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PTCCR: A Path Transmission Costs-Based Multi-Lane Connectivity Routing Protocol for Urban Internet of Vehicles

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ABSTRACT In Internet of Vehicles (IoV), high vehicular mobility causes frequent changes in the density of vehicles, discontinuity in inter-vehicle communication, variation of network topology and constraints for routing protocols. Besides, with vehicular positions and street-level digital maps available, the intersection-based geographic routing becomes indispensable considering its ability for avoid forwarding packets through segments with low network density and high scale of network disconnections. In this paper, considering the benefits of intersection-based routing and challenges of high dynamic IoV, a Path Transmission Costs-based Multi-lane Connectivity Routing protocol (PTCCR) is proposed with the help from intersection nodes and/or neighboring nodes. First, we investigate the multi-lane connectivity based on vehicular speed under free-flow state for various types of road sections. Second, A Path Transmission costs (PTC) measurement mechanism is proposed considering the impact of the sequence of selected sections or intersections on the routing performance. After that, the PTC of sent packets is quantitatively analyzed and used as the path selection metric. Finally, the path with the largest multi-lane connectivity and lowest PTC is selected as the optimal path taking the transmission direction, neighbor's location and destination position into account. Numerical results show that our proposed PTCCR outperforms two state-of-art routings, i.e., the real-time intersection-based segment aware routing protocol (RTISAR) and Reliable Traffic Aware Routing protocol (RTAR), in terms of packet delivery ratio, average end-to-end delay and communication overhead.

INDEX TERMS Internet of vehicles, multi-lane connectivity, path transmission costs, directional transmission.

I. INTRODUCTION

The Internet of Vehicle (IoV) recently evolves as a new theme of research and development from the Intelligent Transportation System (ITS) and Vehicular ad-hoc network (VANETs) [1]–[3]. In fact, one of the main problems of VANET is its limited capacity for processing all collected information on or among vehicles. In addition, vehicles are intermittently connected or disconnected as they fall inside or

outside the radio range of each other. To address these issues, IoV integrates two technological visions together, i.e., networking and intelligence, and expands the communication pattern from V2V (Vehicle to Vehicle) to V2X (Vehicle to Everything), to create an intelligent network [4], [5]. By V2X, IoV enables the exchange of data packets among vehicles, road infrastructures, passengers, drivers, sensors and electric actuators. In addition, to enable geographically separated vehicles to communicate, IoV also employ multi-hop communications relying on intermediate vehicles to forward packets. However, as a type of mobile network, the IoV

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has the problems of traditional wireless networks, involving packets contention, channel interference, power attenuation, hidden and exposed terminal etc. Due to its special characteristics, IoV also faces many other issues, such as high mobility of vehicles which causes intermittent inter-vehicle communication, rapid change of topology, as well as the limitation from geographical layout and traffic rules. Incorporating with above concerns, an reliable, efficient and intelligent routing protocol becomes indispensable for multi-hop communications.

In general, routing protocols are mainly classified into two major categories, i.e., topology based and position based. And the geographic based protocols are also categorized into position based schemes, in which routing path is determined according to geographical coordinates of neighbor and destination nodes. In common sense, topology based protocols fail in high dynamic environment due to frequent change of topology, while the geographic based could better address this issue. However, traditional geographic routing such as GPSR [6] and its improved variants, still have many defects including the detouring problem, multi-hop redundancy, road traffic sparsity and the low-reliability link issue. Furthermore, the urban environment makes things worse considering its layout complexity which consists of many buildings and intersections. Ideally, packets are transmitted along the road layout. In this way, because the link is prone to be disrupted by moving vehicles restricted within the layout, traditional geographical location based routing cannot work well in such an urban environment.

In order to address this issue, the intersection-based routing strategies emerged, where the packets are forwarded along the road sections connected with intersections. Once a packet arrives at an intersection, a new road section is to be selected according to specific criterion. The intersection-based routings outperform the traditional location-based routings under urban environment [7]. Note that for the intersection-based strategy, if the street is found to be inappropriate after the packet was sent to it, the packet may face prolonged delay or have no node available to relay the next-hop transmission. Unfortunately, most existing intersection-based protocols still employ the greedy forwarding rule to select the next relay node within roads and at intersections, which highly attenuate their routing performance [8]. Although greedy-based forwarding reduces the number of hops, it results in a higher packet loss ratio, especially for vehicles with high speed. Moreover, these intersection protocols have no consideration on roads structure as well as vehicular driving direction when approaching intersection areas. In this case, extra latency as well as large possibility of packet loss may be caused. In fact, there are three critical problems needs to be addressed before applying intersection-based routing in urban environment. At first, the two-way multi-lane connectivity should be considered as an important factor for intersection routing. Second, the impact of the sequence of road sections between source and destination on the routing performance, should also be taken into account. Third, the efficiency

of intra-section forwarding is another issue critical to the intersection-based routing. For the sake of simplicity, these three issues are later generalized into the terms “multi-lane connectivity probability,” “selection of road sequence” and “selection of optimal relay node,” respectively.

Additionally, the routing metric has also a great effect on the routing performance. Thereupon, in our work, we proposed a path transmission costs to measure the path quality for packets transmission. Unlike existing protocols, we focus on the transmission costs (PTC) in order to ensure that the packet is delivered successfully from source to destination while avoiding the local maximum problem in present intersection protocols. First, the flooding algorithm is adopted to determine the feasible sequence of intersections to the destination. Next, multi-lane connectivity of each path is computed. For the path whose connectivity satisfies certain predefined conditions, the cost associated with the packet transmission along this path is taken into account. The path which has a high multi-lane connectivity and minimum transmission costs will finally be selected as the optimal path. At last, the packet is forwarded using the location-aware greedy algorithm along the determined optimal path.

The rest of this paper is organized as follows. Section II reviews some related works; Section III discusses the detail of our PTCCR protocol; Section IV evaluates the performance of PTCCR in terms of packet transmission ratio, average end-to-end delay and communication overhead; Our paper is concluded in Section V.

II. RELATED WORK

For traditional routing protocols, e.g., ad-hoc on demand distance vector routing (AODV) [9], an end-to-end path must be established prior to data transmission, and a complete end-to-end route has to be determined through the route discovery process. This requires that all nodes in the path should be connected during data packet transmission. AODV provides loop-free path and is suitable for large scale ad-hoc networks. However, it takes more time to create the routing table and demands higher processing efforts.

On the other hand, the intersection-based routing protocol mainly consists of two parts: 1) it needs to select a sequence of road section, choosing a route of road sections from source to destination; 2) it relays the packet within the road. Note the relayed transmission is completed by vehicular nodes in this road section. The most distant node is greedily chosen for next-hop transmission in the simplest relay strategy.

The selection of road section sequence is a fundamental problem of the intersection-based routing strategy [10]. And the selection is dependent on analysis of the road section's routing property. Based on various routing properties, many routing protocols of this type have been proposed for IoV. Originally, the static property of the street was incorporated into the selection of road sections. Lochert *et al.* [11] and Seet *et al.* [12] determined the path of streets from source to destination based on static map, and the packet

was delivered through original routing. In the geographic source routing (GSR) protocol, the street's static length was defined as the street's routing property. And the sequence of streets which has the shortest length from source to destination was selected as the route. Celes et al. took the vehicle's transportation history into account, and proposed a track-based routing protocol. However, neither static length of the street nor the static history of the vehicle can accurately reflect the street's dynamic routing property and these protocols have high routing overhead because of beacon message [13].

