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DIR: diagonal-intersection-based routing protocol for vehicular ad hoc networks

Yuh-Shyan Chen · Yun-Wei Lin · Ci-Yi Pan

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Abstract In this paper, we present a diagonal-intersection-based routing (DIR) protocol for vehicular ad hoc networks. The DIR protocol constructs a series of diagonal intersections between the source and destination vehicles. The DIR protocol is a geographic routing protocol. Based on the geographic routing protocol, source vehicle geographically forwards data packet toward the first diagonal intersection, second diagonal intersection, and so on, until the last diagonal intersection, and finally geographically reach to the destination vehicle. For given a pair of neighboring diagonal intersections, two or more disjoint sub-paths exist between them. The novel property of DIR protocol is the auto-adjustability, while the auto-adjustability is achieved that one sub-path with low data packet delay, between two neighboring diagonal intersections, is dynamically selected to forward data packets. To reduce the data packet delay, the route is automatically re-routed by the selected sub-path with lowest delay. The proposed DIR protocol allows the mobile source and destination vehicles in the urban VANETs. Experimental results show that the DIR protocol outperforms existing solutions in terms of packet delivery ratio, data packet delay, and throughput.

Keywords Diagonal-intersection · Routing protocol · Wireless network · Intelligent transportation system · Vehicular ad hoc networks

Y.-S. Chen (✉) · C.-Y. Pan
Department of Computer Science and Information Engineering, National Taipei University, Taipei, Taiwan, ROC
e-mail: yschen@mail.ntpu.edu.tw

Y.-W. Lin
Department of Computer Science and Information Engineering, National Chung Cheng University, Chia-Yi, Taiwan, ROC
e-mail: jyneda@gmail.com

1 Introduction

The intelligent transportation system (ITS, [12]) is an emergent system to integrate with the advanced electronics, communications, information, and wireless sensor technology to provide safety and comfort of drivers in highway and urban. ITS is typically classified into two categories, road-to-vehicle communications (RVC) and inter-vehicle communications (IVC). Vehicular ad-hoc network (VANET) is a representative model for IVC. VANET becomes the important issue on providing safety and comfort of passengers. VANET is a restricted form of mobile ad-hoc network (MANET) to provide instant and emergency communications among nearby vehicles. VANET consists of several vehicle devices that contain the distributed operations, self-organization, and multi-hop transmission functions on mobile network environment. The VANET contains highly dynamic topology to support the high speed to vehicles.

VANET, although being a subclass of MANET, has unique characteristics which differentiate VANET from traditional MANET. VANETs are not constrained by scarce energy resources but are rather characterized by high mobility pattern and confined movement. This vehicular network is interconnected with vehicles which have wireless interface and adding antennas or additional communication devices does not cause major problems. Vehicular ad hoc networks (VANETs) have been investigated to be useful in road safety applications to support the intelligent transportation system (ITS) for drivers. Examples of e-safety applications are emergency vehicle approaching warning, vehicle-based road condition warning, intersection collision warning, and lane change warning, etc. To support the e-safety applications, VANETs can be used to alert drivers for e-safety applications by propagating the emergency warning to drivers behind a vehicle [2, 9, 20]. To encourage their development the US FCC commission allocated 75 MHz of dedicated short range communication, or DSRC [27], spectrum at 5.9 GHz to be used for vehicle-to-vehicle, or V2V, communications in VANET.

Routing protocols [7, 10, 16, 17, 19, 23, 24, 26] are emerging and necessary research problem in vehicular ad hoc network (VANETs). One of the challenges posed by this problem is how to develop an efficient routing result in VANETs characterized by the predictive mobility and highly changeable topology. This work attempted to develop a more efficient routing protocol in VANETs.

In this paper, we develop a diagonal-intersection-based routing (DIR) protocol for urban vehicular ad hoc networks. The DIR protocol constructs a routing path, while the DIR routing path is constructed by a series of diagonal intersections between the source and destination vehicles. The DIR protocol is a geographic based routing protocol. According to the geographic routing protocol, source vehicle sends data packet toward the first diagonal intersection, and then the second diagonal intersection, and so on, until toward the last diagonal intersection, and then reach to the destination vehicle. For given a pair of neighboring diagonal intersections, multiple sub-paths exist between them. One contribution of the proposed DIR protocol is the auto-adjustability, while the auto-adjustability is achieved by each sub-path is dynamically selected with consideration of the data packet delay. To reduce the data packet delay, the route is automatically re-routed by the selected sub-path with lowest delay. The DIR protocol with diagonal intersections is designed to allow the mobile source and destination vehicles exist in the urban VANETs. Experimental results show that the proposed DIR protocol outperforms existing solutions in terms of packet delivery ratio, data packet delay, and throughput. The distinctive character of DIR routing protocol is suitable for supporting some real-time applications, such as video streaming [3], video advertisement [25], and online game [18]. Such real-time applications should achieve high packet delivery ratio, throughput and low data packet delay. DIR routing protocol can satisfy the requirement of real-time applications.

The remainder of the paper is organized as follows. In Sect. 2, related works are described. Section 3 overviews the system model, motivation, and basic idea of the developed mechanisms. Section 4 describes the developed DIR protocol. Performance study is presented in Sect. 5. Finally, Sect. 6 concludes the paper.

2 Related works

Geographic routing protocol, such as GPSR [7], is developed for MANETs which always chooses the next hop closer to the destination. The geographic routing protocols are very efficient for the data delivery in MANETs [14, 21, 22], but may not be suitable for sparsely connected vehicular networks. Therefore, new and more efficient geographic routing protocols are recently developed for VANETs in the literatures [5, 6, 10, 23, 24]. First, Naumov et al. [16] incorporated a velocity vector of speed and direction to improve the GPSR protocol by accurately determining the location of a destination. Naumov et al. [16] also introduced AODV [19] with preferred group broadcasting (PGB) that reduces control message overhead by adaptive beaconing based on the number of nearby neighbors. Lochert et al. [11] proposed GPCR, a solution that does not relay on planarization of nodes by taking note of that fact that an urban map naturally forms a planar graph. Lee et al. [8] proposed GpsrJ+ protocol to improve GPCR in delivery ratio and hop count. Ma et al. [13] presented a path pruning algorithm that exploits the channel listening capability to reduce the number of hops in perimeter mode. All of these geographic routing protocols are developed to improve GPSR [7] to provide a suitable routing solution for sparsely connected vehicular networks. Mo et al. [15] proposed the MURU scheme which uses the calculated of expected disconnection degree (EDD) to determine which path is the most robust from source to destination. Granelli et al. [4] proposed the MORA scheme to utilize the distance to destination and the movement direction to choose a better vehicle for data forwarding. Jerbi et al. [6] proposed the GyTAR scheme which the forwarding vehicle greedily selects the next junctions by the vehicle density of a street to forwarding the data packet.

Zhao and Cao developed a vehicle-assisted data delivery (VADD) for VANETs in [26]. The data delivery in VANETs is more complicated by the fact that VANETs are highly mobile and frequently disconnected. To address this issue, VADD protocol adopt the idea of carry and forward, where a moving vehicle carries the packet until a new vehicle moves into its vicinity and forwards the packet. The idea of carry and forward is very attractive and suitable for the VANETs. In addition, Zhao and Cao [26] formally define the VADD delay model. Based on the existing traffic pattern and proposed VADD delay model, VADD protocol can find the best road to forward the packet with the lowest data delivery delay. The most important of VADD protocol is to select a forwarding path with the smallest packet delivery delay. Observe that VADD only considers how to find a path from a mobile vehicle to a coffee shop with a fixed location. However, it is not easily collect the in-time traffic pattern and information. By the inaccurate traffic information, VADD protocol possibly finds the road to forward the packet with the greater data delivery delay. VADD protocol is suitable for finding a path from a mobile source to a fixed-location destination.

To address this problem, Naumov and Gross presented a location-based routing scheme called connectivity-aware routing (CAR) for VANETs [17]. The main property of CAR protocol is the ability to not only locate positions of destinations but also to find connected paths between source and destination vehicles. These paths are auto-adjusted on the fly, with a new discovery process. Following VADD delay model [26], this work aims to develop a new routing protocol to improve the CAR protocol [17] in terms of packet delivery ratio, data packet delay, and throughput.

3 Preliminary

This section describes the system model, delay model, and assumptions, and then explains the basic idea, challenges, and main contributions of this work.

3.1 System model

In this paper, our new delay model is modified from the VADD delay model [26]. Before describing our new delay mode, we first review VADD delay model as follows. The packet delivery delay is formally defined in [26]. Let I_{xy} denote an intersection in a city environment. From VADD delay model [26], Denote $\overline{d}_{x_1y_1,x_2y_2}$ as the expected packet forwarding delay from to if $I_{x_1y_1}$ is a neighboring intersection of $I_{x_2y_2}$, such that

$$\overline{d}_{x_1y_1,x_2y_2} = (1 - e^{-R\cdot\rho_{x_1y_1,x_2y_2}}) \cdot \frac{l_{x_1y_1,x_2y_2}\cdot c}{R} + e^{-R\cdot\rho_{x_1y_1,x_2y_2}} \cdot \frac{l_{x_1y_1,x_2y_2}}{v_{x_1y_1,x_2y_2}},$$

where $r_{x_1y_1,x_2y_2}$ denotes the road from $I_{x_1y_1}$ to $I_{x_2y_2}$, $l_{x_1y_1,x_2y_2}$ is the Euclidean distance for $r_{x_1y_1,x_2y_2}$, $\rho_{x_1y_1,x_2y_2}$ is the vehicle density on $r_{x_1y_1,x_2y_2}$, and $v_{x_1y_1,x_2y_2}$ is the average vehicle velocity on $r_{x_1y_1,x_2y_2}$. R represents the transmission range of each vehicle, and c is a constant used to adjust expected packet forwarding delay to a more reasonable value. The vehicle density $\rho_{x_1y_1,x_2y_2}$ obtains from regular hello message exchange. Hello message records in terms of the number of knew vehicle and the collected velocity information of other vehicle in the same street. Each vehicle can collect the total number of vehicle in a street by accumulating the number of knew vehicle, and add the new information into hello message. Similarly, each vehicle can collect the average vehicle velocity $v_{x_1y_1,x_2y_2}$ from hello message. Although the information about vehicle density and averaged velocity is not real-time precise since the moving vehicles quickly enter and exit the street, the information can still assist us to make routing decision. A recursive function $D_{m,n} = \overline{d}_{m,n} + \sum_{j\in N(n)}(P_{n,j} \times D_{n,j})$ is formally defined in VADD delay model [26] to estimate the total expected packet forwarding delay. This work will modified the recursive function $D_{m,n}$ to construct our DIR protocol to significantly improve the packet forwarding delay than the CAR

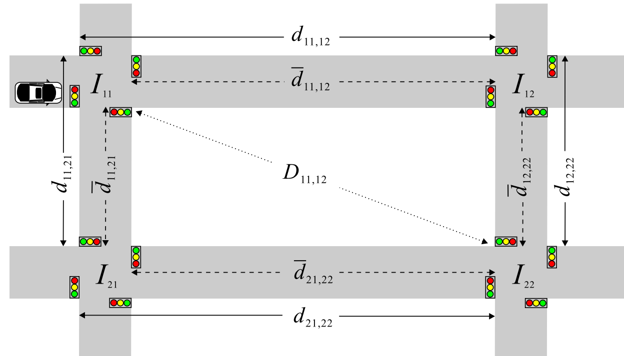

Fig. 1 Our delay model

protocol [17]. For instance, expected packet forwarding delay $\overline{d}_{11,12}, \overline{d}_{11,21}, \overline{d}_{12,22}$, and $\overline{d}_{21,22}$ are given in Fig. 1. Observe that, no traffic light is considered in $\overline{d}_{x_1y_1,x_2y_2}$.

