Master's Thesis

PDPD: Packet Delivery Prediction-based Data Forwarding to Moving Targets in Vehicular Networks

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Department of Electrical and Computer Engineering

(Electrical Engineering)

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Abstract

Vehicular Ad hoc Network (VANET) is one of technologies to realize various ITS services that provide safe driving and efficient traffic condition. VANET consists of moving nodes, and hence its topology frequently changes. In VANETs, multi-hop data delivery is complicated by the fact that vehicular networks are highly mobile and frequently disconnected. In this thesis, we develop a novel forwarding scheme that accounts for the vehicle density, and delivers packets in a reliable and timely manner. We pay attention to the encounter event between two vehicles and the probability of successful transmission at the encounter place to guide forwarding decision. The proposed forwarding scheme uses traffic statistics to predict vehicle encounters, and optimize forwarding decision by taking into consideration the quality of wireless communications. We verify the results through simulations and show that our proposed scheme achieves reliable data transmission in VANET.

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Ⅰ. INTRODUCTION

The convergent technology based on information and communication engineering suggests a new paradigm of Intelligent Transport System (ITS) that combines information technology (IT) with automotive technology. ITS aims to provide the necessary foundation for realizing efficient traffic system and various services such as Advanced Public Transportation system (APTS) and Advanced Traffic Management System (ATMS). Many developed countries have already recognized ITS as a national industrial backbone and tried to solve traffic problems and to advance systems for traffic and vehicles. In this situation, ITS targeting transportation infrastructure, like roads, signals, intellectual vehicles, and wireless communication, have drawn much attention. Among the technologies to realize ITS, wireless communication is one of the key elements to connect drivers, vehicles, and service provider. In particular, through wireless communication, fast and reliable information exchange, which is critical for safety-critical applications, becomes available.

Many countries and companies have developed specialized ITS communication technologies and have standardized communication protocols that are suitable for ITS applications. For example, Dedicated Short Range Communication (DSRC) and IEEE 802.11p Wireless Access in the Vehicular Environment (WAVE) have been developed [1]. WAVE has recently received considerable attention and has already been standardized in IEEE 802.11p and 1609 Working Groups. The Federal Communications Commission (FCC) in US has allocated 75MHz of spectrum in the 5.9GHz band for Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication [2]. IEEE is also working on the IEEE 1609 family of standard for WAVE, through which the network architecture and the protocols for V2V and V2I services will be defined [3], [4], [5], [6].

Vehicular Ad hoc Network (VANET) is one of the core technologies to realize smart ITS for safe driving and efficient traffic management. VANET is a wireless ad-hoc network that consists of vehicles. In VANET, it is assume that each vehicle has wireless transceiver and acts as a network node [7]. Vehicular communications enable mobile users in their vehicle to communicate to the road or to each other for safety and transportation efficiency.

There are many interesting applications of VANETs for disseminating information, e.g., advertisements, parking space, gas station, weather, etc. We classify VANET applications into three groups: Road safety application, traffic efficiency and management application, and infotainment application. Road safety applications aim to help the drivers and decrease the traffic accidents, resulting in reduction of road casualties [8], [9], [10]. To this end, the safety applications provide a way for vehicles to share information with each other, and assist the drivers with additional information that includes vehicle position, vehicle speed, and distance to the car ahead. Such information exchange is imperative to identify hazards on roads, which include slippery roads and potholes, and determine their locations. On the other hand, traffic efficiency and management applications provide local information, maps, and space-relevant messages, for the purpose of traffic flow improvement. Co-operative navigation and detailed speed management are a good example application in this category. Infotainment application often heavily rely on the data from the Internet services. Typical examples include community services, fleet and parking management, and media downloading.