The intra-street vehicle density is usually defined as the street's dynamic property. Al-Mayouf et al. presents real-time intersection-based segment aware routing (RTISAR), an intersection-based segment aware algorithm for geographic routing in VANETs. This routing algorithm provides an optimal route for forwarding the data packets toward their destination by considering the traffic segment status when choosing the next intersection [14]. The intra-street vehicle density is obtained through requirements-driven flooding measurement, and the high-density street was chosen as the route [15]. In essence, it was implicitly assumed in the density-based street selection strategy that the reliability of the route increases with the density of vehicles on the road. However, vehicle density is merely a property of vehicle distribution and cannot accurately capture the street's routing property.

The street's connectivity is also defined as a dynamic property of the street. Yang et al. proposed an adaptive connectivity routing protocol (ACAR), where the intra-street topological connectivity is predicted using a method based on both vehicle density and a mobile model with traffic lights [16]. Rondinone and Gozalvez predicted the average connectivity of multiple hops in the street and then incorporated it into the selection of street path [17]. Although connectivity is an important aspect of the street's dynamic routing property, the instantaneous connectivity strategy is unsuited for the rapidly changing topology of IoV.

A delay model for the street was established and defined as a dynamic property of the street. On this basis, they proposed a delay model-based vehicle-assisted data delivery protocol (VADD). Their model assumed that the street with a high level of vehicular density has a low delay and is thus more entitled to be selected as the route. It is good in multi-hop data delivery and in low data transmission [18]. However, its packet delivery ratio is less in selecting neighbor node and delay is big due to dynamic topology and large traffic. Liu et al. [19] proposed to enable cooperative data delivery based on an evolutionary fuzzy game to ensure more reliable data sharing in VANETs. The V2I routing protocol was also developed for data delivery from facility to vehicle. However, collecting data on global density of vehicles for the purpose of street selection incurs heavy overheads. The adopted analysis model is not flexible and ignores high mobility of vehicles in the street.

How to select an optimal node to forward the packet within the street is essential for a multi-hop routing protocol. The greedy forwarding strategy was first used to design the routing protocol of the Internet of Vehicles. The ICAR [20] is a framework of infrastructure-based VANETs routing protocol, where the number of end-to-end hops was reduced by choosing the neighbor with the largest geographical distance as the optimal forwarding node. In this way, the data was delivered more promptly. Due to its ability to quickly determine and establish the route based on node location, ICAR is characterized by low overhead, high efficiency and desirable extendibility. But it also has some limitations, such as detouring, multi-hop redundancy, road traffic sparsity and poor link reliability.

Abbasi et al. proposed a novel position-based routing protocol [21] to enhance traffic safety and traffic organization and facilitate driving through a smart transportation system. The protocol is referred to as the traffic flow-oriented routing (TFOR) protocol for VANETs which increases packet-delivery ratio and decreases end-to-end delay.

The main contributions of this paper are summarized as follows.

- We proposed a multi-lane connectivity probability model based on vehicular speed under free-flow state for various types of road sections.
- We presented a novel routing metric, i.e., path transmission costs, to measure the path quality for packets transmission.
- We determined the optimal path by considering the sequence of road sections according to multi-lane connectivity of them.
- After the optimal path is chosen, the locations of neighbors are predicted using our envisioned prediction method. In this way, the possibility of packet forwarding to malfunctioned neighbor is enormously reduced.

III. PROTOCOL DESCRIPTION

In this section, we proposed a path transmission costs-based multi-lane connectivity-aware routing protocol for the urban scenario. The aim is to find a route from source to destination node which has the maximum multi-lane connectivity probability and minimum transmission costs so that the packet can be delivered to the destination node efficiently. The proposed protocol jointly considers vehicular mobility, multi-lane connectivity probability, PTC and the different combinations of road sections for a path.

To facilitate the understanding of technical aspects, a table of notations would be useful as illustrated in TABLE 1.

We first make some assumptions about the urban environment to facilitate subsequent analysis. Next, we propose two routing metrics, i.e., multi-lane connectivity probability and PTC, in order to qualitatively analyze the resources consumed for transmission from the current node to the destination node. Based on the two routing variables, we develop

TABLE 1. List of important notations.

parameter	parameter value
V	The set of nodes
E	The edge set
P_i	The connectivity probability of section i
v_i	The speed level
μ_i	The average speed
σ_i	The deviation
R	The communication range
λ_i	The arrival rate of speed v_i
λ	The total arrival rate
p_i	The frequency of the occurrence of velocities at all levels
s	The distance between the last vehicle of the front platoon and the first vehicle of the platoon behind
n	The number of vehicles
L	The road section's length
N_{gap}	There are a disconnection gaps exist over the section H
$N_{platoon}$	The average number of platoons in a single lane
$F_c(n)$	The transmission costs of a packet along the path when it is not successfully delivered to the destination
h_i	The number of hops in the current road section
d_i	The maximum distance in the sender's i th hope
d_r	The mean of the maximum distance per hop
$N(d_i)$	The number of vehicles within the radius d_i
x_i	The distance of the node from its furthest neighbor within the one-hop communication range in the same lane
y_i	The distance of the node from its furthest neighbor within the one-hop communication range in the neighboring lane
(x_c, y_c)	The predicted location of the neighbor
x_c	The horizontal coordinate of the predicted location
y_c	The vertical coordinate of the predicted location
l	The moving distance of the node
t_c	The current moment
T_b	The moment of previous data transmission
v_c	The speed of the node at T_b
θ	The node's moving direction

PTCCR, where the optimal path from source to destination is selected dynamically.

A. ASSUMPTIONS

- There is an IoV environment in the typical urban region consisting of several road sections and intersections. Each of the road sections has multiple lanes and the vehicles drive along different directions.
- Each vehicle can determine its location and speed using the global positioning system (GPS). It can also acquire the destination's location from the position management system.
- All vehicles are able to obtain the information of their neighbors (e.g., speed, acceleration and location) from the periodically transmitted Hello packet.
- In order to choose a route globally, the city's map is abstracted into a directed graph consisting of streets,

$G(V, E, w)$, where V is the set of the node. Each edge $i \in E$ has a weight $0 < P_i < 1$, where P_i denotes the connectivity probability of section i .

B. MULTI-LANE CONNECTIVITY PROBABILITY

The multi-hop forwarding strategy is adopted in this subsection to obtain the accurate formula of the connectivity probability of a road section (i.e. the road between two intersections). Assume that the observer is located at any point in the urban road with free traffic flow. It has been proven in [22] that vehicular speed follows the normal distribution under the free traffic flow. For the speed of vehicle v_i , its probability density function is:

$$f_v(v_i) = \frac{1}{\sqrt{2\pi}\sigma_i} e^{-\frac{(v_i-\mu_i)^2}{2\sigma_i^2}}, \quad (1)$$

where μ_i and σ_i denote the average speed and standard deviation.

The statistical property of platoon is introduced to determine the expression of connectivity probability under the multi-lane scenario. The platoon is seen as a special vehicle and the vehicles in it can communicate with one another. Moreover, platoon members can communicate with the platoon head directly or indirectly. From the work in [23], it is learned that the number of vehicles which pass the observer per unit time follows the Poisson distribution, and the interval of their arrival time follows the exponential distribution. We assume there are m speed levels $v_i, i = 1, 2, \dots, m$, all of which are independent identically distributed and independent of their arrival time. Let R denote the communication range, λ_i denote the arrival rate of speed v_i , and $p_i = \frac{\lambda_i}{\lambda}$ denote the frequency of the occurrence of velocities at all levels.