In this paper, we modified VADD delay model by adding the model of the red/green light in the intersection. Let $C_{x_ay_b}$ denote the interval of time when light changes from red to green at intersection $I_{x_ay_b}$, and $\alpha_{x_ay_b}$ denote the ratio of the residual red light time in $C_{x_ay_b}$. Let $P_{x_ay_b}$ denote the probability of the green light when a vehicle just arrives at intersection $I_{x_ay_b}$. To consider the traffic light at intersection $I_{x_1y_1}$, denote $d_{x_1y_1,x_2y_2}$ as the expected packet forwarding delay from to if $I_{x_1y_1}$ is a neighboring intersection of $I_{x_2y_2}$, such that

$$d_{x_1y_1,x_2y_2} = P_{x_1y_1}\cdot \overline{d}_{x_1y_1,x_2y_2} + (1 - P_{x_1y_1}) \cdot C_{x_1y_1} \cdot \alpha_{x_1y_1}.$$

Let $D_{xy,x+1y+1} = \min\{d_{xy,x+1y} + d_{x+1y,x+1y+1}, d_{xy,xy+1} + d_{xy+1,x+1y+1}\}$. In this case, two disjoint sub-paths $I_{xy} \to I_{x+1y} \to I_{x+1y+1}$ and $I_{xy} \to I_{xy+1} \to I_{x+1y+1}$ are existed between I_{xy} and I_{x+1y+1}. That is, sub-path $I_{xy} \to I_{x+1y} \to I_{x+1y+1}$ is used in our DIR protocol if $d_{xy,x+1y} + d_{x+1y,x+1y+1} < d_{xy,xy+1} + d_{xy+1,x+1y+1}$. In addition, sub-path $I_{xy} \to I_{xy+1} \to I_{x+1y+1}$ is used in our DIR protocol if $d_{xy,xy+1} + d_{xy+1,x+1y+1} < d_{xy,x+1y} + d_{x+1y,x+1y+1}$. This provides the auto-adjustability capability of our DIR protocol. Our DIR protocol adopts expected packet forwarding delay instead of density and distance to select the diagonal intersection due to temporal network fragmentation problem. Figure 2 shows two common scenarios on road $r_{x_1y_1,x_2y_2}$ and $r_{x_3y_3,x_4y_4}$, where $l_{x_1y_1,x_2y_2} = l_{x_3y_3,x_4y_4}$. Road $r_{x_1y_1,x_2y_2}$ in Fig. 2(a) has higher network density ($\rho_{x_1y_1,x_2y_2} = \frac{14}{l_{x_1y_1,x_2y_2}}$) than road $r_{x_3y_3,x_4y_4}$ in Fig. 2(b) ($\rho_{x_3y_3,x_4y_4} = \frac{6}{l_{x_3y_3,x_4y_4}}$). However, road $r_{x_1y_1,x_2y_2}$ in Fig. 2(a) has the temporal network fragmentation problem. Packets should be carried to forward by a vehicle between different network fragmentations. The expected packet forwarding delay intensely grows since packets cannot transmit by multi-hop wireless transmission. Vehicles in Fig. 2(b) has well connectivity; therefore, packets can transmit with multi-hop wireless transmission manner. The expected packet forwarding delay can keep low growing. Observe that, the expected packet forwarding delay can effectively evaluate to selection the diagonal intersection. To consider the traffic light model, new expected packet forwarding delay times $d_{11,12}$, $d_{11,21}$, $d_{12,22}$, and $d_{21,22}$ are also illustrated in Fig. 1.

Therefore, let $D_{x_i y_i, x_j y_j} = D_{x_i y_i, x_i+1 y_i+1}$ if diagonal intersection of $I_{x_i y_i}$ is $I_{x_i+1 y_i+1}$ as shown in Fig. 3(a). In this work, we also consider $D_{x_i y_i, x_j y_j} = D_{x_i y_i, x_i+2 y_i+1}$ or $D_{x_i y_i, x_i+1 y_i+2}$ if diagonal intersection of $I_{x_i y_i}$ is $I_{x_i+2 y_i+1}$ or $I_{x_i+1 y_i+2}$, respectively. Figure 3(b) shows that if we consider $D_{x_i y_i, x_j y_j} = D_{x_i y_i, x_i+2 y_i+1}$, there are three different sub-paths $I_{x_i y_i} \rightarrow I_{x_i y_i+1} \rightarrow I_{x_i y_i+2} \rightarrow I_{x_i+1 y_i+2}$ or $I_{x_i y_i} \rightarrow I_{x_i y_i+1} \rightarrow I_{x_i+1 y_i+1} \rightarrow I_{x_i+1 y_i+2}$ or $I_{x_i y_i} \rightarrow I_{x_i+1 y_i} \rightarrow I_{x_i+1 y_i+1} \rightarrow I_{x_i+1 y_i+2}$ exist between $I_{x_i y_i}$ and $I_{x_i+1 y_i+2}$. Thus, $D_{x_i y_i, x_j y_j} = D_{x_i y_i, x_i+1 y_i+2} = \min\{d_{x_i y_i, x_i y_i+1} + d_{x_i y_i+1, x_i y_i+2} + d_{x_i y_i+2, x_i+1 y_i+2}, d_{x_i y_i, x_i y_i+1} + d_{x_i y_i+1, x_i+1 y_i+1} + d_{x_i+1 y_i+1, x_i+1 y_i+2}, d_{x_i y_i, x_i y_i+1} + d_{x_i y_i+1, x_i+1 y_i+1} + d_{x_i+1 y_i+1, x_i+1 y_i+2}\}$ is calculated to choose one sub-path with the low expected packet forwarding delay between $I_{x_i y_i}$ and $I_{x_i+1 y_i+2}$ from the three different sub-paths. The similar condition is occurred in Fig. 3(c) if considering $D_{x_i y_i, x_j y_j} = D_{x_i y_i, x_i+1 y_i+2}$, three different sub-paths $I_{x_i y_i} \rightarrow I_{x_i y_i+1} \rightarrow I_{x_i+1 y_i+1} \rightarrow I_{x_i+2 y_i+1}$ or $I_{x_i y_i} \rightarrow I_{x_i+1 y_i} \rightarrow I_{x_i+1 y_i+1} \rightarrow I_{x_i+2 y_i+1}$ or $I_{x_i y_i} \rightarrow I_{x_i+1 y_i} \rightarrow I_{x_i+2 y_i} \rightarrow I_{x_i+2 y_i+1}$ exist between $I_{x_i y_i}$ and $I_{x_i+2 y_i+1}$. The $D_{x_i y_i, x_j y_j} = D_{x_i y_i, x_i+2 y_i+1} = \min\{d_{x_i y_i, x_i y_i+1} + d_{x_i y_i+1, x_i+1 y_i+1} + d_{x_i+1 y_i+1, x_i+2 y_i+1}, d_{x_i y_i, x_i+1 y_i} + d_{x_i+1 y_i, x_i+1 y_i+1} + d_{x_i+1 y_i+1, x_i+2 y_i+1}, d_{x_i y_i, x_i+1 y_i} + d_{x_i+1 y_i, x_i+2 y_i} + d_{x_i+2 y_i, x_i+2 y_i+1}\}$ is calculated to choose one sub-path with the low expected packet forwarding delay between $I_{x_i y_i}$ and $I_{x_i+2 y_i+1}$ from the three different sub-paths.

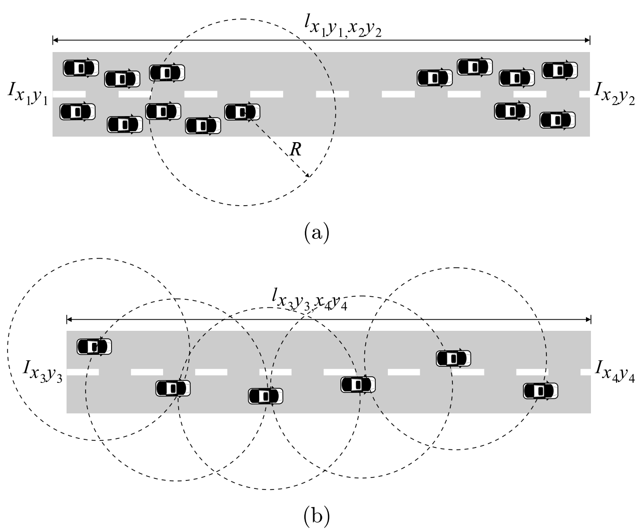

Fig. 2 (**a**) hight density with temporal network fragmentation problem, (**b**) low density with well connectivity

3.2 Basic idea and challenges

The CAR protocol [17] works with anchor points. In CAR protocol, a data packet is forwarding to a neighbor that is geographically closer to the destination. A neighbor closest to the next anchor point is chosen. The process continues until the packet reaches the destination. Therefore, CAR path is constructed by a series of anchor points, let $[I_1, I_2, \ldots, I_i, I_{i+1}, \ldots, I_m]$ denote the anchor-point list, where I_i is the i-th anchor point in the anchor-point list, where $1 \leq i \leq m$. Example is given in Fig. 4, anchor-point list $[I_{11}, I_{21}, I_{22}, I_{32}, I_{34}]$ is constructed between a pair of source and destination vehicles. The data packet is sent from source vehicle and geographically closer to I_{11}, I_{21}, I_{22}, I_{32}, and I_{34}. Finally, the data packet reaches to destination vehicle. As recalled $D_{xy,x+1y+1}$, $D_{11,22} = \min\{d_{11,21} + d_{21,22}, d_{11,12} + d_{12,22}\}$. It is possible to obtain a low packet forwarding delay to change the sub-path from $I_{11} \rightarrow I_{21} \rightarrow I_{22}$ to be $I_{11} \rightarrow I_{12} \rightarrow I_{22}$ if $d_{11,12} + d_{12,22} < d_{11,21} + d_{21,22}$. However, CAR protocol [17] follows the anchor-point list $[I_{11}, I_{21}, I_{22}, I_{32}, I_{34}]$ to forward data packet from

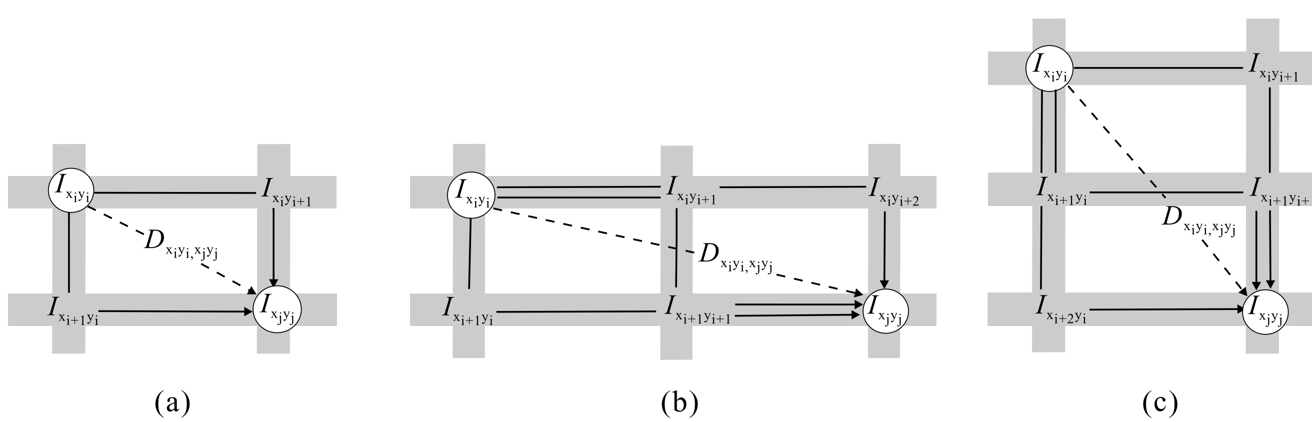

Fig. 3 $D_{x_i y_i, x_j y_j} =$ (**a**) $D_{x_i y_i, x_i+1 y_i+1}$, (**b**) $D_{x_i y_i, x_i+2 y_i+1}$, or (**c**) $D_{x_i y_i, x_i+1 y_i+2}$

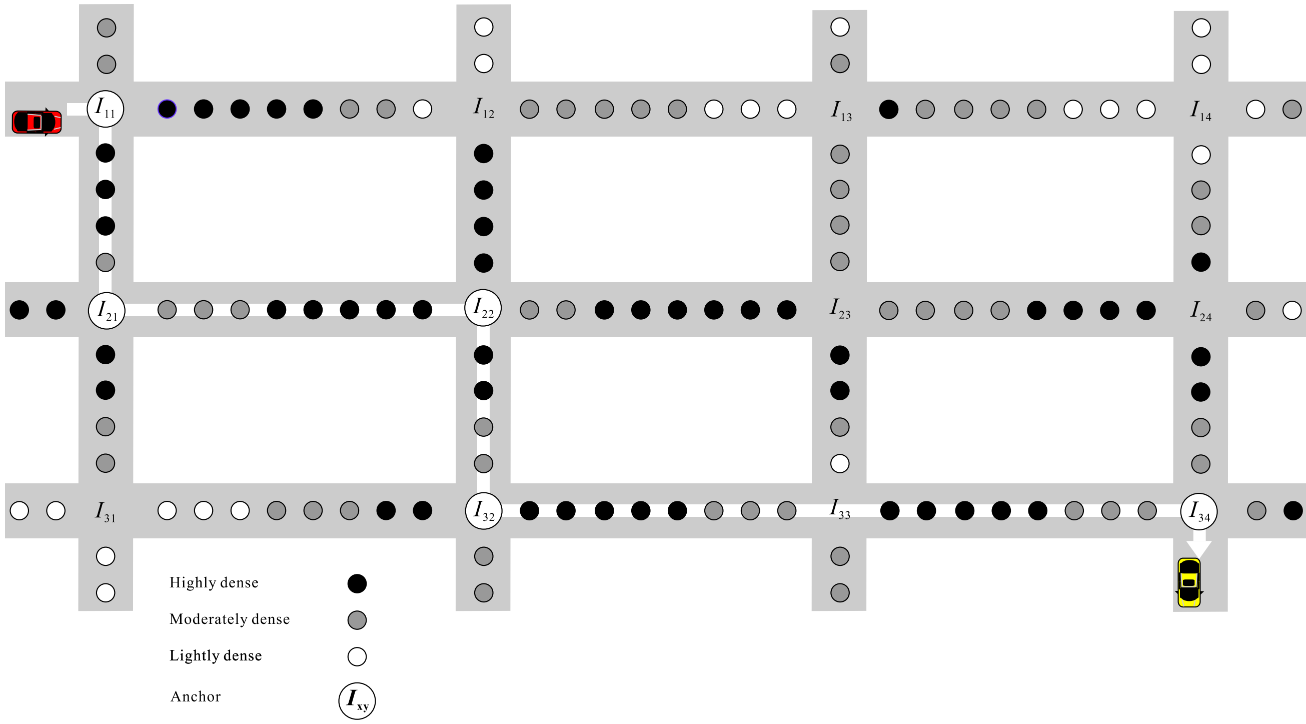

Fig. 4 Example of CAR protocol

the source to the destination even if $D_{11,22}$ is already changed from $d_{11,21} + d_{21,22}$ to $d_{11,12} + d_{12,22}$ due to the traffic status is rapidly changed. This condition is similarly occurred in $D_{22,34}$ in the routing path. This implies that if the route path has auto-adjustability capability to re-route from $I_{11} \rightarrow I_{21} \rightarrow I_{22}$ to $I_{11} \rightarrow I_{12} \rightarrow I_{22}$ and from $I_{22} \rightarrow I_{32} \rightarrow I_{33} \rightarrow I_{34}$ to $I_{22} \rightarrow I_{23} \rightarrow I_{33} \rightarrow I_{34}$ then a path with the lower packet forwarding delay is obtained.

