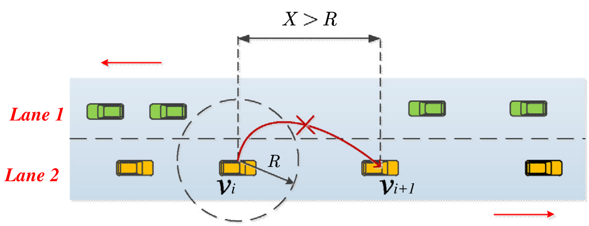
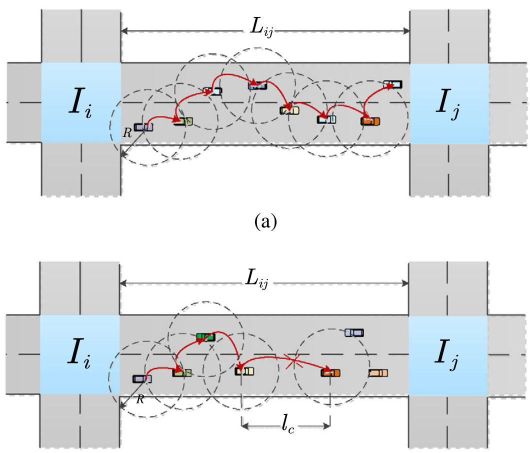


Fig. 2. Illustration of the road section connectivity.



(a)

(b)

Fig. 3. The situation of road section ij. (a) Illustration of fully connected. (b) Illustration of partly connected.

3.2. Road section selection

In this section, we establish an optimization model to select the optimal road path from the source vehicle s to the destination vehicle d based on road section connectivity probability, which is composed of multiple intersections and road sections. We select the path with the minimum delay based on road section connectivity probability, which can be expressed mathematically as follows:

$$\min_{x_{ij}} \sum_{ij\in A} \left(\tau_{ij} \cdot x_{ij}\right) \tag{8a}$$

$$s.t. \quad Con_{ij} \cdot x_{ij} \geqslant \lambda, \tag{8b}$$

$$\sum_{ij\in A} x_{ij} - \sum_{ij\in A} x_{ji} = \begin{cases} 1, \text{ if } i = s, \\ 0, \text{ if } i \in N_I \backslash \{s,d\}, \\ -1, \text{ if } i = d, \end{cases} \tag{8c}$$

where x_{ij} is binary variable, when the intersections (I_i, I_j) is selected, $x_{ij} = 1$. Otherwise, $x_{ij} = 0$. Con_{ij} denotes the connectivity probability of road section ij, λ is the connectivity threshold. A is the set of road section in the road network. The condition (8c) represents the flow conservation constraint that is given by [24], which is used to ensure that each feasible solution obtained from model belongs to a path from vehicle s to vehicle d. N_I denotes the set of intersection in the road network. τ_{ij} represents the data delivery delay of road section ij and the specific analysis is as follows.

In our model, we need to select the road section whose $Con_{ij} \geq \lambda$, which may have the following two situations: one is that the road section ij is fully connected that is no broken link between vehicles, as shown in Fig. 3(a), and the data packets can be transmitted by multi-hop among vehicles. The other is that the road section ij is partly connected, which exists the broken link in a certain part of the road section, as shown in Fig. 3(b), and the forwarding vehicle needs to carry the data for some distance until the next vehicle appears in the communication range R. Therefore, The delay of this two cases can be calculated as follows:

$$\tau_{ij} = \left\lceil \frac{L_{ij}}{R} \right\rceil \cdot t_{hop}, \quad Con_{ij} = 1, \tag{9}$$

$$\tau'_{ij} = \frac{l_c}{\overline{v}} + \left\lceil \frac{L_{ij} - l_c}{R} \right\rceil \cdot t_{hop}, \lambda \leqslant Con_{ij} < 1, \tag{10}$$

where L_{ij} is the length of road section ij, R is the average range of wireless communication, t_{hop} is the average wireless transmission delay per hop. l_c is the distance of vehicles carrying data packets, $\overline{v}$ denotes the average speed of the vehicle carrying data packets.