1) If the platoon in a single lane has M speeds, the direct connectivity probability of this platoon is [24]:

$$p_c = \sum_i p_i p_{vi}(r_0) = \sum_i \frac{\lambda_i}{\lambda} (e^{-\lambda'_i} - \sum_{n=0}^k \frac{e^{-\lambda'_i}}{n!} \gamma(n+1, r_0 n \lambda'_i - \lambda'_i)) \quad (2)$$

The number of vehicles in road section H with a speed of follows the Poisson distribution of order $\lambda'_i = \frac{L\lambda_i}{v_i}$. The connectivity probability of these vehicles is:

$$p_{vi}(r_0) = e^{-\lambda'_i} - \sum_{n=0}^k \frac{e^{-\lambda'_i}}{n!} \gamma(n+1, r_0 n \lambda'_i - \lambda'_i), \quad (3)$$

where $r_0 = \frac{R}{L}$, $r_0 \in L_k(\infty)$, $k = 1, \dots, \infty$, $L_k(\infty) = [\frac{1}{k+1}, \frac{1}{k}]$ and $\gamma(n, x) = \int_0^x t^{n-1} e^{-t} dt$.

In Figure 1, the traffic flows of platoon with different speeds in a single lane are equivalent to the combination of traffic flows with a single speed at different lanes. Consider the scenario of a road with different levels of vehicular densities, where vehicles drive freely. The vehicles in a single lane are divided into several platoons. Two neighboring platoons cannot communicate with each other without

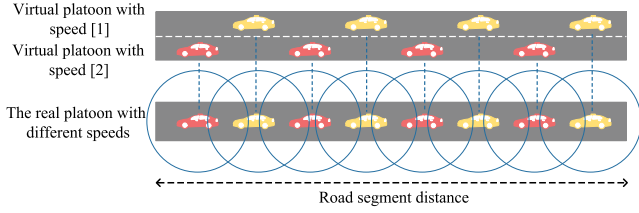


FIGURE 1. Workshop distance distribution between vehicles with two speed levels.

relay of vehicles in other lanes if the interval between them exceeds the vehicle's communication range. From the work in [25], [26], it is learned that the probability density function of the interval between two platoons is:

$$f(s) = pr[s|s > RC] = \frac{\lambda \sum_{i=1}^m \frac{p_i}{v_i} e^{-\lambda \sum_{i=1}^m \frac{p_i}{v_i} s}}{e^{-\lambda \sum_{i=1}^m \frac{p_i}{v_i} \gamma}}, \quad (4)$$

where s denotes the distance between the last vehicle of the front platoon and the first vehicle of the platoon behind.

2) Consider a road section with several platoons.

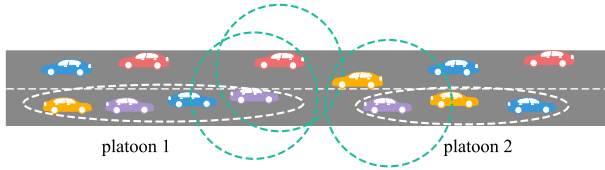


FIGURE 2. An example diagram of two platoon communications.

Assume that in Figure 2, there are two platoons (platoon 1 and platoon 2) in a lane, where the vehicles drive at a speed of v_i . The connectivity probability of vehicles in other lanes between the two platoons is:

$$p_{inter}(1, 2) = \int_R^\infty p_c f(s) ds \quad (5)$$

Taking inter-platoon collaboration into account, the probability that all vehicles across different lanes in this section are interconnected is:

$$P_i = \left(\int_R^\infty p_c f(s) ds \right)^{E(Pr[N_{gap}=a|N(L)=n]) - 1} \quad (6)$$

Consider the scenario where there are several links disrupted in a section H of length L and n vehicles locating along this path follow a Poisson distribution. According to the work in [27], the probability density function is:

$$Pr[N_{gap} = a|N(L) = n] = \left[\frac{1+n}{a} \right] \sum_{i=a}^{\lfloor \frac{L}{R} \rfloor} (-1)^{i-a} \times \left[\frac{1+n-a}{i-a} \right] \left[1 - i\left(\frac{R}{L}\right) \right]^n \quad (7)$$

where R denotes the vehicle's communication radius, L denotes the road section's length, $N_{gap} = a$ indicates that there are a disconnection gaps exist over the section H .

Therefore, the number of platoons in a road section is:

$$N_{platoon} = E(Pr[N_{gap} = a|N(L) = n]) \quad (8)$$

Based on the inter-platoon collaborative connectivity probability, the probability that the vehicles across different lanes in section i are interconnected can be computed as:

$$P_i = (p_{inter}(1, 2))^{N_{platoon} - 1} \quad (9)$$

where P_i denotes that the probability of multiple lanes of vehicles connected to each other in section i , $N_{platoon}$ denotes the average number of platoons in a single lane.

C. PATH TRANSMISSION COSTS

In the street-based routing strategy, the route consists of a sequence of streets from source to destination. Figure 3 regards the net of roads in a city as a graph with connectivity probability as the weight. The path between source and destination is made up of several road sections. Assume the three backbone paths from source to destination are $A \rightarrow B \rightarrow D \rightarrow F$, $A \rightarrow C \rightarrow D \rightarrow F$ and $A \rightarrow C \rightarrow E \rightarrow F$. An optimal path is to be opted from the three choices for packet transmission. The weight of each road section is measured by connectivity, which is labeled in Figure 3.

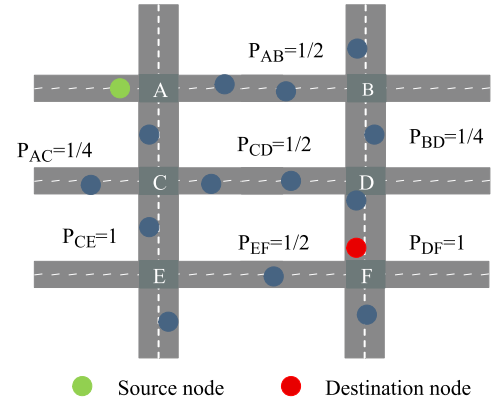


FIGURE 3. The network topology abstraction diagram of section connectivity probability.

The connectivity probability of a path can be computed as the product of connectivity probability of all road sections. Therefore, the path's connectivity probability is $1/2 * 1/4 * 1 = 1/8$ for $A \rightarrow B \rightarrow D \rightarrow F$, $1/4 * 1/2 * 1 = 1/8$ for $A \rightarrow C \rightarrow D \rightarrow F$, and $1/4 * 1 * 1/2 = 1/8$ for $A \rightarrow C \rightarrow E \rightarrow F$. Traditionally, the path with the highest connectivity probability is selected. But the three paths have the same probability of $1/8$. Hence, measuring the path's transmission performance with the connectivity probability alone is insufficient to find the optimal path, highlighting the need for new metrics.

Although the paths have the same connectivity probability, the expected transmission costs for a packet varies with the paths. If a low-quality link is in the vicinity of the destination and certain packet is lost on the link, this failure consumes the current transmission resources and wastes the consumption

of resources since data delivery from the source. Therefore, the consumption of network resources for the transmission of the same data traffic varies with the paths. This is called road section correlation. A road section correlation-based routing metric is proposed in this paper. In addition to the end-to-end connectivity probability, the new metric jointly considers the cost of packet transmission along the path and the consumption of resources.