To overcome the problem, we develop a diagonal-intersection-based routing (DIR) protocol for VANETs. Given a $[I_1, I_2, \ldots, I_m]$ from CAR protocol, a diagonal-intersection list $DIL = [DI_1, DI_2, \ldots, DI_n]$, where DI_i is the i-th diagonal intersection in DIL, where $1 \leq i \leq n$ and $n < m$. Following the sample example in Fig. 4, a diagonal-intersection list $DIL = [DI_1, DI_2, DI_3] = [I_{11}, I_{22}, I_{34}]$ is constructed, as shown in Fig. 5, between the same source and destination vehicles. The data packet is sent from source vehicle and geographically closer to I_{11}, I_{22}, and I_{34}. When a data packet is start at intersection I_{11}, the value of $D_{11,22}$ is re-calculated to determine the sub-path from I_{11} to I_{22}. If $D_{11,22} = d_{11,12} + d_{12,22}$, then a sub-path $I_{11} \rightarrow I_{12} \rightarrow I_{22}$ is determined. Sub-path $I_{11} \rightarrow I_{21} \rightarrow I_{22}$ is used if $D_{11,22} = d_{11,21} + d_{21,22}$. This condition is occurred in I_{22} to determine the sub-path from I_{22} to I_{34}, which is depended on the value of $D_{22,34}$. If $I_{22} \rightarrow I_{23} \rightarrow I_{33} \rightarrow I_{34}$ is used if $D_{22,34} = d_{22,23} + d_{23,33} + d_{33,34}$. In addition, another sub-path $I_{22} \rightarrow I_{32} \rightarrow I_{33} \rightarrow I_{34}$ is possibly used if $D_{22,34} = d_{22,32} + d_{32,33} + d_{33,34}$ is obtained. Example is given in Fig. 5, compared with CAR protocol [17], a new routing path, $I_{11} \rightarrow I_{12} \rightarrow I_{22} \rightarrow I_{23} \rightarrow I_{33} \rightarrow I_{34}$, with the lower packet forwarding delay is obtained. Efforts will be made in this work to develop a diagonal-intersection-based routing protocol to provide the auto-adjustability capability to search for a routing path with the lower packet forwarding delay.

4 DIR: diagonal-intersection-based routing protocol

The DIR: diagonal-intersection-based routing protocol is split into destination discovery, data forwarding, and path maintenance phases as follows.

4.1 Destination discovery

We provide two algorithms, A and B, for the destination discovery. Algorithm A is extracted $DIL = [DI_1, DI_2, \ldots, DI_n]$ from CAR's anchor-point list $[I_1, I_2, \ldots, I_m]$. Algorithm B is directly constructed $DIL = [DI_1, DI_2, \ldots, DI_n]$ without considering CAR's identified anchor-point list $[I_1, I_2, \ldots, I_m]$.

We first present algorithm A. Consider anchor-point list $[I_1, I_2, \ldots, I_m]$ is identified from CAR protocol [17], the main work of destination discovery phase is to construct a diagonal-intersection list $DIL = [DI_1, DI_2, \ldots, DI_n]$, where DI_i is the i-th diagonal intersection in DIL, where $1 \leq i \leq n$

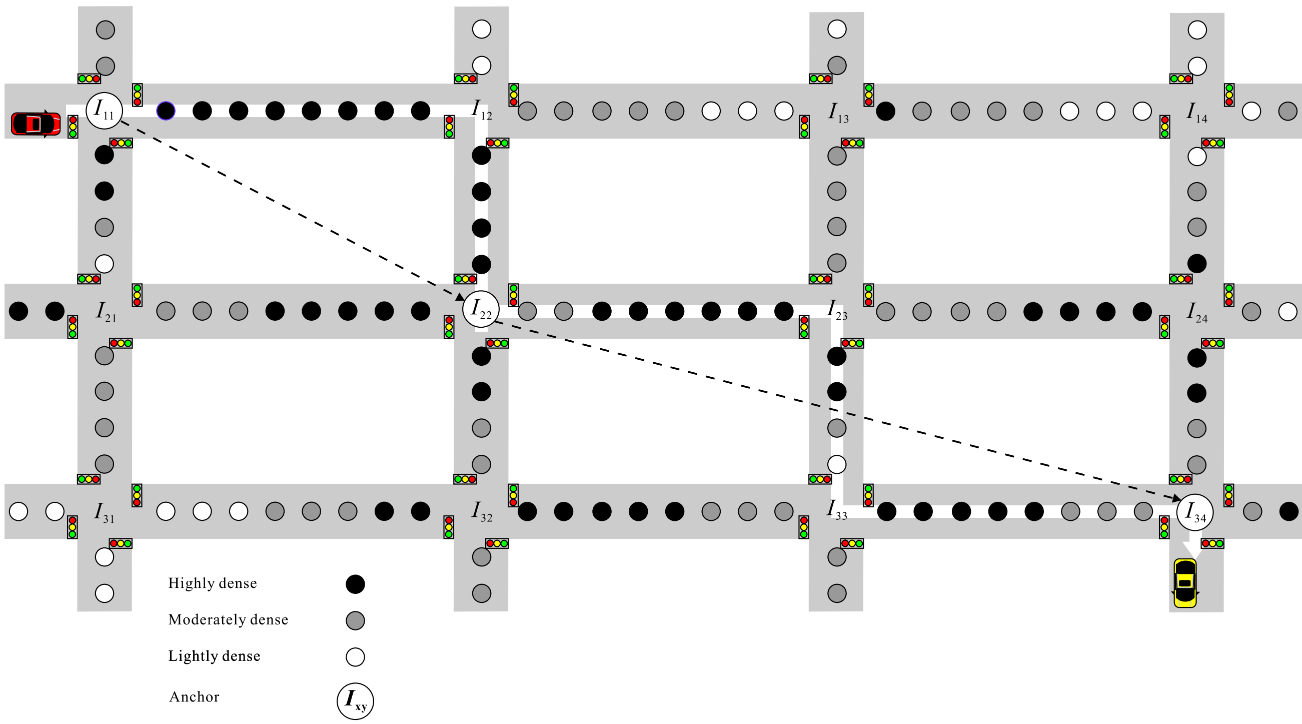

Fig. 5 Example of DIR protocol using algorithm A

and $n < m$. Without loss of generality, let anchor-point list $[I_{x_1y_1}, I_{x_2y_2}, \ldots, I_{x_my_m}]$ be $[I_1, I_2, \ldots, I_m]$. To construct a DIR route with least-delay, the algorithm A is given as follows.

S1. Initially, let $DI_1 = I_{x_1y_1} = I_1$, $I_{x_\alpha y_\beta} = I_{x_my_m} = I_m$. Set index variable i be 1, where variable i indicates the traversal index in anchor-point list $[I_{x_1y_1}, I_{x_2y_2}, \ldots, I_{x_my_m}]$. Let initial diagonal-intersetion list $DIL = [DI_1]$.

S2. Let $d_{I_{x_iy_i}}(I_{x_\alpha y_\beta}) = D_{x_iy_i, x'_iy'_i} + d_{I_{x'_iy'_i}}(I_{x_\alpha y_\beta})$. If the equation satisfies one of the following conditions,

$$\begin{cases} \text{if } |x_i - x'_i| = 1 \cap |y_i - y'_i| = 1 & \text{or} \\ \text{if } |x_i - x'_i| = 2 \cap |y_i - y'_i| = 1 & \text{or} \\ \text{if } |x_i - x'_i| = 1 \cap |y_i - y'_i| = 2, \end{cases}$$

and $I_{x'_iy'_i}$ is in $[I_{x_1y_1}, I_{x_2y_2}, \ldots, I_{x_my_m}]$, then insert $I_{x'_iy'_i}$ into DIL.

S3. If algorithm A cannot find a suitable diagonal intersection from $I_{x_iy_i}$, let $I_{x'_iy'_i} = I_{x_{i+1}y_{i+1}}$.

S4. Let $I_{x_iy_i} = I_{x'_iy'_i}$. If $I_{x_iy_i} \neq I_{x_my_m}$, then go to step S2. Otherwise, $DIL = [DI_1, DI_2, \ldots, DI_n]$ is extracted from $[I_{x_1y_1}, I_{x_2y_2}, \ldots, I_{x_my_m}]$, where $1 \leq i \leq n$ and $n < m$.

Observe that, step 3 is used to solve the case if algorithm A cannot find a suitable diagonal intersection from $I_{x_iy_i}$. In the worse case, our identified result is same as given $[I_1, I_2, \ldots, I_m]$. For example as shown in Fig. 4, $[I_{11}, I_{21}, I_{22}, I_{32}, I_{34}]$ is constructed by CAR protocol [17]. As illustrated in Fig. 5, $[DI_1, DI_2, DI_3] = [I_{11}, I_{22}, I_{34}]$ is extracted from $[I_{11}, I_{21}, I_{22}, I_{32}, I_{34}]$.

Algorithm B is directly constructed $DIL = [DI_1, DI_2, \ldots, DI_n]$ without using the input of CAR protocol. Let $d_{I_{x_1y_1}}(I_{x_my_m})$ denote cost of least-delay path from intersection $I_{x_1y_1}$ to $I_{x_my_m}$, where $I_{x_my_m}$ is the closest intersection to the destination. Then, $d_{I_{x_1y_1}}(I_{x_my_m}) = \min\{D_{x_1y_1,x_2y_2} + d_{I_{x_2y_2}}(I_{x_my_m})\}$, where $I_{x_2y_2}$ is one neighboring diagonal intersection of $I_{x_1y_1}$ and $D_{x_1y_1,x_2y_2}$ is the expected packet forwarding delay from $I_{x_1y_1}$ to $I_{x_2y_2}$. The dynamic programming is used to construct the least-delay path from intersection $I_{x_1y_1}$ to $I_{x_my_m}$.

S1. Initially, let $DIL = [I_{x_1y_1}]$ and $I_{x_iy_i} = I_{x_1y_1}$.