Based on the above analysis, the objective function can be written as :

$$\min_{x_{ij}} \sum_{ij\in A} \left[(1-U)\tau_{ij} + U\tau'_{ij}\right] \cdot x_{ij} \tag{11a}$$

$$s.t. \quad Con_{ij} \cdot x_{ij} \geqslant \lambda, \tag{11b}$$

$$\sum_{ij\in A} x_{ij} - \sum_{ij\in A} x_{ji} = \begin{cases} 1, \text{ if } i = s, \\ 0, \text{ if } i \in N_I \backslash \{s,d\}, \\ -1, \text{ if } i = d, \end{cases} \tag{11c}$$

$$U = \begin{cases} 0, \quad \text{Con}_{ij} \cdot x_{ij} = 1, \\ 1, \lambda \leqslant \text{Con}_{ij} \cdot x_{ij} < 1. \end{cases} \tag{11d}$$

where x_{ij} is a binary variable, when the road section ij is selected, $x_{ij} = 1$. Otherwise, $x_{ij} = 0$. Con_{ij} denotes the connectivity probability of road section ij, λ is the connectivity threshold and we assume that $\lambda = 0.8$. A is the set of road section in the road network. N_I denotes the set of intersection in the road network. U is a binary variable. When the connectivity probability of road section $Con_{ij} = 1$, $U = 0$. Otherwise, $U = 1$. τ_{ij} and τ'_{ij} represent the data delivery delay of two different situation on the road section ij, respectively.

For the solution of the optimization model, because the optimization variable x_{ij} is a binary variable, which denotes the road section composed of two intersections I_i and I_j, the model belongs to 0–1 integer linear programming problem. We propose the optimal road path algorithm for routing protocol as follow.

Algorithm 1 The optimal road path algorithm for routing protocol

s-source vehicle, d-destination vehicle
U-binary variable
Con_{ij}-road section connectivity probability
τ_{ij}, τ'_{ij}-data delivery delay on the road section
Begin
while $s \neq d$ **do**
  for each road section **do**
    Calculate Con_{ij};
    if $Con_{ij} = 1$ **then**
      $U = 0$, calculate τ_{ij}.
    else if $\lambda \leqslant Con_{ij} < 1$ **then**
      $U = 1$, calculate τ'_{ij}.
    end if
  end for
  Get the objective function Eq. (11a).
  Use *intlinprog* function to get optimal X^*.
end while
Choose the path with the minimum value of the objective function as the optimal road path.
End

In Algorithm 1, we can get the optimal solution of road path X^* that is a vector composed of 0 and 1, which is composed of road sections for forwarding data packets. The existence of the solution in the proposed algorithm is related to the set of connectivity probability threshold λ. When vehicle density in the network topology is sparse, if the threshold

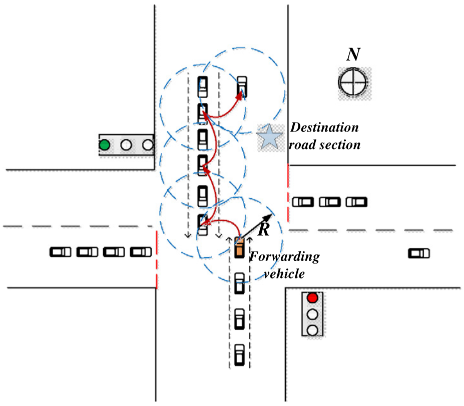


Fig. 4. Illustration of packet delivery.

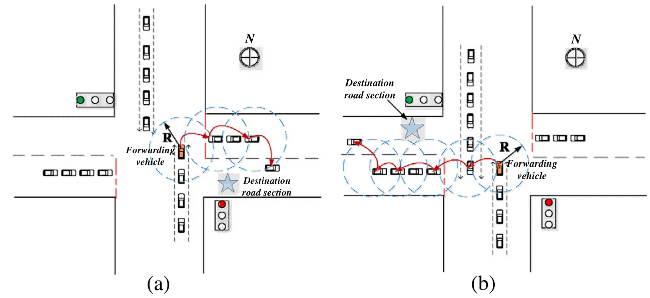


Fig. 5. Illustration of packet delivery. (a) The destination road section is in the east direction. (b) The destination road section is in the west direction.

λ is set too large, there will be no solution. At this time, we should decrease λ to weaken the constraint on the road section connectivity probability. When vehicle density in the network topology is dense, if the threshold λ is set too small, there will be multiple solutions. At this time, we should increase λ to strengthen the constraint on the road section connectivity probability. If there are exactly two solutions, one path is selected as the optimal road path and the other is the alternative road path.

Here is the complexity analysis of proposed algorithm.

Theorem 1. *The complexity of proposed optimal road path algorithm for routing protocol is* $O\left(n^2+2n\right)$.