Let $F_c(n)$ denote the transmission costs of a packet along the path when it is not successfully delivered to the destination. It can be computed as:

$$F_c(n) = h_1(1 - P_1) + (h_1 + h_2)P_1(1 - P_2) + \dots + (h_1 + \dots + h_n)P_1P_2\dots P_{n-1}(1 - P_n), \quad (10)$$

where P_i denotes the connectivity probability of the i th road section from source to destination, h_i denotes the number of hops in the current road section, d_i denotes the maximum distance in the sender's i th hope.

$$h_i = \lceil \frac{L}{d_i} \rceil \quad (11)$$

Given a street with a length of L , the average number of hops for data transmission is:

$$h = \lceil \frac{L}{d_r} \rceil, \quad (12)$$

where $\lceil \cdot \rceil$ denotes the round-up operation, $d_r = \text{mean}(d_1, d_2, \dots, d_n)$ represents mean of the maximum distance per hop.

This paper focuses on the scenario of urban road with two opposite lanes. The traffic on two lanes is mutually independent. Assume that all vehicles at same lane drive at the same speed of v_i , and the vehicles on the same lane follow the Poisson distribution. First, we analyze the probability density function of d_i in single lane. The location of vehicles follows the homogeneous Poisson distribution with the parameter as λd . Let $N(d_i)$ denote the number of vehicles within the radius d_i . The probability that there are k vehicles within the radius d_i is:

$$P(x = k) = \frac{(\lambda d_i)^k e^{-\lambda d_i}}{k!} \quad (13)$$

In the communication range, the probability that the data packet has a length of d_i at the i th hop is:

$$\begin{aligned} P(d_i) &= \frac{P(N(d_i) > 0)}{P(N(d_R) > 0)} \\ &= \frac{1 - e^{-\lambda d_i}}{1 - e^{-\lambda d_R}} \end{aligned} \quad (14)$$

The corresponding probability density function is:

$$f(d_i) = \frac{\lambda e^{-\lambda d_i}}{1 - e^{-\lambda d_R}}, \quad 0 < d_i < R \quad (15)$$

In what follow, we analyze the distribution of vehicles in the two-direction lanes based on the single-lane situation. Consider the double-lane scenario in Figure 4, the neighbors

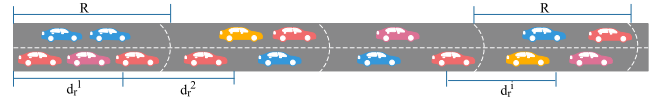


FIGURE 4. Two-lane schematic.

of a node can be classified into two categories, i.e. those in the same lane and those in the neighboring lane. Let x_i and y_i denote the distance of the node from its furthest neighbor within the one-hop communication range in the same lane and in the neighboring lane, respectively. Therefore, the one-hop transmission distance of the i th hop is $D_i = \max(x_i, y_i)$.

For the one-hop packet transmission, we have:

$$D_i = \max(x_i, y_i) \quad (16)$$

$$\begin{aligned} F_{D_i}(d_i) &= \Pr(D_i \leq d_i) = \Pr(x_i \leq d_i, y_i \leq d_i) \\ &= F_{X_i}(d_i) \cdot F_{Y_i}(d_i) \\ &= \frac{1 - e^{-d_i \lambda_1}}{1 - e^{-R \lambda_1}} \cdot \frac{1 - e^{-d_i \lambda_2}}{1 - e^{-R \lambda_2}} \end{aligned} \quad (17)$$

From Equation 17, it is learned that the expectation of D_i is:

$$E(D_i) = d_r = \int_0^R d_i \cdot dF_{D_i}(d_i) \quad (18)$$

In order to accurately reflect the costs of packet transmission from source to destination, let $PTC(n)$ (Path Transmission Costs) denote the transmission costs of packet along the path of n road sections. It represents the redundant transmission costs of each path after the packet is successfully delivered to the destined vehicle. $PTC(n)$ can be written as:

$$PTC(n) = \frac{F_c(n) + n \prod_{i=1}^n P_i}{\prod_{i=1}^n P_i}, \quad (19)$$

where P_i denotes the connectivity probability of the i th road section in the path from source to destination. The routing metric is designed to guarantee that the optimal path consists of the road sections which are in the vicinity of the destination and which have high link quality. If a low-quality link is in the vicinity of the destination and certain packet is lost on the link, this failure consumes the current transmission resources and wastes the consumption of resources since data delivery from the source. Therefore, the road section with a small $PTC(n)$ is incorporated into our transmission path.

Protocol Design: A novel street-centric routing protocol based on $PTC(n)$ is described in this sub-section. A succession of streets from source to destination constitutes a complete path.

D. PREDICT THE LOCATION OF NEIGHBOR NODES

1) THE SELECTION OF PATH INVOLVING INTERSECTIONS

Let P_{th} denote the threshold of the connectivity probability. And the connectivity probability of road sections each can be computed using the periodically exchanged beacon and the historical information. The connectivity probability of a path can be computed as the product of the connectivity

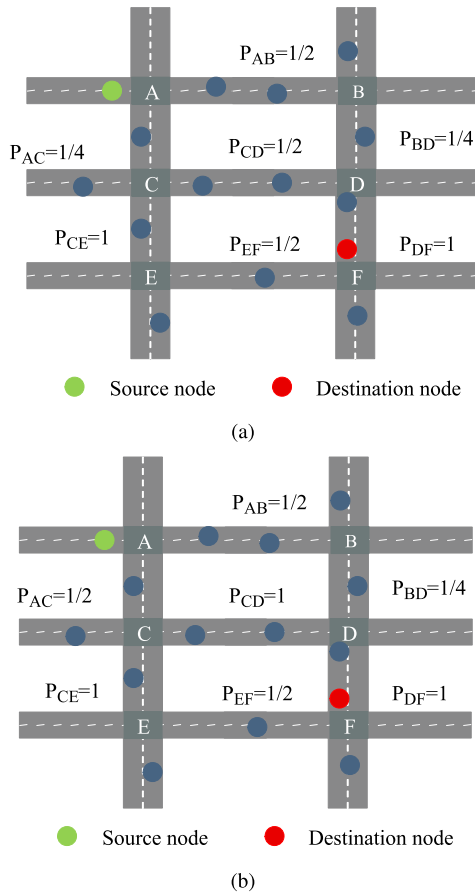


FIGURE 5. Network topology abstraction diagram.

probability of all road sections. For a path of n road sections, its connectivity probability is:

$$P_i(n) = P_1 P_2 \cdots P_n, \quad (20)$$

where P_i denotes the multi-lane connectivity probability of the i th road section. Consider the path of sections $A \rightarrow B \rightarrow C$, its connectivity probability is $P_{AB} \cdot P_{BC}$. Adding a new edge (road section) to the path reduces the connectivity probability. Therefore, the Dijkstra algorithm can be modified and the paths which satisfy Equation 21 is added to the set of paths S .

$$P_i(n) \geq P_{th}, \quad (21)$$

Choice about the road section is then made based on the number of elements in the set. If the set has one road section only, we select this section to forward data. If there is more than one element in the set, we compute the PTC from source to destination, and select the path with the smallest cost to forward data. If $S = \phi$, we select the path with the smallest redundant transmission cost to forward data.