S2. If $d_{I_{x_iy_i}}(I_{x_my_m}) = \min\{D_{x_iy_i,x_jy_j} + d_{I_{x_jy_j}}(I_{x_my_m})\}$ and

$$\begin{cases} \text{if } |x_i - x_j| = 1 \cap |y_i - y_j| = 1 & \text{or} \\ \text{if } |x_i - x_j| = 2 \cap |y_i - y_j| = 1 & \text{or} \\ \text{if } |x_i - x_j| = 1 \cap |y_i - y_j| = 2 & \text{or} \\ \text{if } |x_i - x_j| = 1 \cap |y_i - y_j| = 0 & \text{or} \\ \text{if } |x_i - x_j| = 0 \cap |y_i - y_j| = 1 \end{cases}$$

and if $I_{x_jy_j}$ is more closer to destination than $I_{x_iy_i}$, then insert $I_{x_jy_j}$ into DIL. Observe that, two more cases of $|x_i - x_j| = 1 \cap |y_i - y_j| = 0$ and $|x_i - x_j| = 0 \cap |y_i -$

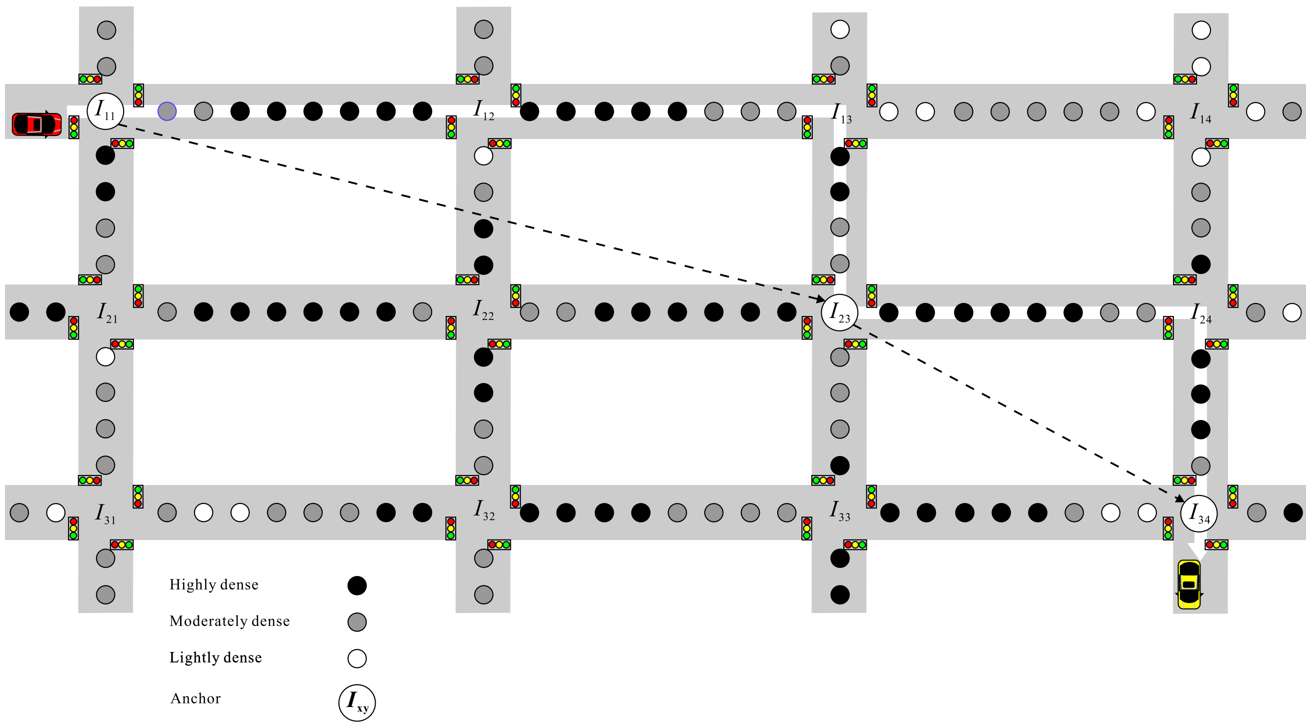

Fig. 6 Example of DIR protocol using algorithm B

$y_j| = 1$ are considered if algorithm B cannot find a diagonal intersection from $I_{x_i y_i}$.

S3. Let $I_{x_i y_i} = I_{x_j y_j}$. If $I_{x_i y_i} \neq I_{x_m y_m}$, then go to step S2, where $I_{x_m y_m}$ is the closest intersection to the destination. Otherwise, go to step S4.

S4. $DIL = [DI_1, DI_2, \ldots, DI_n]$ is constructed, where $1 \leq i \leq n$.

For example as given in Fig. 6, we initially have $[DI_1] = [I_{11}]$, $d_{I_{11}}(I_{34}) = \min\{D_{11,22} + d_{I_{22}}(I_{34}), D_{11,23} + d_{I_{23}}(I_{34}), D_{11,32} + d_{I_{32}}(I_{34})\}$, I_{23} is selected and appended into $[DI_1, DI_2] = [I_{11,} I_{23}]$. Finally, $[DI_1, DI_2, DI_3] = [I_{11,} I_{23}, I_{34}]$ is constructed by algorithm B, which is not obtained from CAR's $[I_{11}, I_{21}, I_{22,} I_{32,} I_{34}]$.

4.2 Data forwarding

Given that $DIL = [DI_1, DI_2, \ldots, DI_i, DI_j, \ldots, DI_n]$ has been constructed by the destination discovery phase, data forwarding operation between DI_i and DI_j is described as follows, where $1 \leq i, j \leq n-1$. Specially, if $I_{x_i y_i} = DI_i$ and $I_{x_j y_j} = DI_j$, and we have the following limitation in this work.

$$\begin{cases} |x_i - x_j| = 1 \cap |y_i - y_j| = 1 & \text{or} \\ |x_i - x_j| = 2 \cap |y_i - y_j| = 1 & \text{or} \\ |x_i - x_j| = 1 \cap |y_i - y_j| = 2. & \end{cases}$$

This is because that the link cost and traffic information between $I_{x_i y_i}$ and $I_{x_j y_j}$ is needed to maintain at $I_{x_i y_i}$ by sending control messages through any possible sub-paths between $I_{x_i y_i}$ and $I_{x_j y_j}$. It is surely that more different sub-paths exist between $I_{x_i y_i}$ and $I_{x_j y_j}$ to obtain more lower expected packet forwarding delay if we relax this limitation as $|x_i - x_j| = \alpha \cap |y_i - y_j| = \beta$, where α and $\beta \geq 2$. However, this control message cost is high. To keep the low message overhead, we only consider this limitation in this paper. Observe that DIR protocol does not consider the case of $|x_i - x_j| = 0$ or $|y_i - y_j| = 0$. There exist multi-paths from a pair of adjacent intersections, $I_{x_i y_i}$ and $I_{x_j y_j}$, where $|x_i - x_j| \neq 0$ and $|y_i - y_j| \neq 0$. DIR protocol tries to select one sub-path with low packet forwarding delay among multi-paths.

Thus, expected packet forwarding delay $D_{x_i y_i, x_j y_j}$ is re-calculated between $I_{x_i y_i}$ and $I_{x_j y_j}$. The data forwarding operation is adjusted based on the new re-calculated expected packet forwarding delay $D_{x_i y_i, x_j y_j}$. The main work of data forwarding operation is to determine a routing sub-path with lowest expected packet forwarding delay $D_{x_i y_i, x_j y_j}$ from $I_{x_i y_i}$ to $I_{x_j y_j}$. The data forwarding operation is formally given as follows if the data packet is at intersection $I_{x_i y_i}$.

S1. Data packet is at intersection $I_{x_i y_i}$. The link cost between $I_{x_i y_i}$ to $I_{x_j y_j}$ is periodically maintained at $I_{x_i y_i}$, such that node in $I_{x_i y_i}$ can keep the most accurate traffic

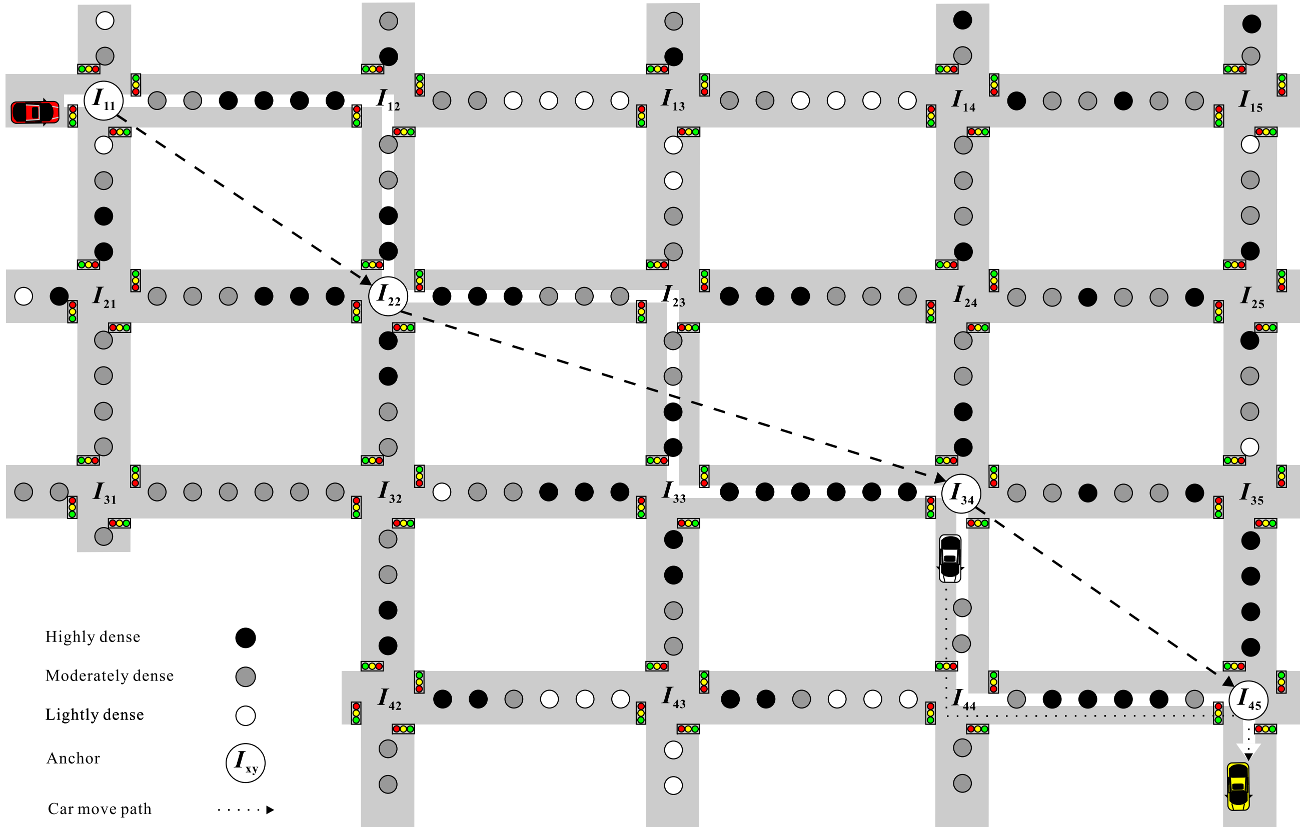

Fig. 7 Example of path maintenance

information to re-calculates $D_{x_i y_i, x_j y_j}$ as follows, where

$$\begin{cases} |x_i - x_j| = 1 \cap |y_i - y_j| = 1 & \text{or} \\ |x_i - x_j| = 2 \cap |y_i - y_j| = 1 & \text{or} \\ |x_i - x_j| = 1 \cap |y_i - y_j| = 2, & \text{as follows.} \end{cases}$$

S2. If $|x_i - x_j| = 1 \cap |y_i - y_j| = 1$, two different sub-paths $I_{x_i y_i} \to I_{x_i y_i+1} \to I_{x_i+1 y_i+1}$ or $I_{x_i y_i} \to I_{x_i+1 y_i} \to I_{x_i+1 y_i+1}$ exist between $I_{x_i y_i}$ and $I_{x_i+1 y_i+1}$. $D_{x_i y_i, x_j y_j} = D_{x_i y_i, x_i+1 y_i+1} = \min\{d_{x_i y_i, x_i y_i+1} + d_{x_i y_i+1, x_i+1 y_i+2}, d_{x_i y_i, x_i+1 y_i} + d_{x_i+1 y_i, x_i+1 y_i+1}\}$ is re-calculated to choose one sub-path with the low expected packet forwarding delay between $I_{x_i y_i}$ and $I_{x_i+1 y_i+1}$ from the two different sub-paths. Packet is forwarding along with this selected sub-path.

S3. If $|x_i - x_j| = 2 \cap |y_i - y_j| = 1$, three different sub-paths $I_{x_i y_i} \to I_{x_i y_i+1} \to I_{x_i y_i+2} \to I_{x_i+1 y_i+2}$ or $I_{x_i y_i} \to I_{x_i y_i+1} \to I_{x_i+1 y_i+1} \to I_{x_i+1 y_i+2}$ or $I_{x_i y_i} \to I_{x_i+1 y_i} \to I_{x_i+1 y_i+1} \to I_{x_i+1 y_i+2}$ exist between $I_{x_i y_i}$ and $I_{x_i+1 y_i+2}$. $D_{x_i y_i, x_j y_j} = D_{x_i y_i, x_i+1 y_i+2} = \min\{d_{x_i y_i, x_i y_i+1} + d_{x_i y_i+1, x_i y_i+2} + d_{x_i y_i+2, x_i+1 y_i+2}, d_{x_i y_i, x_i y_i+1} + d_{x_i y_i+1, x_i+1 y_i+1} + d_{x_i+1 y_i+1, x_i+1 y_i+2}, d_{x_i y_i, x_i y_i+1} + d_{x_i y_i+1, x_i+1 y_i+1} + d_{x_i+1 y_i+1, x_i+1 y_i+2}\}$ is re-calculated to choose one sub-path with the low expected packet forwarding delay between $I_{x_i y_i}$ and $I_{x_i+1 y_i+2}$ from the three different sub-paths. Packet is forwarding along with this selected sub-path.