Proof. The road section set is $|V| = n$ in grid topology, the number of road sections that need to calculate the connectivity probability is n. Then we need to calculate the data delivery delay of each road section and the time complexity of each operation is $O(2n)$. Using $intlinprog$ to solve the optimal road path, the time complexity is $O\left(n^2\right)$. Therefore, the time complexity of proposed algorithm is $O\left(n^2+2n\right)$.

3.3. Relay node selection at the intersection

After the intersections and the corresponding road sections is selected, we discuss how to select suitable relay nodes at an intersection in order to reduce the influence of traffic lights on data delivery delay. When the width of the intersection is smaller than the communication radius of the vehicle ($W \le R$), vehicles can forward packets to the destination road section by one-hop. Therefore, we discuss this situation that the width of an intersection is larger than the range of wireless communication ($W > R$) in this section.

Guo et al. [11] analyzed the traffic flow at an intersection under traffic lights' operation and adopted opposite lane and left-turn lanes to reduce the data delivery delay. However, they only considered the destination road segment is in the north, as shown in Fig. 4, and did not discuss the situation that the destination road segment is in another direction. Therefore, we supplement it with the other two directions. We suppose the forwarding vehicle is located in the south of the current intersection, and the destination road segment is in the east and west respectively. The analysis is as follows:

Case1: The traffic light is green.

When the destination road section is in the east of the current intersection. As shown in Fig. 5(a), the forwarding vehicle drives northward, and then forwards the packet to the head vehicle of the waiting queue on the eastern road. When the destination road section is in the west of the current intersection. As shown in Fig. 5(b), the forwarding vehicle forwards the packet to the first opposite vehicle entering its communication range, then transmits the packet to the head vehicle of the waiting queue on the western road.

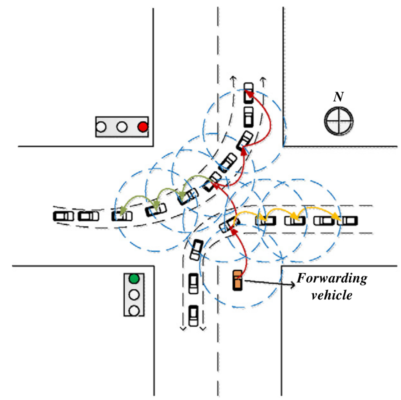


Fig. 6. Illustration of packet delivery.

Case2: The traffic light is red.

In this case, relay nodes selection is as same as [11], as shown in Fig. 6, which uses two left-turn lanes to forward the packet to the destination road section.

3.4. Relay node selection between intersections

In this section, we further optimize the routing strategy by further selecting suitable next-hop vehicle on the road section, which aims to establish more stable links between vehicles for forwarding packets. For forwarding data packets between intersections, GyTAR [5] selected the neighbor vehicle with the highest speed as the next-hop node based one-hop neighbor information. And DMJSR [14] adopted greedy forwarding, which considers the position of neighboring vehicles and selects a vehicle that is closest to the destination as the next-hop node. However, they do not jointly consider the position, speed, and direction of one-hop neighbor vehicles, which may increase the hop counts and appear the situation that communication links between vehicles often break.

In this paper, we improve the greedy forwarding method based on the position, speed, and direction of vehicles, which considers the number of neighbor vehicular nodes in the communication range of the forwarding vehicle. Here, we define the lane whose moving direction of vehicles is the same as data transmission direction as "forward", and the other lane whose moving direction of vehicles is opposite to data transmission direction as "backward". Each vehicle maintains a neighbor table, which contains the position, speed, and direction of its neighbor vehicles. This neighbor table is updated by exchanging Hello message periodically. Before forwarding the data packet, the packet carrier vehicle firstly consults its neighbor table to know about the latest information of its neighbor vehicles and then selects the next-hop neighbor vehicle as follows.

Case3: When the communication range of packet carrier vehicle includes multiple one-hop neighbor vehicles.

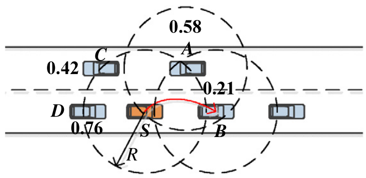


Fig. 7. Multiple vehicles in the communication range.