- As shown in the Figure 5(a), we assume that $P_{th} = 1/8$, the sender is located at intersection A and the destination is at intersection F. The sender sends packet to the destination. First, the connectivity probability of the three candidate paths is all $1/8$, $A \rightarrow B \rightarrow D \rightarrow F$,

$A \rightarrow C \rightarrow D \rightarrow F$, $A \rightarrow C \rightarrow E \rightarrow F$. The three paths are thus added to set S , and $S = P_{ABDF}, P_{ACDF}, P_{ACEF}$. There are three elements in the set. The PTC from the current node to the destination needs to be computed, which is 13 for path $ABDF$, 11 for path $ACDF$ and 12 for path $ACDF$. The path $ACDF$ is finally selected for packet transmission.

- As shown in the Figure 5(b), we assume that $P_{th} = 1/4$, the sender is located at intersection A and the destination is at intersection F. The sender sends packet to the destination. First, the connectivity probability of the three candidate paths is computed and found to be less than the threshold P_{th} . The PTC from the current node to the destination needs to be computed, which is 13 for path $ABDF$, 11 for path $ACDF$ and 12 for path $ACEF$. The path $ACDF$ with the smallest transmission cost is finally selected for packet transmission.
- As shown in the Figure 5(b), we assume that $P_{th} = 1/2$, the sender is located at intersection A and the destination is at intersection F. The sender sends packet to the destination. First, the connectivity probability of the three candidate paths is computed as $P_{ABDF} = 1/8$, $P_{ACDF} = 1/2$ and $P_{ACEF} = 1/4$. Because only $P_{ABDF} > P_{th}$, the path $ACDF$ is added to set S and $S = P_{ACDF}$. It has one sole element, which is thus selected for packet transmission.

2) THE SELECTION OF NEXT HOP WITHIN ONE ROAD SEGMENT

Due to frequent changes of topology in IoV, the traditional greedy forwarding algorithm is unable to determine the information of neighboring nodes accurately. In consequence, it is likely that no appropriate node is available for next-hop transmission of a packet. For example, in forwarding the packet, the current neighbor might move out of the communication range or is no longer the closest neighbor to the destination. Whatever happens, the number of hops is increased or the packet is not forwarded successfully. In this context, a location prediction algorithm is needed to estimate the location of the neighbor in advance and then compute the location of the node when the packet is being forwarded.

The current location of the neighbor is predicted using the location prediction method and the packet is forwarded to the furthest neighbor. The location prediction method can be written as:

$$(x_c, y_c) = (x_i, y_i) + (s \cdot \cos\theta, s \cdot \sin\theta), \quad (22)$$

where (x_c, y_c) denotes the predicted location of the neighbor, x_c denotes the horizontal coordinate of the predicted location and y_c denotes the vertical coordinate of the predicted location, (x_i, y_i) denotes the location of the neighbor, x_i denotes the horizontal coordinate of the location and y_i denotes the vertical coordinate, l denotes the moving distance of the node and $l = (t_c - T_b) \cdot v_c$, t_c denotes the current moment, T_b denotes the moment of previous data

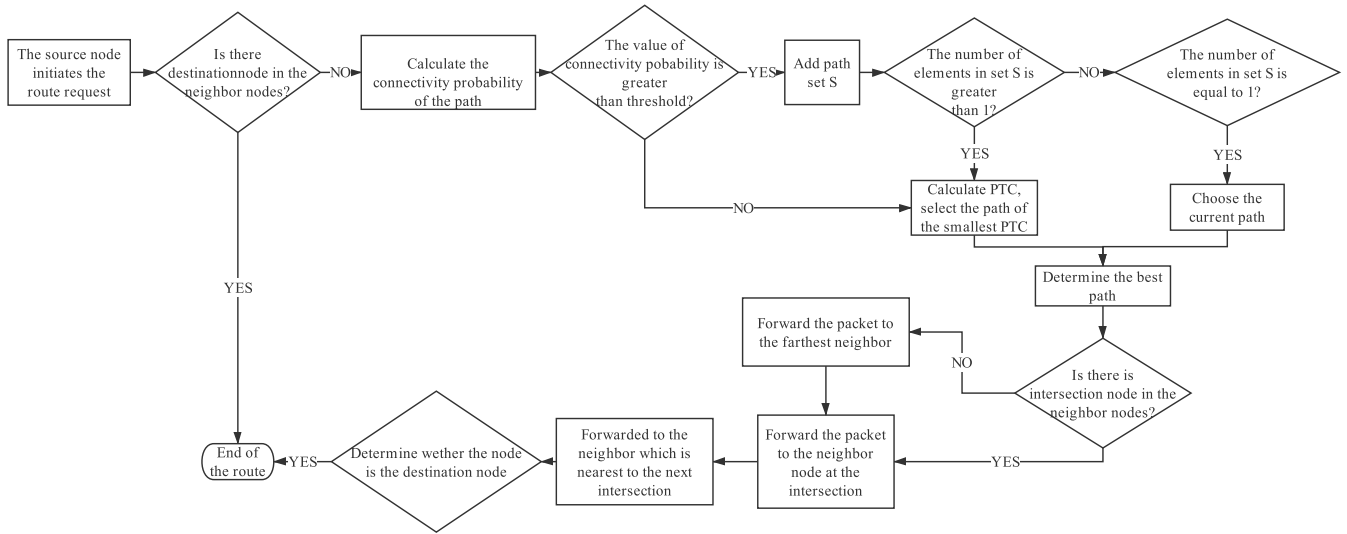


FIGURE 6. PTCCR protocol flowchart.

transmission, v_c denotes the speed of the node at T_b , θ denotes the node's moving direction.

The packet forwarding node predicts the furthest neighbor from it using the location prediction algorithm and then forwards the packet to this neighbor. If no appropriate neighbor is found, the packet is carried in the store-and-forward strategy and then forwarded until appropriate neighbor occurs.

3) OVERALL DESIGN OF THE PROTOCOL

Figure 6 shows the process of the proposed PTCCR protocol, details of which are given below.

- After obtaining the information of nodes, the sender issues a routing request to search for a path to the destination.
- It also checks whether the destination is its neighbor. If it is, the packet is forwarded to the destination and the routing process is terminated. Otherwise, the sender acquires the location of a destination and intersection from the GPS receiver. All intersections within the requested domain are flooded to determine the sequence of intersections in the path to destination.
- Afterwards, the multi-lane connectivity probability of each path to destination is computed and compared with the threshold.
- If the connectivity probability is above the threshold, add the path to set S and make choice about the road section based on the number of elements in the set. If the set has only one road section, choose it to forward the data. If it has two or more road sections, compute the redundant cost of transmission from source to destination. The path with the smallest cost is selected to forward data. If the set is empty, select the path with the smallest cost to forward data.
- The location of neighbors within the street is predicted using the location prediction method. The packet is

forwarded to the neighbor closest to the next intersection. The node which receives the packet compares the node label in the packet with its own label. If the two labels are identical, it means the node is the destination.

- The routing process ends.

IV. PERFORMANCE EVALUATION

A. SIMULATION ENVIRONMENT

The proposed analysis model and PTCCR algorithm are simulated in this sub-section. MATLAB is used to simulate the model for analysis of road connectivity. Consider the simulation scenario of multi-lane road without traffic light. The vehicles drive freely and independently. Simulation is focused on the relationship of the average number of tuples in a single lane and the multi-lane indirect connectivity probability with the vehicle's communication range and the road length.