S4. If $|x_i - x_j| = 1 \cap |y_i - y_j| = 2$, three different sub-paths $I_{x_i y_i} \to I_{x_i y_i+1} \to I_{x_i+1 y_i+1} \to I_{x_i+2 y_i+1}$ or $I_{x_i y_i} \to I_{x_i+1 y_i} \to I_{x_i+1 y_i+1} \to I_{x_i+2 y_i+1}$ or $I_{x_i y_i} \to I_{x_i+1 y_i} \to I_{x_i+2 y_i} \to I_{x_i+2 y_i+1}$ exist between $I_{x_i y_i}$ and $I_{x_i+2 y_i+1}$. $D_{x_i y_i, x_j y_j} = D_{x_i y_i, x_i+2 y_i+1} = \min\{d_{x_i y_i, x_i y_i+1} + d_{x_i y_i+1, x_i+1 y_i+1} + d_{x_i+1 y_i+1, x_i+2 y_i+1}, d_{x_i y_i, x_i+1 y_i} + d_{x_i+1 y_i, x_i+1 y_i+1} + d_{x_i+1 y_i+1, x_i+2 y_i+1}, d_{x_i y_i, x_i+1 y_i} + d_{x_i+1 y_i, x_i+2 y_i} + d_{x_i+2 y_i, x_i+2 y_i+1}\}$ is re-calculated to choose one sub-path with the low expected packet forwarding delay between $I_{x_i y_i}$ and $I_{x_i+2 y_i+1}$ from the three different sub-paths. Packet is forwarding along with this selected sub-path.

Example is given in Fig. 6, packet is forwarding along sub-path $I_{11} \to I_{12} \to I_{13} \to I_{23}$ and then packet is forwarding along sub-path $I_{23} \to I_{24} \to I_{34}$.

4.3 Path maintenance

If source and destination are fixed, the data forwarding is done based on the constructed $DIL = [DI_1, DI_2, \ldots, DI_n]$ in the data forwarding phase. However, if source and destination are mobile, then $DIL = [DI_1, DI_2, \ldots, DI_n]$ is needed

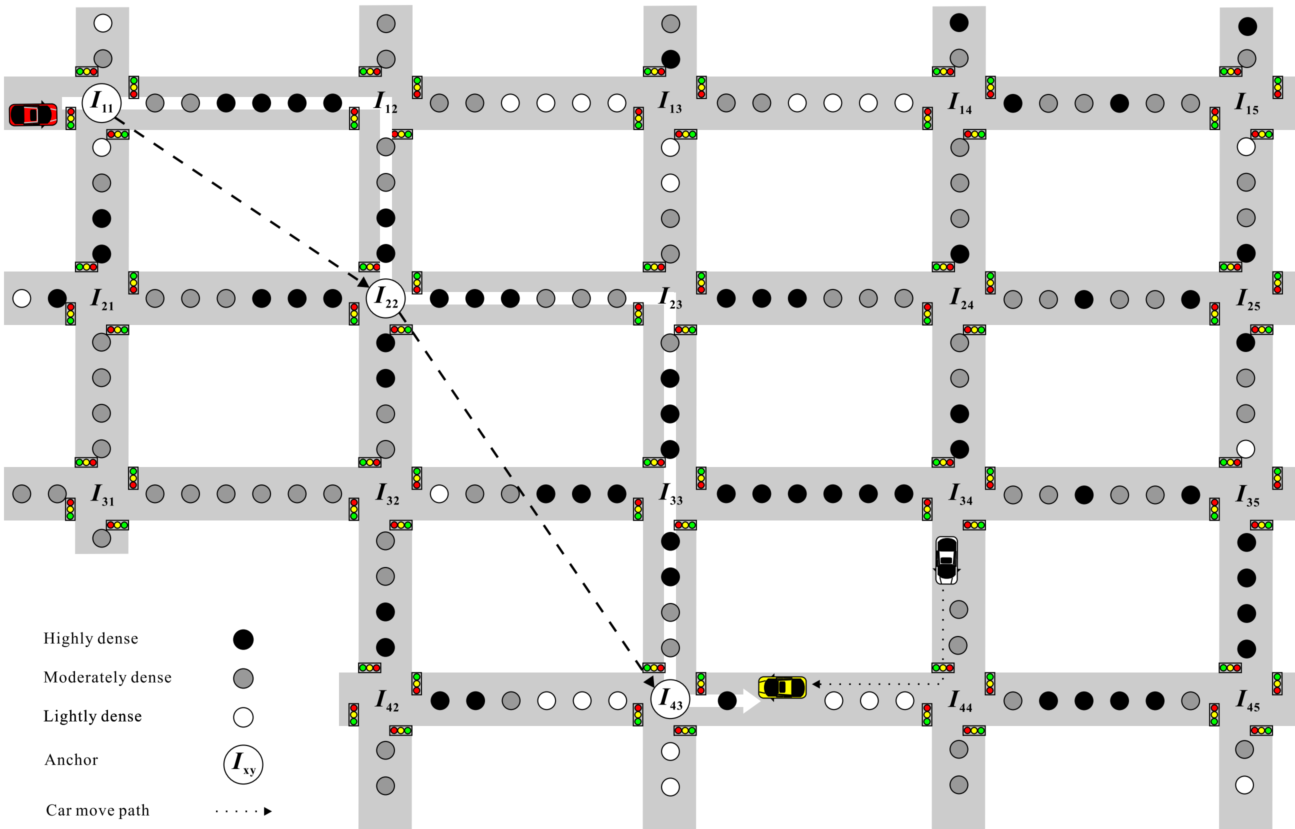

Fig. 8 Example of path maintenance

to be adjusted and maintained. In the following, we will describe how to adjust and maintain the *DIL* when source or destination are moving to different locations. Without loss of generality, we only investigate how to dynamically adjust the $DIL = [DI_1, DI_2, \ldots, DI_{n-1}, DI_n]$ to be new $DIL' = [DI'_1, DI'_2, \ldots, DI'_{m-1}, DI'_m]$ if the destination is moving to different location. The formal algorithm to have the adjusted DIL' is given as follows.

S1. If the destination is moving and far away the last $DI_{current\_last}$ in the current *DIL*, a new DL_{new_last} is identified and appended into *DIL*. Repeatedly perform S1 step until the destination is fixed. A new $DIL' = [DI'_1, DI'_2, \ldots, DI'_{m-1}, DI'_m]$ is constructed. Go to S3 step.

S2. If the destination is moving and near to a DI_j, where DI_i is in the current *DIL*, and DI_j is a diagonal-intersection of DI_i, then $DIL' = [DI_1, DI_2, \ldots, DI_i, DI_j]$ is constructed.

S3. A new DIL' is constructed.

Example is given in Fig. 7 if the destination is moving from I_{34} to I_{45}, $DIL' = [I_{11}, I_{22}, I_{34}, I_{45}]$ is constructed by adding I_{45} into $DIL = [I_{11}, I_{22}, I_{34}]$. Similar example is given in Fig. 8 if the destination is moving to I_{43}, $DIL' = [I_{11}, I_{22}, I_{43}]$ is obtained. Based on the descriptions, we may have the similar result if the source is moving to a different location; the details is omitted herein.

5 Simulation results

Our paper presents a diagonal-intersection-based routing (DIR) protocol in VANETs. To evaluate our DIR protocol, Naumov et al.'s CAR protocol [17] and our proposed DIR protocol are mainly implemented using NCTUns 4.0 simulator and emulator [1]. Our simulator considers a 4000 m × 4000 m square street area and adopted the random mobility model. Table 1 gives all simulation parameters.

Before discussing with the simulation results, some notations are defined. We first define *network density* (ND), ND is the average number of vehicles divided the maximum number of vehicles in a VANETs. The high probability of the data forwarding through vehicles will be if ND is large. Let P_{green_light} denote the probability of the green light when a vehicle arrives at each intersection, where $0 \leq P_{green\_light} \leq 1$. To discuss with the effect of P_{green_light}, all intersections are assumed to have the same P_{green_light} in the simulation discussion. Let $P_{traffic\_changed}$ denote the probability that the traffic status is changed between intersection I and I_n, where I_n is a neighboring intersection of I

and $0 \leq P_{traffic\_changed} \leq 1$. Observe that if the traffic status is changed between intersection I and I_n, it indicates that the different sub-path with the lower packet forwarding delay should be used to reduce the total packet delivery delay from the source to the destination. Basically, our DIR protocol improves more packet delivery delay if $P_{traffic\_changed}$ is large. In our simulation, the performance metrics to be observed are:

- The *packet delivery ratio* (PDR) is total number of packets successfully received by destination vehicle divided by the total number of packets sent by the source vehicle.
- The *packet delivery delay* (PDD) is the average time cost of data packet traveled from the source to the destination.
- The *message overhead* (MO) which includes both control and data messages is the amount of total packets transmitted by source vehicle.

Table 1 Simulation parameters

Parameter	Value
Simulation area	4000 m × 4000 m
Number of vehicles	60–600
Transmission range	250 m
Vehicle speed	10 or 60 km/h
Intersection distance	1 km
Data packet size	1400 bytes
Beacon interval	2 beacon/sec
Packet TTL	60 sec
Time of traffic sign	100 sec
Simulation time	300 sec

- The *throughput* (TP) is the total number of data packets the destination vehicle received per second.

An efficient routing protocol in a VANETs is achieved with a high PDR, low PDD, low MO, and high TP.

5.1 Packet delivery ratio (PDR)

The simulation results of PDR under various NDs, P_{green_light} and $P_{traffic\_changed}$ are shown in Figs. 9–11. Figure 9 shows that the observed PDR under various ND, where P_{green_light} and $P_{traffic\_changed}$ are fixed at 0.5. Figures 9(a) and (b) illustrate the average PDR under speed is 10 Km/h and 60 Km/h, respectively. For each case, the curve of DIR_B was higher than that of the DIR_A, and the curve of DIR_A was higher than that of CAR. The PDR was high where the ND is high. This is because that the higher network density provides more successful transmission opportunities for vehicles to forward message to the next vehicle more closer to destination. For the effect of ND, it was observed that when the moving speed is high, then the corresponding PDR of DIR_A, DIR_B, and CAR decreases.

Figures 10 shows the performance of the PDR under various P_{green_light}, where the ND and $P_{traffic\_changed}$ is fixed at 0.5 and speed is fixed at 10 Km/h and 60 Km/h. Similarly, the curve of CAR was lower than that of the DIR_A, and the curve of DIR_A was lower than that of DIR_B. It is observed that the higher P_{green_light} is, the higher the PDR will be. This is because that high P_{green_light} implies that a vehicle can more successfully pass the intersection. This possibly increases the value of PDR. For the effect of P_{green_light}, it was observed that when the average moving speed is high, then the corresponding PDR of DIR_A, DIR_B, and CAR decreases.

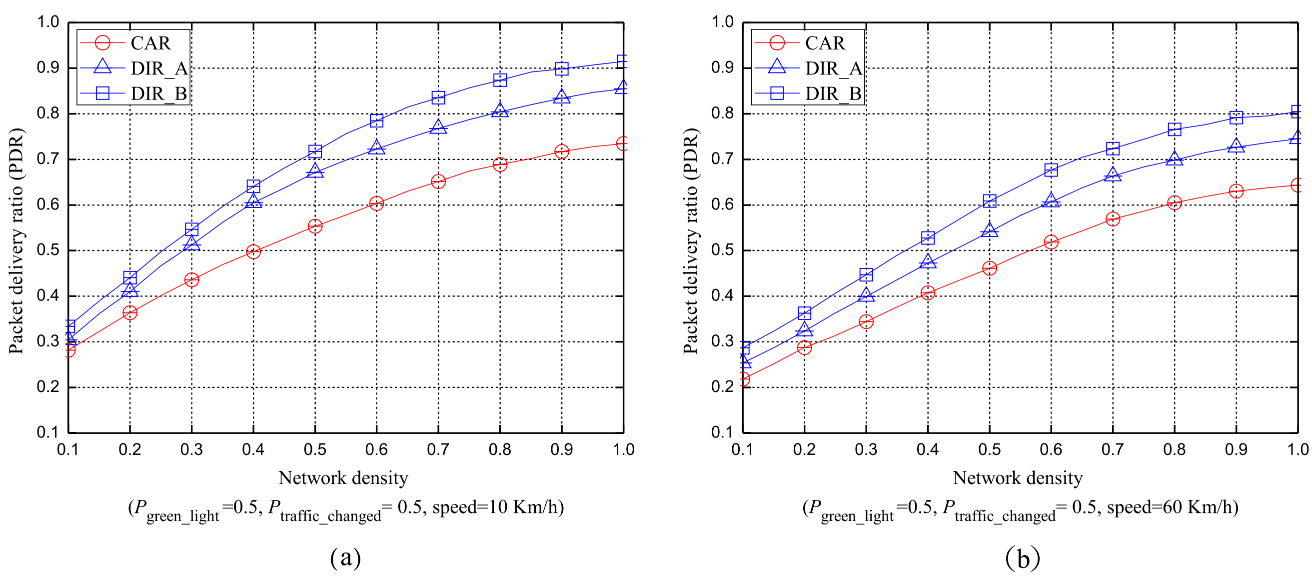

Fig. 9 Performance of the packet delivery ratio (PDR) vs. network density, where speed is fixed at (**a**) 10 Km/h and (**b**) 60 Km/h