VANET can be considered as a special type of ad hoc networks characterized by high mobility and self-organization of the nodes like Mobile Ad hoc Network (MANET). In these networks, each vehicle has to behave as a router, which allows a node to communicate with other nodes outside its transmission range via multi-hop relays. As VANET is a special class of MANET, VANET shares some common characteristics with MANET but its own special characteristics. In [11], the authors distinguish VANET from other ad hoc networks in the following aspects:

- Highly dynamic topology: the topology of VANET frequently changes due to the high-speed movement of vehicles. Suppose that two vehicles at speed 60*km/h* (16.66*m/sec*) are driving in the opposite direction of each other and their communication range is 200*m*. In this case, the link between them will last approximately for 6 seconds.
- Frequently disconnected network: For the same reason, high mobility may cause a disconnection of individual vehicles to VANET. It is commonly expected that frequent disconnections occur when the vehicular density is low. Since many applications need to access the Internet periodically, the connectivity problem should be addressed. The installation of several roadside relay nodes can be a potential solution to provide reliable connectivity in such sparse networks.
- Sufficient energy and storage: In many cases, the vehicles in VANET has a sufficient amount of energy and computing power, and thus energy saving or low computational complexity are not a significant problem.
- Geographical aspect of communications: In most communication networks, the two communication parties are identified by ID or unique address. In VANETs, certain applications (e.g., in safety applications) require geographical addressing such that the information can be disseminated within a geographical area.
- Mobility modeling and predication: Since vehicles are constrained by roads and streets, their

mobility and topology changes will be different from random mobility. We can take advantage of such constraints when we design the network protocols for VANETs.

- Various communication environments: VANET usually operate either in highway traffic scenarios or in city scenarios. In the former, the environment is relatively simple and straightforward since vehicles are often on the line-of-sight. In contrast, in the latter, there are many obstacles such as buildings and trees, and it is common that two vehicles are not on the line-of-sight.

- Hard delay constraints: VANET applications may not require high-rate data transmission, and however, instead, have strict delay requirements. Road safety applications are a good example. An urgent message such as an accident or a brake event has to be delivered within a certain time interval, and this maximum value is more crucial than average performance.

- Interaction with other sensors: In vehicles, there are many different types of on-board sensors for driving information, such as GPS that provides the location information for the routing purpose. These sensor readings can be used for communications in VANETs.

As one of key research topics in VANET, many routing protocols for VANET have been developed and evaluated based on MANET routing protocols. Generally, mobile ad hoc routing protocols requires reliable packet delivery and low delivery delay, with minimal communication overhead and network resource. MANET routing protocols can be largely classified into two categories: proactive routing and reactive on-demand routing [12]. The proactive routing protocol calculates a route from one node to all other nodes in advance. Representative proactive protocols are Destination-Sequenced Distance-Vector (DSDV) and Optimized Link State Routing (OLSR). In contrast, the reactive routing protocol discovers a route only when it is explicitly requested. Dynamic Source Routing (DSR), and Ad hoc On Demand Distance Vector (AODV) are most widely used.

Although many routing protocols have been developed in MANET, most of them do not work well in VANET. It has been shown that many previous routing protocols for MANETs perform poorly in VANETs [13], [14]. One of the main problems is that the previous routing protocols fail to achieve stable route information. The high vehicle mobility cause frequent route failures if the route between the source and the destination is represented by a sequence of intermediate nodes. It leads to many packet drops, and significant amount of overhead for route recovery and failure notification, results in low delivery performance and high delay.

To overcome those problems of MANET routing protocol, various position-based routing protocols, which are known to be useful in VANET, are proposed. Assuming that each vehicle has infinite energy supply and external equipment, such as GPS and Navigation, position-based routing protocols perform greedy forwarding based on the position of the source, the destination, and their neighbor nodes. This improves network efficacy by reducing heavy overhead and long delay. However, they have the following additional problems: overhead of location service, inaccurate location information of nodes due to high mobility, and unreliable packet forwarding due to high node density. High node mobility not only changes the connectivity of individual vehicles but also varies the node density, which impacts on the quality of communications: severe interference in high node density and poor connectivity in low node density.