In order to evaluate the performance of the proposed protocol PTCCR, it is compared with two intersection-based routing protocols, ICAR and TFOR. The real-world urban environment is simulated via MATLAB, where the vehicles are initialized across the map. According to the characteristics of IoV and the urban environment, the moving range of the vehicle is confined to the street and its speed follows uniform distribution between 30km/h and 60km/h. The data flow of IoV is generated through a constant bit rate (CBR). Each CBR connection is loaded into a pair of randomly selected vehicles. Media access control (MAC) is based on the distributed coordination function (DCF) technology. The Hello packet that all vehicles send at an interval of 1s at the same time are used to iteratively collect information of nodes within one-hop distance. Other simulation parameters are given in Table.2.

The following metrics are used to evaluate the routing performance.

TABLE 2. Simulation parameters.

parameter	parameter value
Simulator Area	2000m*1500m
MAC model	802.11DCF
Number of Nodes	100,120,140,...260
Communication range	250m
Channel Data Rate	2Mbps
Min. Speed	30km/h
Max. Speed	60km/h
Traffic Type	CBR
Packet size	512bytes
Beacon Interval	1s
Traffic Flow	Free-flow

- **Packet delivery ratio:** it is computed as the ratio of the total number of packets successfully received by all destined vehicles to the total number of packets sent by the source at the network layer.
- **Average end-to-end delay:** it is computed as the average length of time needed for a packet to be delivered from source to destination. Note that the carry time of the packet in the vehicle caused due to network partitioning is included.
- **Communication overhead:** it is the proportion of time spend in a routing.

Different urban environments are simulated in this paper by varying the following experimental parameters. And the unicast routing protocol is evaluated comprehensively in this way.

- **Number of vehicles:** it is varied to evaluate the influence of vehicle density on the routing protocol's performance.
- **Number of CBR connection pairs:** it is varied to evaluate the influence of data traffic on the routing protocol's performance.

B. SIMULATION RESULTS

1) AVERAGE NUMBER OF PLATOONS

Assume that the IoV invariably consist of one-way lanes with a length of $1\text{km} - 3\text{km}$. The vehicles drive at a constant speed of 60km/h . Figure 7 shows the variation of the average number of platoons with the vehicle's communication range and length of road section. The blue, green and yellow lines denote the number of nodes 20, 30 and 40, respectively. It can be observed from the figure that $N_{platoon}$ decreases with the vehicle's communication range. The reason is that when the vehicle's communication range increases, the vehicle is able to communicate with the node further away, resulting in a reduced number of platoons in average. And it also can be seen that $N_{platoon}$ increases with the length of road section. The reason is that the distance between vehicles increases with the length of road section, resulting in an increased number of platoons on average.

2) MULTI-LANE CONNECTIVITY PROBABILITY

The variation of multi-lane connectivity probability is shown in Figure 8 (a) and 8(b). It can be observed from

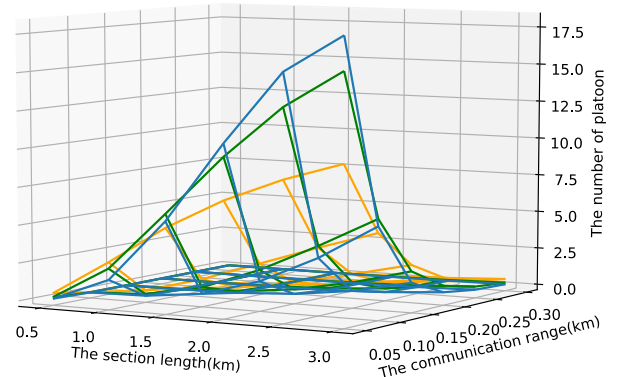
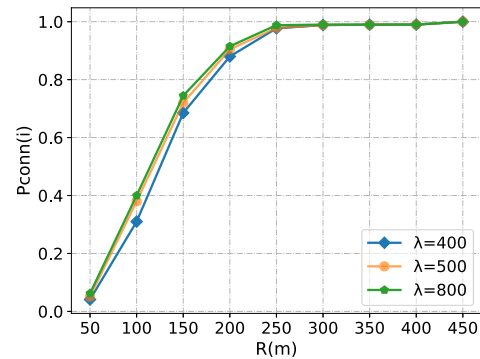
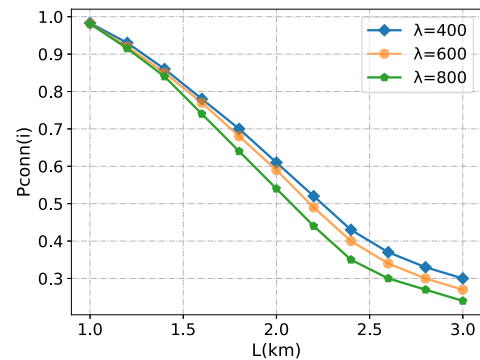
**FIGURE 7.** The number of platoon vs. communication range and section length.**(a)** The relationship between Connected probability and communication range.**(b)** The relationship between Connected probability and section length.**FIGURE 8.** The multi-lane connectivity probability.

Figure 8 (a) that the multi-lane connectivity probability increases with vehicle's communication range, as accords with the reality. Particularly, the multi-lane connectivity probability approximates to 1 when $R \geq 300\text{m}$. That is, all vehicles in a multi-lane road of 1 km can communicate with one another in the one or multi-hop manner. Figure 8 (b) shows the variation of the multi-lane connectivity probability with the length of road section under different overall arrival rates of the vehicle given a communication range of $R = 250$. It can be learned that the road section's

connectivity probability decreases with the road section's length. The reason is that the distance between vehicles increases with the road section's length, given the same number of vehicles. Meanwhile, the multi-lane connectivity probability increases with the vehicle's arrival rate. That is, the probability of communication between platoons increases with vehicular density.

3) INFLUENCE OF THE NUMBER OF VEHICLES ON THE ROUTING PERFORMANCE

Figure 9 (a) shows the packet delivery ratio under a varying number of vehicles given a random speed in the range from 30km/h to 60km/h. The packet delivery ratio increases for the three routing protocols, because the network connectivity improves with the number of vehicles, resulting in a smaller possibility of network partitioning for the vehicle. In the case of network sparsity, network connectivity becomes the bottleneck of the routing performance. Therefore, the packet delivery ratio increases considerably when the number of vehicles rises from 100 to 200. If the number of vehicles exceeds 200, channel contention becomes the major bottleneck of connectivity and the packet delivery ratio of the three routing protocols is stabilized. The proposed PTCCR protocol considers the cost of failed transmission of a packet, and optimizes network performance by fully exploiting network resources. Hence, the proposed protocol is superior to the other two ones in terms of packet delivery ratio.