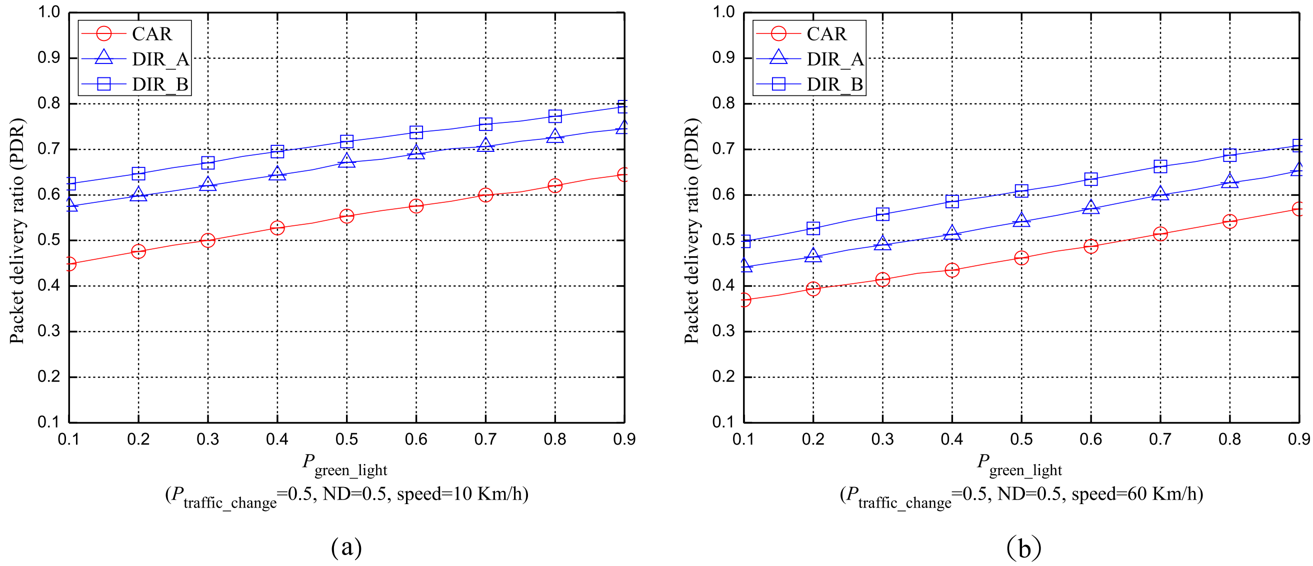

Fig. 10 Performance of the packet delivery ratio (PDR) vs. P_{green_light}, where speed is fixed at (**a**) 10 Km/h and (**b**) 60 Km/h

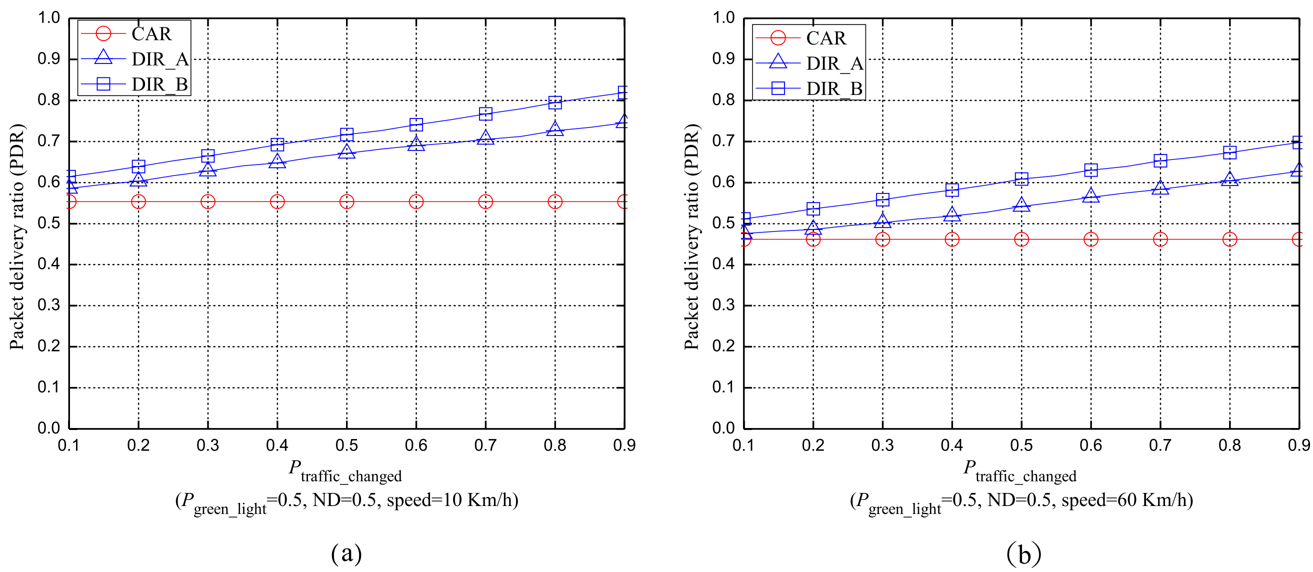

Fig. 11 Performance of the packet delivery ratio (PDR) vs. $P_{traffic\_changed}$, where speed is fixed at (**a**) 10 Km/h and (**b**) 60 Km/h

Figure 11 give the performance of the PDR under various $P_{traffic\_changed}$, where the ND and P_{green_light} are fixed at 0.5 and moving speed is fixed at 10 Km/h and 60 Km/h. The curve of CAR was lower than that of the DIR_A, and the curve of DIR_A was lower than that of DIR_B. For the curve of DIR_A and DIR_B, the higher $P_{traffic\_changed}$ is, the higher the PDR will be. This indicates that the design of CAR protocol does not consider the important factor of $P_{traffic\_changed}$. The PDR of DIR_A and DIR_B is high as the $P_{traffic\_changed}$ increases. But, the PDR of CAR is fixed as the $P_{traffic\_changed}$ increases. This implies that DIR protocol has better performance of PDR than CAR protocol. For the effect of $P_{traffic\_changed}$, it was observed that when the average moving speed is high, then the corresponding PDR of DIR_A, DIR_B, and CAR decreases.

5.2 Packet delivery delay (PDD)

The simulation results of the PDD under various ND, P_{green_light} and $P_{traffic\_changed}$ are shown in Figs. 12–14. Figures 12(a)(b) show the performance of the PDD for all possible ND (ranging from 0.1 to 1), where $P_{green\_light} = P_{traffic\_changed} = 0.5$ and the moving speed is fixed at 10 Km/h and 60 Km/h, respectively. For each case, the

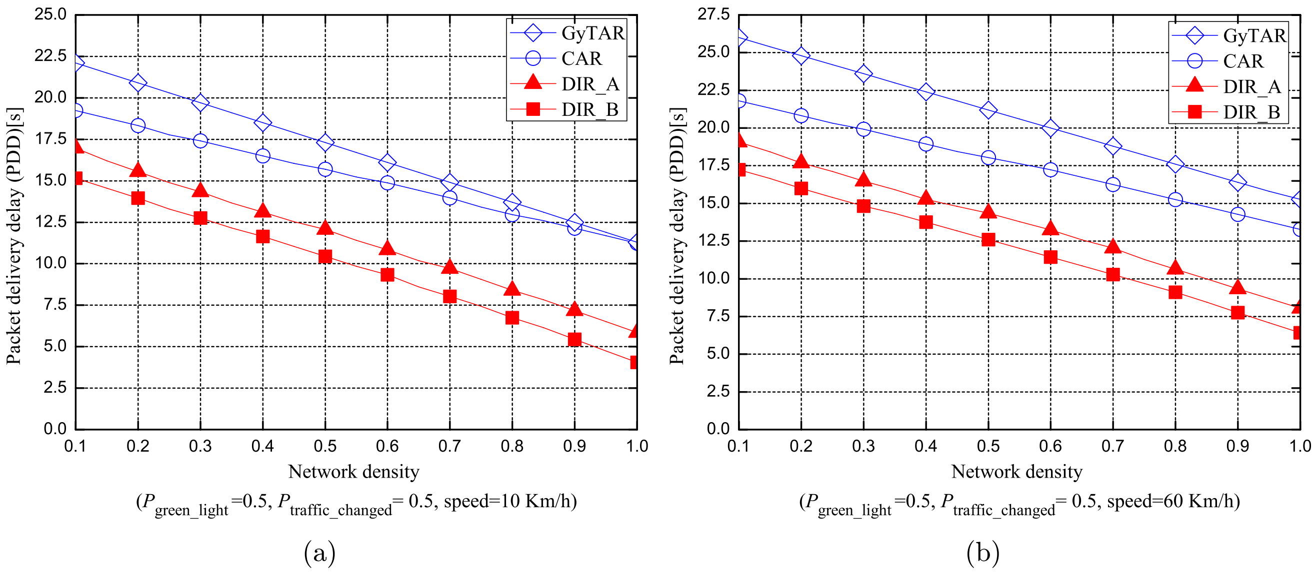

Fig. 12 Performance of the packet delivery delay (PDD) vs. network density, where speed is fixed at (**a**) 10 Km/h and (**b**) 60 Km/h

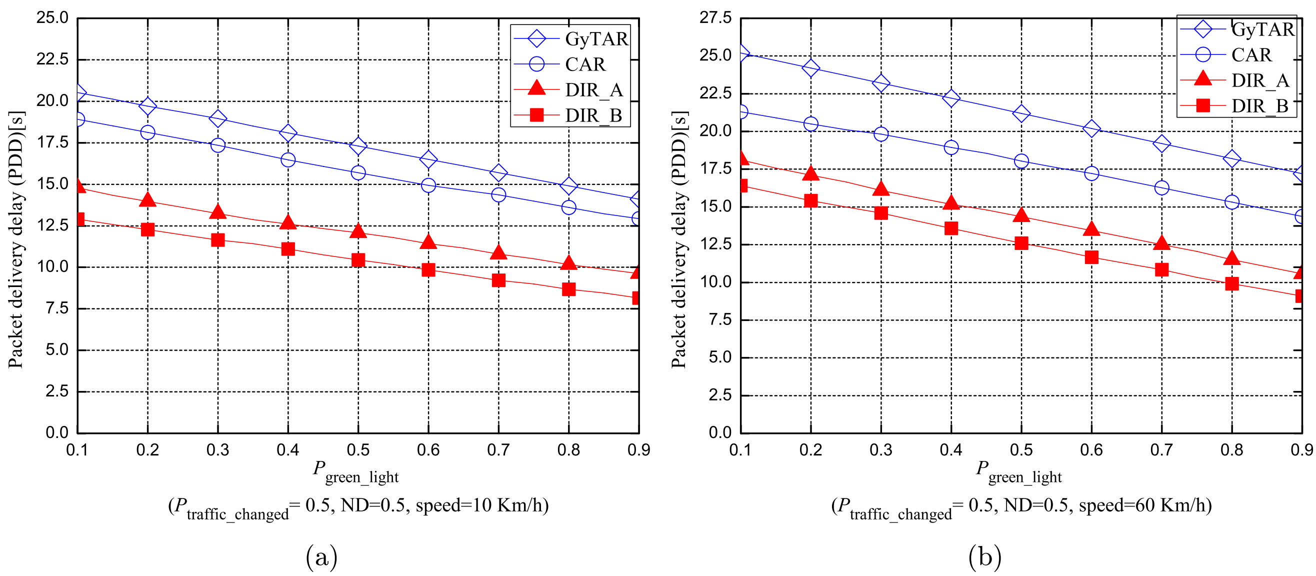

Fig. 13 Performance of the packet delivery delay (PDD) vs. P_{green_light}, where speed is fixed at (**a**) 10 Km/h and (**b**) 60 Km/h

curve of DIR_B was lower than that of the DIR_A, the curve of DIR_A was lower than that of CAR, and the curve of CAR was lower than that of GyTAR. In general, the PDD drops as the ND increases. This is because that the higher network density provides more successful transmission opportunities for vehicles to significantly reduce the PDD. For the effect of ND, it was observed that when the moving speed is high, then the corresponding PDR of DIR_A, DIR_B, CAR, and GyTAR increases.

Figures 13(a)(b) give the performance of the PDD vs. P_{green_light} (ranging from $0.1 \leq P_{green\_light} \leq 0.9$), where $\text{ND} = P_{traffic\_changed} = 0.5$ and the moving speed is fixed to 10 Km/h and 60 Km/h, respectively. The curve of GyTAR was higher than that of the CAR, the curve of CAR was higher than that of the DIR_A, and the curve of DIR_A was higher than that of DIR_B. It is observed that PDR drops as P_{green_light} increases. This is because that high P_{green_light} implies that a vehicle can more successfully pass the intersection. This surely decreases the value of PDD. For the effect of P_{green_light}, it was observed that when the moving speed is high, then the corresponding PDR of DIR_A, DIR_B, CAR, and GyTAR increases.