In this situation, we mainly consider the position and speed of neighbor vehicular nodes and define an instability coefficient IC to select the best next-hop node with a minimum IC. In detail, the instability coefficient is composed of the distance difference between the vehicle carrying the data packet and its neighbor vehicle to the destination vehicle and the speed difference between them. The difference in distance and speed can reflect the stability of the link between two adjacent vehicles. Therefore, the instability coefficient IC expression is as follows:

$$IC = \alpha\varphi\left(d_{nb}, d_i\right) + \beta\omega\left(v_{nb}, v_i\right), \tag{12}$$

$$\varphi\left(d_{nb}, d_i\right) = \frac{d_{nb}}{d_i}, \omega\left(v_{nb}, v_i\right) = \frac{\left|v_{nb} - v_i\right|}{v_i}. \tag{13}$$

Here d_{nb} is the distance from a neighbor vehicle to the destination, d_i is the distance from the vehicle carrying a packet to the destination, v_{nb} is the average speed of neighbor vehicles, v_i is the average speed of current vehicle carrying a packet. α, β are weight factors, $\alpha, \beta \in [0, 1]$ and $\alpha + \beta = 1$. $\varphi(d_{nb}, d_i)$ is used to judge whether a neighbor vehicle is closer to the destination than the current vehicle. To decrease hop counts, it is necessary to select a vehicle with a relatively small value of $\varphi(d_{nb}, d_i)$. $\omega(v_{nb}, v_i)$ reflects the speed difference between current vehicle and neighbor vehicle. To improve the stability of the communication link, a relatively small speed difference between the two vehicles is better.

As shown in Fig. 7, there are multiple vehicular nodes within the communication range of forwarding vehicle S and each vehicular node has a value of IC. Vehicle B is selected as the next one-hop node because of the smallest instability coefficient $IC = 0.21$ among neighbor vehicles, which indicates that vehicle B is closest to the destination and has the smallest speed difference with forwarding vehicle S.

Case4: When there is only one vehicle in the communication range of the vehicle which carries a packet.

In this case, because there are vehicles in different directions on a two-way lane, we need to discuss whether to forward the data packet to this vehicle based on position and moving direction.

Case4(**a**): There is only one backward vehicle in the communication range of source vehicle S.

As shown in Fig. 8(a), there is only one backward vehicle A in the communication range of vehicle S. Firstly, we determine whether the condition $d_{S,D} > d_{A,D}$ is satisfied. If it is satisfied, the next step is to consider whether there exist next-hop nodes within the range of vehicle A. If there exits vehicle B which meet condition $d_{A,D} > d_{B,D}$, the final step is to determine whether the link between vehicle A and vehicle B will be broken at the next moment.

We assume that the coordinates of vehicles S, A, B at time t are (x_S, y_S), (x_A, y_A), (x_B, y_B), and the coordinates of them at next time t_1 can be calculated as follows

$$\begin{cases} \Delta t = t_1 - t \\ x'_S = x_S + \Delta t \times v_x^S \\ y'_S = y_S + \Delta t \times v_y^S, \end{cases} \tag{14}$$

where v_x^S and v_y^S represent the velocity components of vehicle S in the x direction and y direction, respectively. In the same way, (x'_A, y'_A) and (x'_B, y'_B) can be calculated. Then the distance between vehicles are approximated as follows

$$d_{SA} = \sqrt{\left(x_S - x_A\right)^2 + \left(y_S - y_A\right)^2}, \tag{15}$$

$$d_{AB} = \sqrt{\left(x'_A - x'_B\right)^2 + \left(y'_A - y'_B\right)^2}. \tag{16}$$

According to the above analysis, the backward vehicle can be selected as the next-hop vehicular node only when $d_{SA} \le R$ and $d_{AB} \le R$. If this backward vehicle does not meet the above condition, the data packet may be carried away from the destination if vehicle S forwards the packet to this backward vehicle. Therefore, in this situation, source vehicle S should adopt a carry-and-forward mechanism until an appropriate node in its communication range is found.

Case4(**b**): There is only one forward vehicle in the communication range of the packet carrier vehicle S.

In this case, we use position information of this forward vehicle to select. If $d_{S,D} > d_{B,D}$, as shown in Fig. 8(b), this forward vehicle B is selected as next-hop node. Otherwise, the packet carrier vehicle S adopts a carry-and-forward mechanism.

Case5: There are no neighboring vehicles within the communication range of the packet carrier vehicle. In this case, as shown in Fig. 9, the packet carrier vehicle will adopt carry-and-forward mechanism and hold the packet until an appropriate vehicular node in the communication range is found.