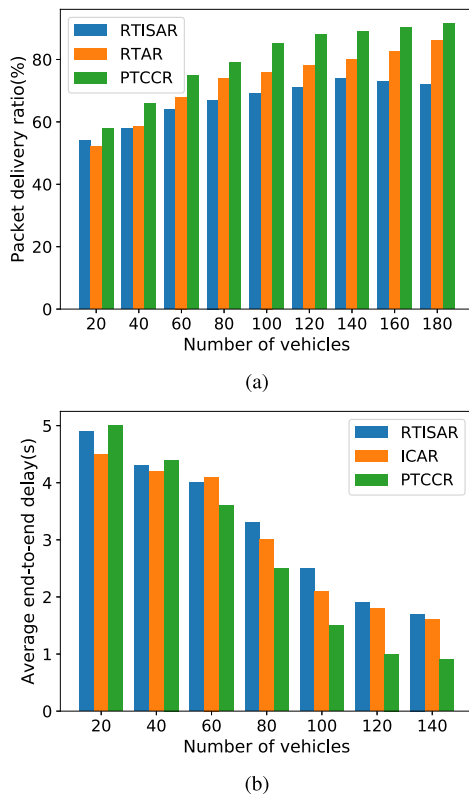


FIGURE 9. The packet delivery ratio and average end-to-end delay under a varying number of vehicles.

Figure 9 (b) shows the average end-to-end delay under a varying number of vehicles given a random speed in the range from 30km/h to 60km/h. Generally speaking, the average end-to-end delay is in reverse proportion to the number of vehicles for the three routing protocols. In the case of node sparsity, network connectivity becomes the major bottleneck of the routing performance. If the network is partitioned during packet transmission, the packet will be carried until an appropriate neighbor within the communication range is met, resulting in a seriously prolonged end-to-end delay in average. Due to this reason, the average end-to-end delay of the three routing protocols decreases considerably with the vehicular density when the number of vehicles rises from 100 to 200. After the number of vehicles exceeds 200, contention for channel among the vehicles emerges as the major contributor to delay. The average end-to-end delay of the three protocols thus approaches to a stable level. By jointly considering the frequent change of IoV topology and the consumption of network resources, the proposed PTCCR protocol enables the packet to be transmitted along the street efficiently and reduces the possibility of packet transmission under network partitioning.

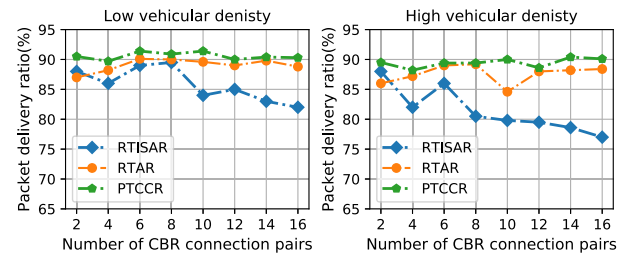


FIGURE 10. Packet delivery ratio vs. CBR connection in different vehicular density.

Figure 10 shows the packet delivery ratio under a varying number of CBR connection pairs given a random speed in the range from 30km/h to 60km/h in different vehicular density. In the low vehicular density, the packet delivery ratio is in reverse proportion to the number of CBR connection pairs for the three routing protocols. When the network is not saturated with data traffic, the limited size of the buffer queue in the vehicle is the major contributor to packet loss. Compared with RTISAR and RTAR, the packet delivery ratio of PTCCR is improved effectively. For example, PTCCR obtains 90.5% packet delivery ratio for 2 CBR connections. By contract, RTISAR and RTAR obtain 88% and 87% packet delivery ratio for 2 CBR connections. In the proposed PTCCR protocol, the dynamic information of neighboring streets that the vehicle collects at the intersection underlies the routing decision and the transmission costs are considered for efficient data forwarding. Improvement in the packet delivery ratio is achieved in this way. In the high vehicular density, the packet delivery ratio of PTCCR routing is better than that of RTISAR and RTAR routing. Compared with the low-vehicular density environment, the packet delivery ratio in the high-vehicular density is improved, for the following reasons: the higher the

density is, the higher the connectivity rate will be, and the better the packet delivery ratio will be.

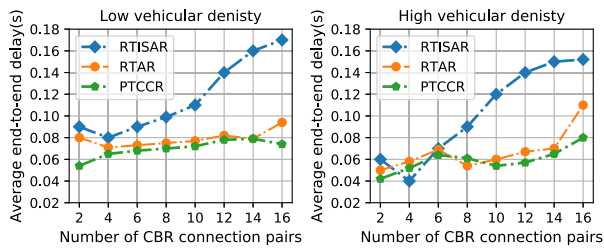


FIGURE 11. Average end-to-end delay vs. CBR connection in different vehicular density.

Figure 11 shows the average end-to-end delay under a varying number of CBR connection pairs in different vehicular density. Specifically, in low vehicular density, when CBR=8, the average end-to-end delay of PTCCR, RTISAR and RTAR is 0.07s, 0.0995s, 0.07s respectively. The reason is that PTCCR chooses the path segment with the highest connectivity to transmit the data packet, regardless of whether the path segment is far from the destination node, which increase end-to-end delay. When the number of CBR connection pairs continues to grow, the prolonged delay of packet in the queue causes further increase in the average end-to-end delay. In addition to taking the packet transmission costs into account, the proposed PTCCR protocol selects a globally optimal route for the packet by making the routing decision dynamically at the intersection. Therefore, PTCCR achieves improvement in the routing performance while minimizing the consumption of network resources. In the high vehicular density, we can see that the end-to-end delay of PTCCR is lower than that of RTISAR and RTAR. For example, when CBR=8, the average end-to-end delay of PTCCR, RTISAR and RTAR is 0.061s, 0.09s, 0.054s. However, the average end-to-end delay of RTISAR and RTAR routes increases greatly with the increase of CBR number, while the end-to-end delay of PTCCR routing tends to be stable.

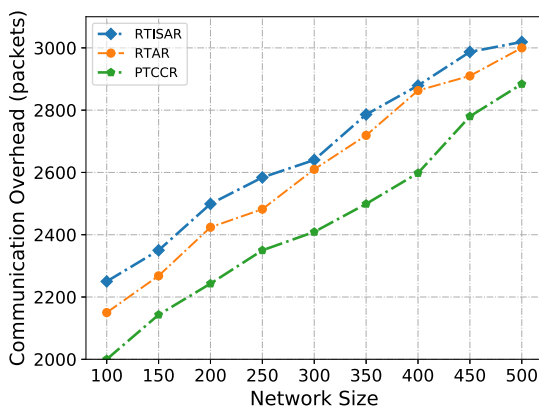


FIGURE 12. Communication overhead vs. network size.

Figure 12 describes the performance of PTCCR, RTISAR and RTAR in communication overhead as the number of

nodes increases. The number of nodes increases along with communication overhead because of the packet rate relating to the number of nodes. PTCCR gets the lowest communication overhead compared with RTISAR and RTAR. Specifically, PTCCR obtains 2409 packets when 300 nodes in the urban IoV. Instead, RTISAR and RTAR obtain 2640 and 2600 packets, respectively.

V. CONCLUSION

In this paper, considering the uniform distribution of vehicles and dynamic network topology in urban IoV, a path transmission costs based multi-lane connectivity routing protocol for urban IoV. First, we present the multi-lane connectivity probability model based on vehicle speed in a free-flow state, and then deduce the multi-lane connectivity probability in each road section. Second, considering that different positions of road sections will have an important impact on the routing performance, the transmission costs of data packets sent from the source node is quantitatively analyzed and used as the path selection metric. The path with the largest multi-lane connectivity probability and lowest PTC is selected as the optimal path. Last, the optimal neighbor nodes are determined by our proposed prediction method. Numerical results show that our proposed protocol outperform the RTISAR and RTAR protocols in terms of packet transmission ratio, average end-to-end delay and communication overhead. Our future work will investigate the possibility to introduce swarm intelligence into the intersection-based routing and employ the information centric networking with software defined functions. We will also explore the routings between different platoons or fleet of vehicles, which is popular in autonomous driving conditions.