Figures 14(a)(b) illustrate the performance of the PDD vs. $P_{traffic\_changed}$ (ranging from $0.1 \leq P_{traffic\_changed} \leq 0.9$),

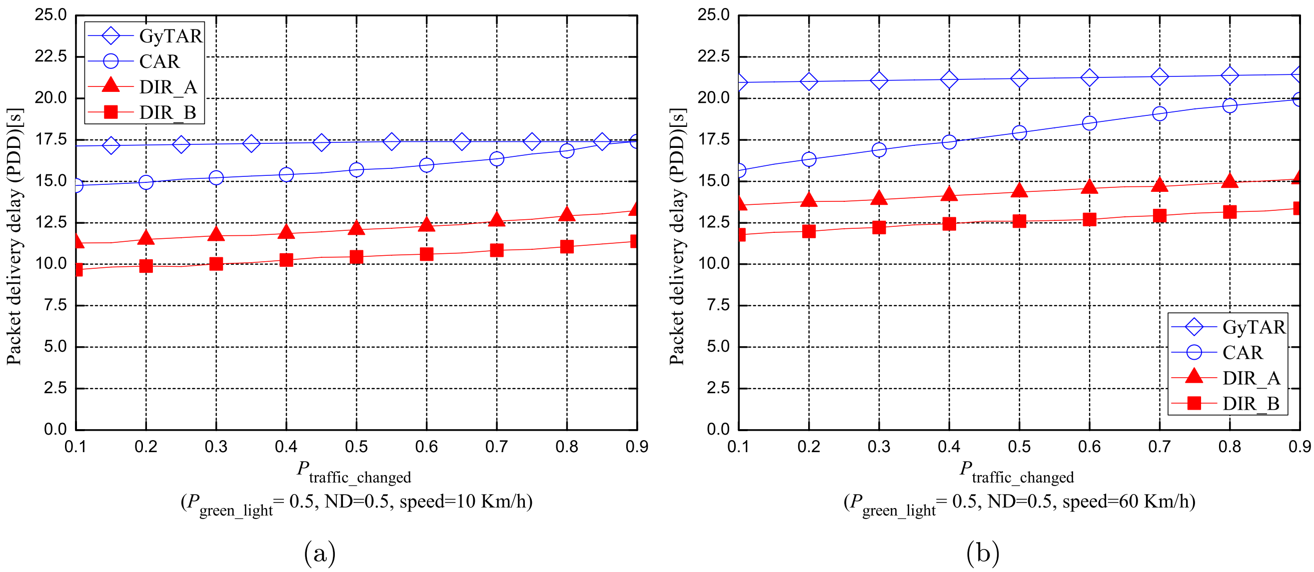

Fig. 14 Performance of the packet delivery delay (PDD) vs. $P_{traffic\_changed}$, where speed is fixed at (**a**) 10 Km/h and (**b**) 60 Km/h

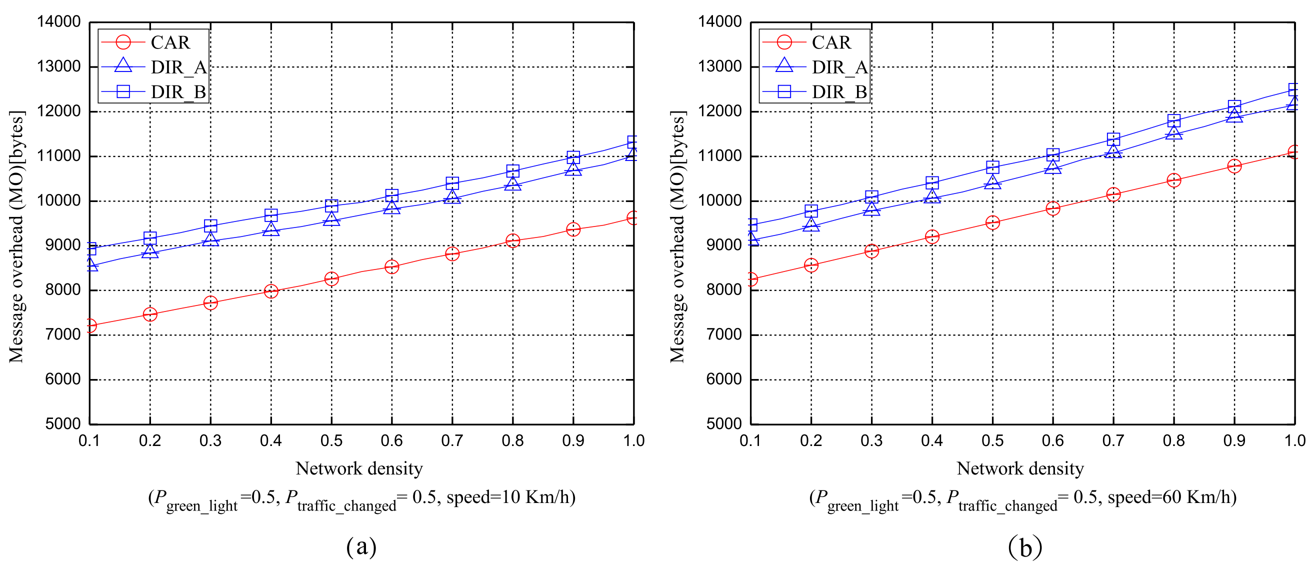

Fig. 15 Performance of the message overhead (MO) vs. network density, where speed is fixed at (**a**) 10 Km/h and (**b**) 60 Km/h

where $ND = P_{green\_light} = 0.5$ and the moving speed is fixed to 10 Km/h and 60 Km/h, respectively. The curve of GyTAR was higher than that of the CAR, the curve of CAR was higher than that of the DIR_A, and the curve of DIR_A was higher than that of DIR_B. For the curve of DIR_A and DIR_B, the higher $P_{traffic\_changed}$ is, the lower the PDD will be. This indicates that the design of CAR protocol does not consider the important factor of $P_{traffic\_changed}$. GyTAR selects the next street at junctions; therefore, there is only slight effect by the changed traffic. The PDD of DIR_A, DIR_B, and CAR are increased as the $P_{traffic\_changed}$ increasing. But, the PDD of GyTAR is slightly increased as the $P_{traffic\_changed}$ increases. This implies that DIR protocol has better performance of PDD than CAR protocol. For the effect of $P_{traffic\_changed}$, it was observed that when the moving speed is high, then the corresponding PDD of DIR_A, DIR_B, CAR, and GyTAR increases.

5.3 Message overhead (MO)

Message overhead which includes both control and data messages is the amount of total packets transmitted by source vehicle. Figures 15–17 shows the simulation results of the message overhead (MO) for the CAR, DIR_A and DIR_B. The higher the value of MO is, the larger the number

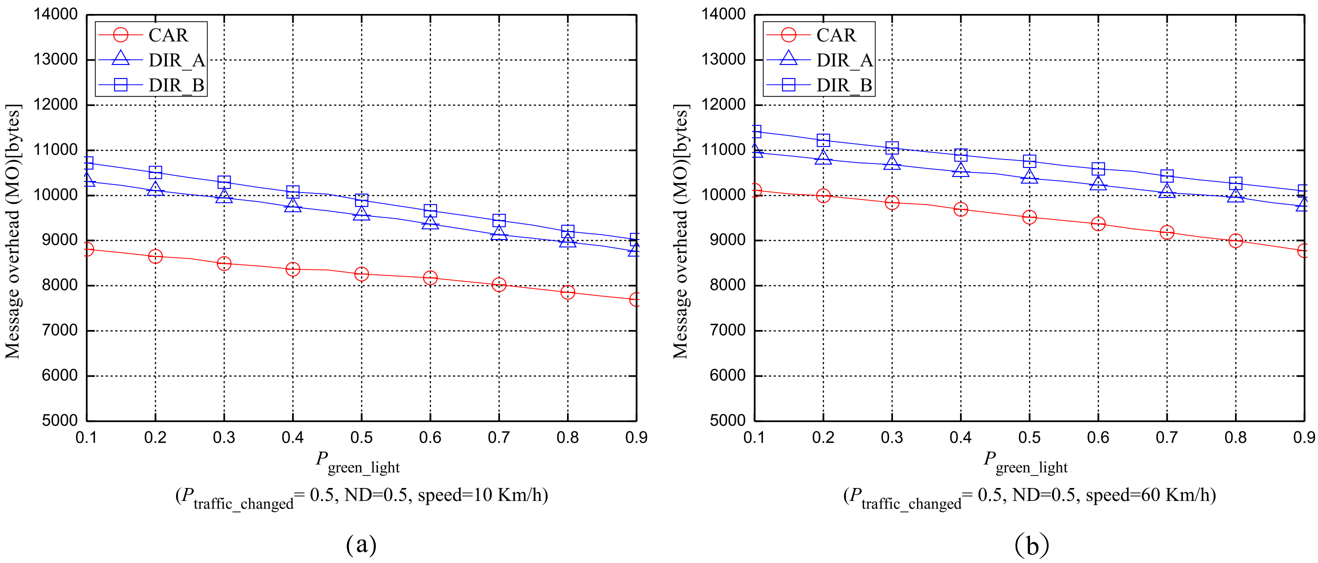

Fig. 16 Performance of the message overhead (MO) vs. P_{green_light}, where speed is fixed at (**a**) 10 Km/h and (**b**) 60 Km/h

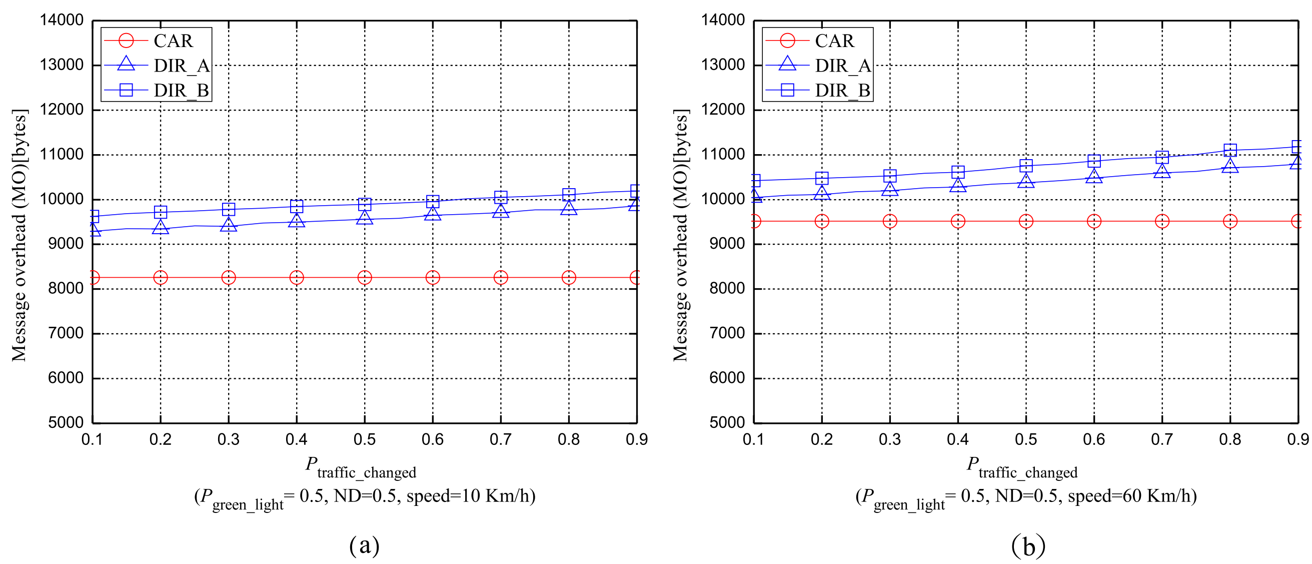

Fig. 17 Performance of the message overhead (MO) vs. $P_{traffic\_changed}$, where speed is fixed at (**a**) 10 Km/h and (**b**) 60 Km/h

of packers will be. Figures 15(a)(b) show the performance of the MO vs. various ND (ranging from 0.1 to 1), were $P_{green\_light} = P_{traffic\_changed} = 0.5$, where the moving speed is fixed at 10 Km/h and 60 Km/h, respectively. The curve of DIR_B was higher than that of the DIR_A, and the curve of DIR_A was higher than that of CAR. The MO drops as ND decreases. For the effect of ND, when the moving speed is high, then the corresponding MO of DIR_A, DIR_B, and CAR increases.

Figures 16(a)(b) give the performance of the MO vs. various P_{green_light} (ranging from $0.1 \leq P_{green\_light} \leq 0.9$), were ND $= P_{traffic\_changed} = 0.5$, where the moving speed is fixed at 10 Km/h and 60 Km/h, respectively. The curve of CAR was lower than that of the DIR_A, and the curve of DIR_A was lower than that of DIR_B. The MO drops as P_{green_light} increases. For the effect of P_{green_light}, when the moving speed is high, then the corresponding MO of DIR_A, DIR_B, and CAR increases.