Based on the above analysis of selecting a next-hop node, we divide traffic lights at the intersection into three situations to discuss routing.

(1) When both sides of traffic lights are red, there are two waiting queues near two intersections.

In this case, the data packet is forwarded along the waiting queue on the backward lane, and then the data can be forwarded according to the selection method of the next-hop mentioned above. Finally, the packet

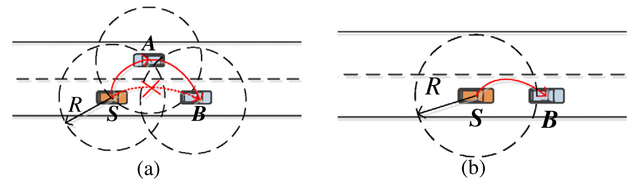


Fig. 8. Only one backward vehicle in the communication range. (a) A backward vehicle. (b) A forward vehicle.

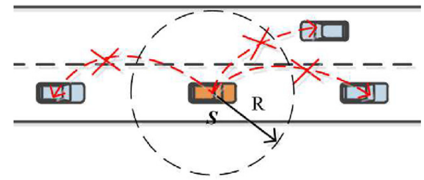


Fig. 9. None vehicle in the communication range.

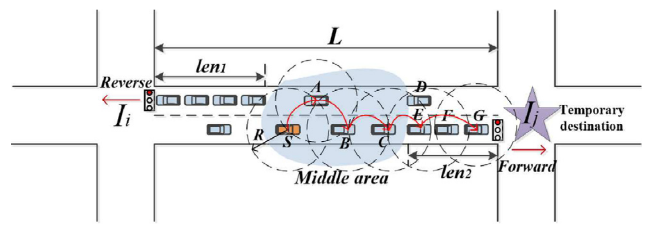


Fig. 10. Traffic lights are red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

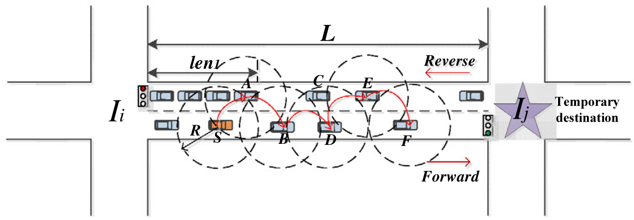


Fig. 11. Traffic lights are asynchronous.

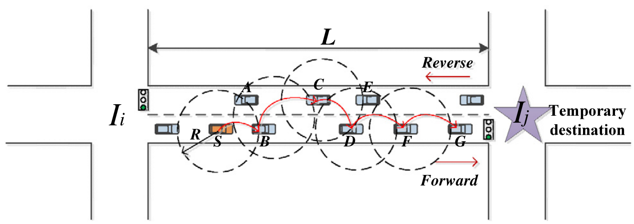


Fig. 12. Traffic lights are green. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

is forwarded along the waiting queue on the forward lane by multi-hop. The routing path shown in Fig. 10 is $S \rightarrow A \rightarrow B \rightarrow C \rightarrow E \rightarrow G$.

(2) When one side of the traffic light is red and the other is green.

In this case, the waiting queue on the backward lane is used to forward. Then the packet is forwarded to the destination intersection, according to the selection method of next-hop mentioned above. The routing path shown in Fig. 11 is $S \rightarrow A \rightarrow B \rightarrow D \rightarrow E \rightarrow F$.

(3) When both sides of traffic lights are green, there is no waiting vehicle queue near two intersections.

In this case, there has not the phenomenon of vehicle gathered near the intersection. Therefore, according to the next-hop selection method mentioned above, the data packet will be forwarded to the intersection, which is near the destination vehicle. The routing path shown in Fig. 12 is $S \rightarrow B \rightarrow C \rightarrow D \rightarrow F \rightarrow G$.

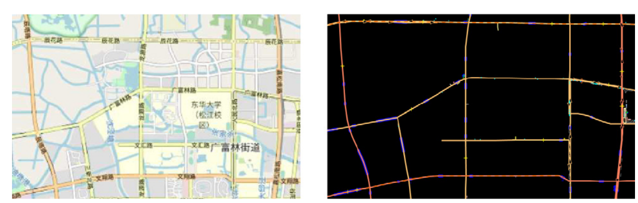
3.5. Routing algorithm

Based on the analysis of Sections 3.1–3.4, in this section, we propose a multiple intersection selection routing algorithm, which includes the optimal road path selection for forwarding data packets, the selection of relay nodes at the intersection and the selection of relay nodes on the road section of the determined road path. The routing algorithm is as follow.