In this thesis, we develop a reliable and timely data forwarding scheme that considers both delivery time and delivery ratio. The proposed forwarding scheme uses traffic statistics to predict vehicle encounters, and optimize forwarding decision by taking into consideration the quality of wireless communications.

This thesis is organized as follows. Section 2 summarizes related work. Section 3 provides the system model. Section 4 explains our data forwarding scheme, and Section 5 evaluates its performance. Finally, Section 6 concludes this thesis.

Ⅱ. RELATED WORK

In VANETs, many data forwarding schemes use the carry-and-forward approach, where a vehicle carries message until it can transmit the message to the destination or to a relay node. Traffic information (e.g., traffic density and average vehicle speed per road segment) is commonly used to guide the forwarding operation.

Greedy Perimeter Stateless Routing (GPSR) is proposed by Brad Karp and H. T. Kung of Harvard University in 2000 [15]. This protocol does not establish a fixed route, and instead, uses the destination location and the neighboring vehicles' to make a data forwarding decision. The vehicle that has a packet to send transmits the packet to its neighboring vehicles that are geographically closer to the destination. In the meantime, it is possible to occur that the vehicle with the message is the closest to the destination among those in its neighbors, while it cannot directly transmit the data to the destination yet. In such a 'local maximum' case, GPSR switches to the perimeter mode, under which the packet is forwarded based on right-hand rule (rather than the shortest distance). Under GPSR, each vehicle broadcasts its position information periodically, and thus all the vehicles maintain the table of neighbor nodes. The source node that already knows the location of the destination takes a greedy approach and selects the closest node to destination node using the position information of neighbor nodes. If the source node cannot detect a closer node than itself, GPSR operates on the perimeter mode. GPSR works in a greedy manner and needs only the knowledge of the forwarding node's immediate neighbors. It has been shown to perform well in highway scenarios with distributed nodes, and to suffer from poor performance in city scenarios. In particular, GPSR outperforms DSR in many aspects [16] in terms of packet delivery ratio and protocol overhead. There are also a couple of weaknesses: the overhead to acquire the position of the destination is not taken into consideration, and it may cause a touring loop in a planar graph with cross-edges.

Greedy Perimeter Coordinator Routing (GPCR) is another solution for routing in VANET. It does not use the source routing or require the street maps [17]. Instead, it assumes that the vehicles within a road segment naturally consists of a planar graph, and thus a greedy forwarding would be sufficient in the forwarding over the road segment. In GPCR, since actual routing decisions are made only at a junction, it stops forwarding a packet at the end of the road segment (i.e., at the junction). The vehicle at the junction is called a Coordinator. To know whether the node is at junction, two strategies are proposed. First, all the nodes exchange beacon messages. We find a node at junction, if there are three nodes x, y, z, such that node *x* has *y* and *z* in its neighbor list, nodes y and z are in transmission range of each other, and nodes y and z do not have each other in their neighbor list. The second strategy uses correlation coefficient that relates neighbor to the node. If the coefficient is 0, it signifies that there is no relationship between position of the neighbors and the node is at junction. The authors of [17] have conducted ns-2 simulations with a real city topology, Berlin, Germany. The results show that GPCR outperforms GPSR in terms of packet delivery ratio when the routes have a larger number of hops.

Geographic Source Routing (GSR) is another position-based routing protocol with assistance of GPS-based navigation system, and it is developed for city environments [18]. A vehicle, which has a packet to send, starts a route discovery procedure called Reactive Location Service (RLS) and can obtain the position of the destination. Once it obtains the location information, packets are forwarded to an intermediate vehicle that is closest to the destination, which is called as greedy position-based routing. However, it has been known that the route discovery does not perform well in light-traffic vehicular networks.