Figures 17(a)(b) illustrate the performance of the MO vs. various $P_{traffic\_changed}$ (ranging from $0.1 \leq P_{traffic\_changed} \leq 0.9$), were ND $= P_{green\_light} = 0.5$, where the moving speed is fixed at 10 Km/h and 60 Km/h, respectively. The curve of CAR was lower than that of the DIR_A, and the curve of DIR_A was lower than that of DIR_B. The MO of CAR_A and CAR_B drops as $P_{traffic\_changed}$ decreases. The MO of

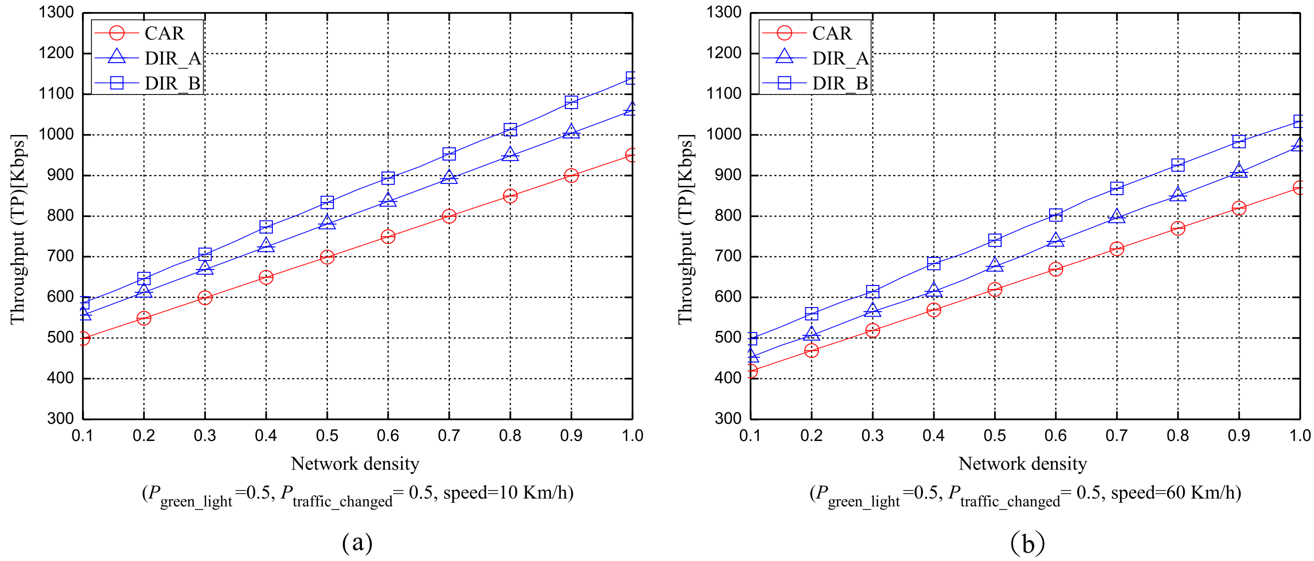

Fig. 18 Performance of the throughput (TP) vs. network density, where speed is fixed at (**a**) 10 Km/h and (**b**) 60 Km/h

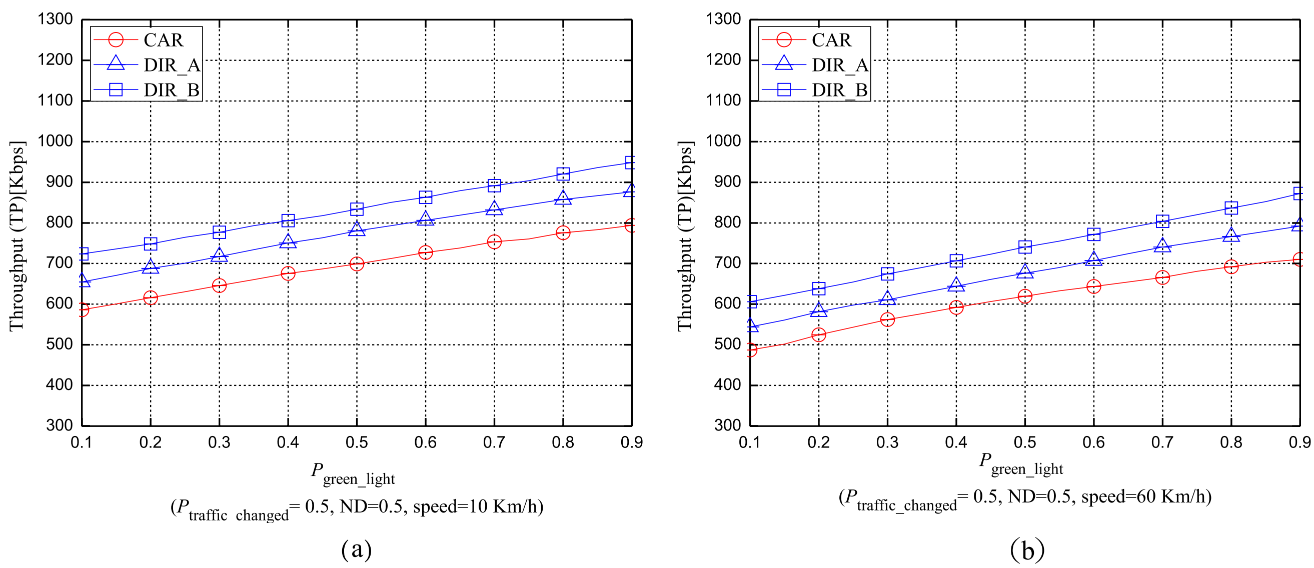

Fig. 19 Performance of the throughput (TP) vs. P_{green_light}, where speed is fixed at (**a**) 10 Km/h and (**b**) 60 Km/h

CAR is fixed as $P_{traffic\_changed}$ increases. For the effect of $P_{traffic\_changed}$, when the moving speed is high, then the corresponding MO of DIR_A, DIR_B, and CAR increases.

5.4 Throughput (TP)

Figures 18–20 provide the simulation results of throughput (TP). The higher the value of TP is, the higher the performance of the DIR protocol is. Figures 18(a)(b) show the performance of the TP vs. ND (ranging from 0.1 to 1), were $P_{green\_light} = P_{traffic\_changed} = 0.5$ and the moving speed is fixed at 10 Km/h and 60 Km/h, respectively. The curve of DIR_B was higher than that of the DIR_A, and the curve of DIR_A was higher than that of CAR. The TP drops as ND decreases. For the effect of ND, when the moving speed is high, then the corresponding TP of DIR_A, DIR_B, and CAR increases.

Figures 19(a)(b) illustrate the performance of the TP vs. P_{green_light} (ranging from $0.1 \leq P_{green\_light} \leq 0.9$), were $\text{ND} = P_{traffic\_changed} = 0.5$ and the moving speed is fixed at 10 Km/h and 60 Km/h, respectively. The curve of CAR was lower than that of the DIR_A, and the curve of DIR_A was lower than that of DIR_B. The TP increases as P_{green_light} increases. For the effect of P_{green_light}, when the moving speed is high, then the corresponding TP of DIR_A, DIR_B, and CAR increases.

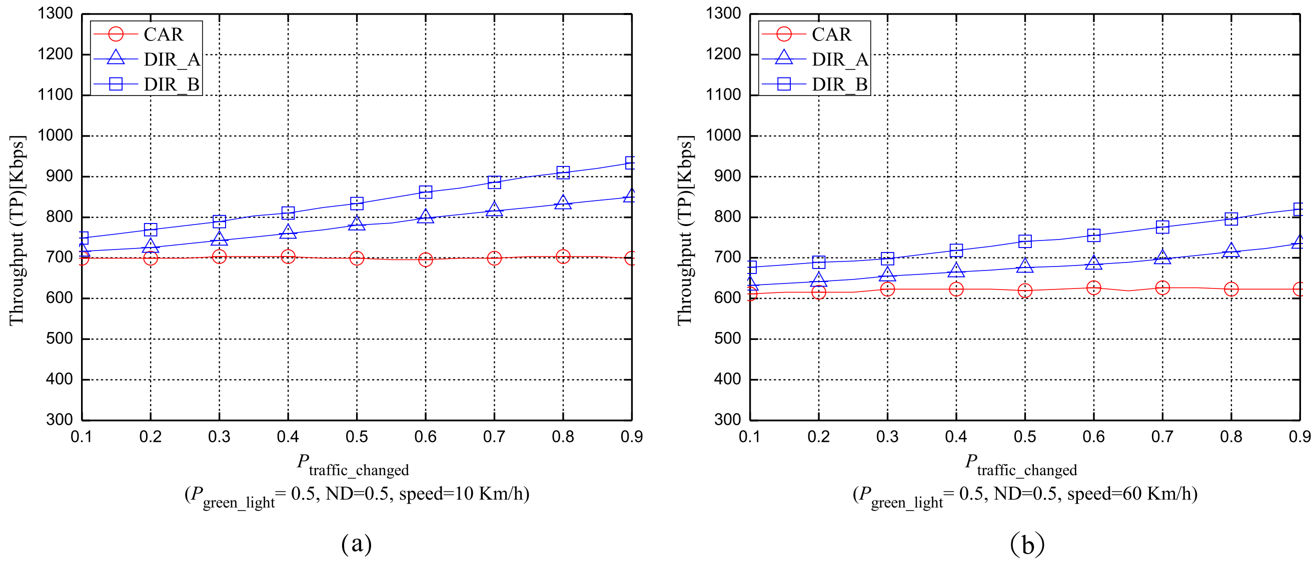

Fig. 20 Performance of the throughput (TP) vs. $P_{traffic\_changed}$, where speed is fixed at (**a**) 10 Km/h and (**b**) 60 Km/h

Figure 20(a) display the performance of the TP vs. $P_{traffic\_changed}$ (ranging from $0.1 \leq P_{traffic\_changed} \leq 0.9$), where ND $= P_{green\_light} = 0.5$ and moving speed is fixed to 10 Km/h and 60 Km/h, respectively. The curve of CAR was lower than that of the DIR_A, and the curve of DIR_A was lower than that of DIR_B. The TP of CAR_A and CAR_B drops as $P_{traffic\_changed}$ decreases. The TP of CAR is fixed as $P_{traffic\_changed}$ increases. For the effect of $P_{traffic\_changed}$, when the moving speed is high, then the corresponding MO of DIR_A, DIR_B, and CAR increases.

In summary, our DIR protocol is a truly efficient routing protocol which achieve high packet delivery ratio, a low packet delivery delay, and a high throughput.

6 Conclusion

In this paper, we present a new "diagonal-intersection-based" routing (DIR) protocol for vehicular ad hoc networks. The main results of the DIR routing protocol are summarized as follows; (1) the DIR protocol builds a new "geographic" routing protocol which is a fully distributed algorithm to possibly collect a series of diagonal intersections as the anchor points for the geographic routing operations, (2) the DIR protocol offers an auto-adjustability capability to dynamically select a sub-path with low packet delivery delay between a pair of adjacent diagonal intersections, (3) the DIR protocol can significantly reduce the packet delivery delay, packet delivery ratio, and throughput. Performance achievements compared to existing protocols. In the future works, the performance of algorithm B can be further improved by considering more characteristics of a VANET since the algorithm B costs high time complexity to consider the multiple diagonal intersections to obtain the minimum expected packet forwarding delay. Besides, the irregular street model is also developing as a new DIR protocol. Moreover, future work involves developing a diagonal-intersection-based multicast protocol which supports applications of multiple destinations in VANETs.

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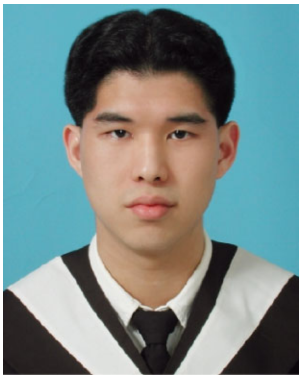
Yuh-Shyan Chen received the B.S. degree in Computer Science from Tamkang University, Taiwan, ROC, in June 1988 and the M.S. and Ph.D. degrees in Computer Science and Information Engineering from the National Central University, Taiwan, ROC, in June 1991 and January 1996, respectively. He joined the faculty of Department of Computer Science and Information Engineering at Chung-Hua University, Taiwan, ROC, as an associate professor in February 1996. He joined the Department of Statistic, National Taipei University in August 2000, and joined the Department of Computer Science and Information Engineering, National Chung Cheng University in August 2002. Since 2006, he has been a Professor at the Department of Computer Science and Information Engineering, National Taipei University, Taiwan. Prof. Chen is now serving as chair of Institute of Communication Engineering, National Taipei University, Taiwan, ROC, and Vice Chair of Task Force on "Telecommunications" of Intelligent Systems Applications Technical Committee, IEEE Computational Intelligence Society from 2007. Prof. Chen served as Editor-in-Chief of International Journal of Ad Hoc and Ubiquitous Computing (SCIE), Editorial Board of Telecommunication System Journal (SCIE), EURASIP Journal on Wireless Communications and Networking (SCIE), and Mobile Information Systems (SCIE). He served as Guest Editor of ACM/Springer Mobile Networks and Applications (MONET), Telecommunication Systems, Wireless Communications and Mobile Computing, EURASIP Journal on Wireless Communications and Networking, The Computer Journal, Wireless Personal Communications, International Journal of Communication Systems, and IET Communications. His recent research topics include wireless communications, mobile computing, and next-generation personal communication system.



Yun-Wei Lin received the B.S. degree in Computer and Information Science from the Aletheia University, Taiwan, ROC, in June 2003 and the M.S. degree in Computer Science and Information Engineering from National Chung Cheng University, Taiwan, ROC, in July 2005. His research interests include mobile ad hoc networks, wireless sensor network, and vehicular ad hoc networks.

Ci-Yi Pan received the B.S. degree in Department of Avionics from the China University of Science and Technology, Taiwan, ROC, in June 2003 and the M.S. degree in Graduate Institute of Communication Engineering from National Taipei University, Taiwan, ROC, in July 2008. His research interests include mobile ad hoc networks and vehicular ad hoc networks.