In Algorithm 2, DC denotes the number of neighbor vehicular nodes in the communication range of the forwarding vehicle, $DC = 11$ represents there are multiple neighbor vehicles in the communication range of the forwarding vehicle; $DC = 10$ represents there is only one neighbor vehicle in the communication range of the forwarding vehicle; $DC = 00$ represents there is none neighbor vehicle in the communication range of the forwarding vehicle. Line 13 to Line 18 present the process of relay nodes selection at an intersection. Line 19 to Line 27 describes the process of selecting the next-hop vehicular node according to three cases.

Algorithm 2 Multiple intersection selection routing algorithm

1: s-the source vehicle, d-the destination vehicle
2: $d_{s,d}$-the distance between s and d
3: n_{insec}-the number of intersection between s and d
4: T_S-the traffic lights status
5: DC-the number of one-hop neighbor nodes of the forwarding vehicle
6: **if** $d_{s,d} \leq R$ **then**
7: Forward packet to V_d.
8: **else if** $n_{insec} = NULL$ **then**
9: go to Line 19.
10: **else if** $n_{insec} \neq NULL$ **then**
11: invoke Algorithm 1/*optimal road path selection*/.
12: **end if**
13: **if** packet arrives at an intersection **then**
14: **if** $T_S = G$ /*green light*/ **then**
15: Select relay node based on Case 1 in Section 3.3.
16: **else if** $T_S = R$ /*red light*/ **then**
17: Select left-turn lanes as relay nodes.
18: **end if**
19: **else if** packet is on straight road section **then**
20: **if** $DC = 11$ **then**
21: Calculate IC based on Eq. (12).
22: Select next-hop with minimum IC.
23: **else if** $DC = 10$ **then**
24: Select next-hop based on Case 4 in Section 3.4.
25: **else if** $DC = 00$ **then**
26: Carry and forward.
27: **end if**
28: **end if**



(a) (b)

Fig. 13. Illustration of simulation scenario. (a) Illustration of Songjiang district map. (b) Illustration of simplified road network.

4. Performance analysis

In this section, we present the simulation results of multiple intersection selection routing protocol (MISR) in terms of end-to-end delay and packet delivery rate. For performance comparison, we compare GyTAR [5] and DMJSR [14] with MISR.

4.1. Simulation environment

We evaluate the performance of the proposed protocol using SUMO [8] and NS-2 simulators [9]. As shown in Fig. 13(a), we consider a realistic urban scenario in Songjiang district, Shanghai, China. Firstly, we use the Java OpenStreetMap (JOSM) [25] to extract the traffic road network information and simplify the content of Fig. 13(a), as shown in Fig. 13(b). Then, with the SUMO in Songjiang district urban region, vehicles are set into the area of 2000 m × 2000 m, which contains 18 road intersections and 24 road sections. SUMO outputs a tcl file that records the vehicular nodes' mobile trace, which including the node's speed and position. Finally, the tcl file is imported into NS2 for simulating the performance of the routing protocol.

In the simulation scenario, we set source vehicle and destination vehicle in different road sections, therefore, there exists next intersection selection and next-hop selection in the process of data delivery. The traffic lights are synchronized and the time ratio of red light and green light is 1:1. The communication range of vehicles is 250 m. The rest of the simulation parameters are summarized in Table 2.

Table 2
Simulation parameters.

Simulation parameters	Values
scenario length (m)	2000
scenario width (m)	2000
speed of vehicles (km/h)	30 ∼ 55
range of mobile nodes	100 ∼ 350
communication range (m)	250
MAC Protocol	802.11
CBR send rate	0.1
maximum packet size (byte)	1500
total simulation time (s)	300
weighting factors	$\alpha = 0.5,\ \beta = 0.5$

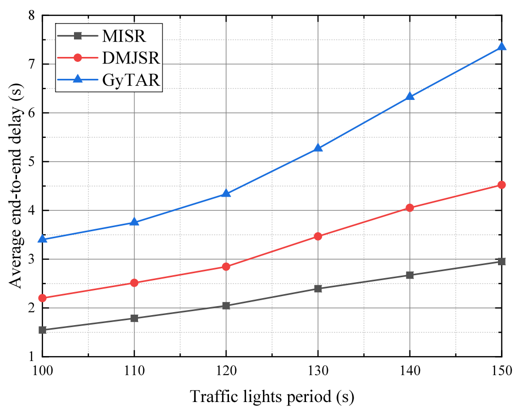


Fig. 14. Average end-to-end delay vs. Traffic lights period.