REFERENCES

- [1] L. Liu, C. Chen, B. Wang, Y. Zhou, and Q. Pei, "An efficient and reliable QoF routing for urban VANETs with backbone nodes," *IEEE Access*, vol. 7, no. 1, pp. 38273–38286, 2019.
- [2] T. Qiu, X. Wang, C. Chen, M. Atiquzzaman, and L. Liu, "TMED: A spider-Web-like transmission mechanism for emergency data in vehicular ad hoc networks," *IEEE Trans. Veh. Technol.*, vol. 67, no. 9, pp. 8682–8694, Sep. 2018.
- [3] T. Qiu, J. Liu, W. Si, and D. O. Wu, "Robustness optimization scheme with multi-population co-evolution for scale-free wireless sensor networks," *IEEE/ACM Trans. Netw.*, vol. 27, no. 3, pp. 1028–1042, Jun. 2019.
- [4] J. Contreras-Castillo, S. Zeadally, and J. A. Guerrero-Ibañez, "Internet of vehicles: Architecture, protocols, and security," *IEEE Internet Things J.*, vol. 5, no. 5, pp. 3701–3709, Oct. 2018.
- [5] T. Qiu, R. Qiao, and D. Wu, "EABS: An event-aware backpressure scheduling scheme for emergency Internet of Things," *IEEE Trans. Mobile Comput.*, vol. 17, no. 1, pp. 72–84, Jan. 2018.
- [6] B. Karp and H. T. Kung, "GPSR: Greedy perimeter stateless routing for wireless networks," in *Proc. 6th Annu. Int. Conf. Mobile Comput. Netw.*, 2000, pp. 243–254.
- [7] S. K. Bhoi, P. K. Sahu, M. Singh, P. M. Khilar, R. R. Sahoo, and R. R. Swain, "Local traffic aware unicast routing scheme for connected car system," *IEEE Trans. Intell. Transp. Syst.*, to be published. doi: 10.1109/TITS.2019.2918161.
- [8] T. S. J. Darwish, K. A. Bakar, and K. Haseeb, "Reliable intersection-based traffic aware routing protocol for urban areas vehicular ad hoc networks," *IEEE Intell. Transp. Syst. Mag.*, vol. 10, no. 1, pp. 60–73, Jan. 2018.
- [9] C. E. Perkins and E. M. Royer, "Ad-hoc on-demand distance vector routing," in *Proc. 2nd IEEE Workshop Mobile Comput. Syst. Appl. (WMCSA)*, Feb. 2003, pp. 90–100.

- [10] C. Chen, L. Liu, T. Qiu, Z. Ren, J. Hu, and F. Ti, "Driver's intention identification and risk evaluation at intersections in the Internet of vehicles," *IEEE Internet Things J.*, vol. 5, no. 3, pp. 1575–1587, Jun. 2018.
- [11] C. Lochert, H. Hartenstein, J. Tian, H. Fussler, D. Hermann, and M. Mauve, "A routing strategy for vehicular ad hoc networks in city environments," in *Proc. Intell. Vehicles Symp.*, Jun. 2003, pp. 156–161.
- [12] B.-C. Seet, G. Liu, B.-S. Lee, C.-H. Foh, K.-J. Wong, and K.-K. Lee, "A-STAR: A mobile ad hoc routing strategy for metropolis vehicular communications," in *Proc. Int. Conf. Res. Netw.* Berlin, Germany: Springer, 2004, pp. 989–999.
- [13] C. Celes, F. A. Silva, A. Boukerche, R. M. de Castro Andrade, and A. A. F. Loureiro, "Improving VANET simulation with calibrated vehicular mobility traces," *IEEE Trans. Mobile Comput.*, vol. 16, no. 12, pp. 3376–3389, Dec. 2017.
- [14] Y. R. B. Al-Mayouf, N. F. Abdullah, O. A. Mahdi, S. Khan, M. Ismail, M. Guizani, and S. H. Ahmed, "Real-time intersection-based segment aware routing algorithm for urban vehicular networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 19, no. 7, pp. 2125–2141, Jul. 2018.
- [15] S. M. Hanshi, T.-C. Wan, M. M. Kadhum, and A. A. Bin-Salem, "Review of geographic forwarding strategies for inter-vehicular communications from mobility and environment perspectives," *Veh. Commun.*, vol. 14, pp. 64–79, Oct. 2016.
- [16] R. Sehgal, V. Nehra, and P. Dahiya, "Routing issues and related routing protocols in VANETs: A review," *IUP J. Comput. Sci.*, vol. 12, no. 3, pp. 7–44, 2018.
- [17] J. Liu, J. Wan, Q. Wang, P. Deng, K. Zhou, and Y. Qiao, "A survey on position-based routing for vehicular ad hoc networks," *Telecommun. Syst.*, vol. 62, no. 1, pp. 15–30, 2016.
- [18] S. Boussoufa-Lahlal, F. Semchedine, and L. Bouallouche-Medjkoune, "Geographic routing protocols for vehicular ad hoc NETWORKS (VANETs): A survey," *Veh. Commun.*, vol. 11, pp. 20–31, Jan. 2018.
- [19] J. Liu, X. Wang, G. Yue, and S. Shen, "Data sharing in VANETs based on evolutionary fuzzy game," *Future Gener. Comput. Syst.*, vol. 81, no. 1, pp. 141–155, 2018.
- [20] N. Alsharif and X. S. Shen, "iCARI: Intersection-based connectivity aware routing in vehicular networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Sydney, NSW, Australia, Jun. 2014, pp. 2731–2735.
- [21] I. A. Abbasi, B. Nazir, A. Abbasi, S. M. Bilal, and S. A. Madani, "A traffic flow-oriented routing protocol for VANETs," *EURASIP J. Wireless Commun. Netw.*, vol. 2014, no. 1, p. 121, 2014.
- [22] G. Sun, Y. Zhang, D. Liao, H. Yu, X. Du, and M. Guizani, "Bus-trajectory-based street-centric routing for message delivery in urban vehicular ad hoc networks," *IEEE Trans. Veh. Technol.*, vol. 67, no. 8, pp. 7550–7563, Aug. 2018.
- [23] R. Durrett, *Probability: Theory and Examples*, vol. 49. Cambridge, U.K.: Cambridge Univ. Press, 2019.
- [24] S. Kwon, Y. Kim, and N. B. Shroff, "Analysis of connectivity and capacity in 1-D vehicle-to-vehicle networks," *IEEE Trans. Wireless Commun.*, vol. 15, no. 1, pp. 8182–8194, Dec. 2016.
- [25] L. Liu, C. Chen, Z. Ren, and F. R. Yu, "An intersection-based geographic routing with transmission quality guaranteed in urban VANETs," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Kansas City, MO, USA, May 2018, pp. 1–6.
- [26] M. Zarei, A. M. Rahmani, and H. Samimi, "Connectivity analysis for dynamic movement of vehicular ad hoc networks," *Wireless Netw.*, vol. 23, no. 3, pp. 843–858, Apr. 2017.
- [27] S.-I. Sou and Y. Lee, "End-to-end performance for SCF-based vehicular routing over multiple communication gaps," *IEEE Commun. Lett.*, vol. 18, no. 6, pp. 1015–1018, Jun. 2014.



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