Vehicle-Assisted Data Delivery (VADD) makes use of a stochastic model based on vehicle traffic statistics [19]. It aims to reduce packet delivery delay from a mobile source to stationary destination. Static-node-assisted Adaptive Data Dissemination protocol for Vehicular networks (SADV) is a forwarding scheme with help of static relay nodes that are placed at intersections [20]. The relay nodes contribute to achieve predictable data delivery delay. Once a vehicle carries a packet, it continues the carrying unless it receives explicit request from a relay node. If it receives a request from a relay node (at intersection), who can make a better decision with global information, it forwards the packet to the relay node. The relay node holds the packet for a while and sends a carrying request to another vehicle that can improve the delivery performance. Each relay node keeps estimating delivery delay between the other relay nodes according to dynamic traffic envinronments. In SADV, multi-path routing mechanism can be used to reduce the data delivery delay, which, however, increases the system overhead. Both VADD and SADV utilize traffic information such as traffic density and average vehicle speed for better forwarding operations. Although they perform well in dense vehicular networks because the behavior of individual vehicle is relatively insensitive to the forwarding performance, they often suffer from poor performance in sparse networks.

Trajectory-Based Data Forwarding (TBD) is data forwarding scheme for V2I communications [21]. Utilizing vehicular traffic statistics and vehicle trajectory information, TBD improves end-to-end delivery delay. For I2V (Infrastructure-to-Vehicle) communications, the authors of [22] have proposed Trajectory-based Statistical Forwarding (TSF). TSF speculates the location where the destination vehicle will pass by and forwards the packet to the location. The location is chosen such that the packet delivery delay is minimized and the packet delivery probability is sufficiently high. TBD and TSF consider vehicle trajectory information that is available from GPS-based navigation systems. Although these protocol overcome the limitation of VADD and SADV (prone to errors in sparse networks), they are based on the assumption of no failure in packet transmission, and do not consider the quality of wireless links that highly depend on vehicle traffic.

Ⅲ. SYSTEM MODEL AND MOTIVATION

In this section, we describe the system model and provide the motivation. We assume that the travel paths for vehicles and the traffic statistics of the roads are available. When a vehicle has a packet to send, it needs to decide to which intermediate vehicle it can forward the packet for relay to the destination in a reliable and timely fashion.

We describe the network environment in consideration for vehicle-to-vehicle data forwarding in road networks. We consider a VANET where vehicles in proximity can communicate with each other through wireless interface, e.g., DSRC. We assume that there are two different types of vehicles in the network as shown in Fig. 1: private vehicles and public vehicles.

- *Private Vehicle* has limited communication capability. They can only communicate with nearby vehicles and cannot directly connect to the Internet.

- *Public Vehicle* can communicate with nearby private vehicles, and in addition, it directly connects to the Internet through Wide Area Network (WAN). For private vehicles, it can play the role of a backhaul node to the Internet and serves the packets from the private vehicles. Public vehicles operate following a predetermined route. We assume that the routes and the locations of public vehicles are known.

When a private vehicle has a packet for the Internet service, it tries to reach one of the available public vehicles, either by directly carrying the packet to the public vehicle or by transmitting the packet for relay to another private vehicle that will encounter the public vehicle. To this end, when two private vehicles are within the communication distance, they exchange necessary information including the expected time to encounter a public vehicle.

For the information exchange, each vehicle equips a DSRC communication device and can communicate with each other in proximity. DSRC is the standard protocol stack for vehicular communications, and adopts Carrier Sensing Medium Access (CSMA) Collision Avoidance (CA) as in the IEEE 802.11 protocols [23]. Under CSMA/CA, if a vehicle has a data packet to send, it senses wireless channel and exercises a *random backoff* while the channel is idle, as follows. Each wireless