4.2. Simulation results

We present the performance comparison of end-to-end delay and packet delivery fraction under different traffic lights period, number of vehicles and vehicular velocity. The detailed analysis is described as follows.

4.2.1. The evaluation of different traffic lights period

We compare the performance of the three routing protocols under different traffic light period. We set the number of vehicular node is 200 and increase the traffic lights period from 100 s to 150 s. The first half of the traffic lights period is green light time and the second half is red light time.

Figs. 14 and 15 show the trend of average end-to-end delay and packet delivery ratio as the traffic lights period. The green line in the figures represents the time of green light and the red line represents the time of red light. With the increase of traffic lights period, the end-to-end delay increases and the packet delivery ratio decreases. With the increase of traffic lights period, more vehicles will gather near intersections and the number of mobile vehicles on the middle road section will decrease because of the increase of red lights time, which will increase the possibility of broken links on the middle road section. MISR selects the optimal road path based on the connectivity probability of moving vehicles, rather than based on the vehicular density, which can avoid selecting these road sections with high vehicle density but weak connectivity due to vehicle aggregation near intersections. Compared to GyTAR and DMJSR, our routing protocol decreases the end-to-end delay by 55.97% and 31.67% on average and increase the packet delivery ratio by 22.43% and 10.70% on average, respectively.

4.2.2. The evaluation of different number of vehicles

We compare the performance of the three routing protocols under the different number of vehicles. The traffic lights period is set as 120 s and the max velocity of vehicles is set as 55 km/h.

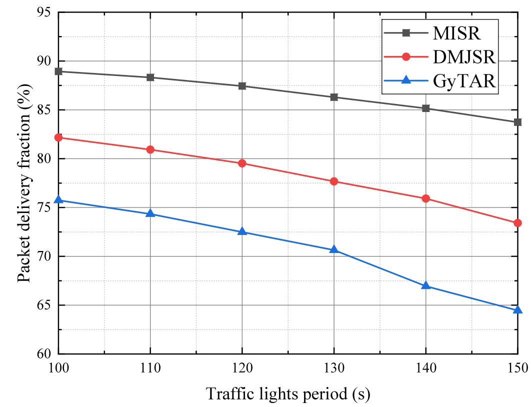


Fig. 15. Packet delivery fraction vs. Traffic lights period.

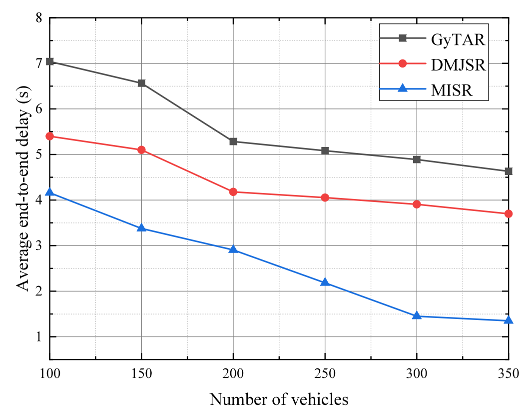


Fig. 16. Average end-to-end delay vs. Number of vehicles.

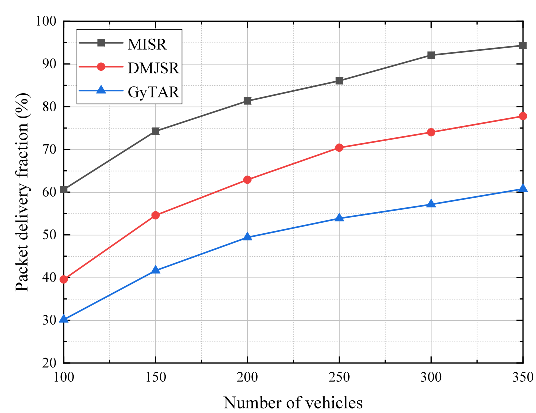


Fig. 17. Packet delivery fraction vs. Number of vehicles.

Figs. 16 and 17 show the trend of average end-to-end delay and packet delivery ratio as the number of vehicles. With the increase of number of vehicles, the average end-to-end delay decreases and the packet delivery ratio increases of all the three routing protocols. This is because the number of vehicles on the road section increases, the communication links between vehicles are more difficult to break, which lead to lower delay and packet loss rate. MISR can select the optimal road path for forwarding packets, which is composed of road sections with high connectivity and less delay. As for relay node selection, MISR considers relay node selection at the intersection and selects more better next-hop node based on the speed, distance and direction of vehicles to enhance link stability between vehicles on the road section. Compared to GyTAR and DMJSR, MISR decreases the end-to-end delay

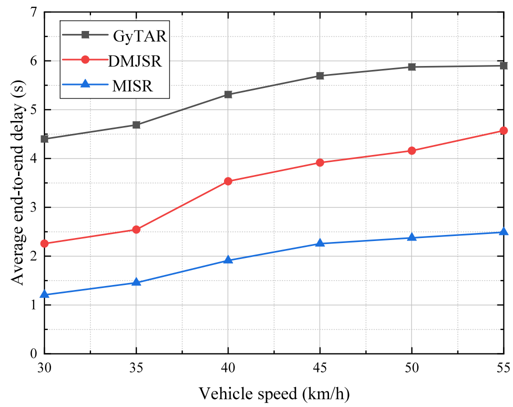


Fig. 18. Average end-to-end delay vs. Vehicular velocity.

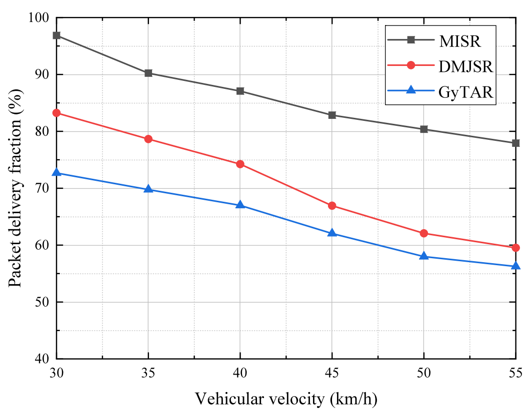


Fig. 19. Packet delivery fraction vs. Vehicular velocity.

by 53.94% and 41.44% on average and increases the packet delivery ratio by 66.84% and 28.86% on average, respectively.

4.2.3. The evaluation of different vehicular velocity

We compare the performance of the three routing protocols under different vehicular velocity. The traffic lights period is set as 120 s and the number of vehicles is set as 200.

Figs. 18 and 19 show the trend of average end-to-end delay and packet delivery ratio as the vehicular velocity. With an increasing of vehicular velocity, the end-to-end delay increases and the packet delivery ratio decreases. This is because network topology changes rapidly and the communication links between vehicles become unstable with the increase of velocity, which makes next-hop node selection more difficult. MISR considers the velocity difference between vehicles on each road section of the determined road path and selects more better next-hop node by discussing the number of neighbor vehicles of the current packet-carrying vehicle node. Compared to GyTAR and DMJSR, MISR decreases the end-to-end delay by 63.3% and 44.27% on average and increases the packet delivery ratio by 33.59% and 21.34% on average, respectively.

5. Conclusion

An efficient and reliable routing protocol is crucial in VANETs. In this paper, we proposed a multiple intersection selection routing protocol based on road section connectivity probability for efficient data delivery in the urban environment. We presented a method to calculate road section connectivity probability with traffic lights consideration for urban VANETs. Based on the road section connectivity probability, we established an optimization model to select the optimal road path from the source vehicle to the destination vehicle with the minimum total data delivery delay of road sections. After the optimal road path is selected, we discussed how to select relay nodes at an intersection and road section. As for next-hop selection on the road section, we jointly considered the position, speed, and moving direction of the one-hop neighbor vehicle on a two-way lane. Simulation results have demonstrated that proposed protocol can improve the packet delivery ratio and reduce end-to-end delay.

In the future, we will incorporate social factors of vehicles into the model and select next-hop vehicular nodes based on social attributes to improve communication quality.

CRediT authorship contribution statement

Shuang Zhou: Conceptualization, Methodology, Software, Writing – original draft, Validation, Investigation, Formal analysis, Writing – review & editing. **Demin Li:** Conceptualization, Validation, Supervision, Writing – review & editing. **Qinghua Tang:** Visualization. **Yue Fu:** Data curation. **Chang Guo:** Validation, Supervision. **Xuemin Chen:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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