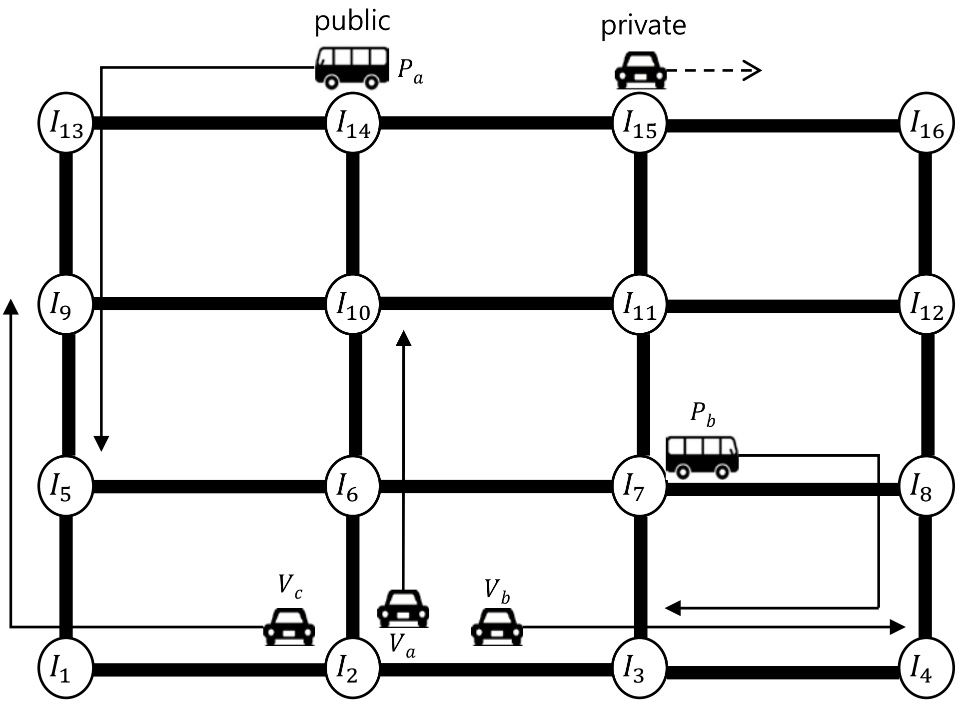


Fig. 1. Vehicular network with two types of vehicles (private and public vehicle).

node has a backoff timer, which decreases only when the channel is idle. When a vehicle has a data packet, it randomly chooses an integer within a range and decreases the integer value by one for a fixed time of idle channel. The fixed time length is called a *time slot*. When the timer expires (i.e., when the integer value becomes 0), the vehicle transmits the data packet. Due to the timer granularity of a time slot, there is a possibility that multiple vehicles transmit simultaneously if their timers expire at the same time slot. If the two transmissions are close with each other within their transmission range, both of them fail, which is called as collision. If a packet transmission fails due to a collision, the vehicle retransmits the packet to improve reliability. However, in VANET, since the vehicles move and their transmission range is limited, the maximum number of retransmissions is upper bounded.

So far, the previous works [19], [21], [22] tried to achieve timely packet delivery in VANETs under the assumption of no packet loss. However, in dense areas, e.g. city area, packet loss due to collision is unavoidable under the standard DSRC operation with CSMA/CA. In this case, multiple vehicles are likely to attempt to transmit at the same time, and it is challenging to deliver packets in a reliable manner. We consider the forwarding problem in urban areas, where the packet loss event is not rare.

We consider a vehicular network with a map (i.e., roads and intersections), the set V of the private vehicles, and the set P of the public vehicles, where the public vehicles (e.g., buses) are connected to the Internet through WAN. We number all the intersections on the map. For example, in Fig. 1, we let I_i denote intersection i, and let $L_{i,j}$ denote the road segment identified by two intersections I_i and I_j. Suppose that the source $V_a \in V$ generates a packet. Depending on its path, it may or may not encounter a public vehicle. Further, even if it encounters a public vehicle, it may fail to transmit the packet if they encounter in a crowded area. To deliver the packet in a reliable and timely manner, the source V_a has an option to transmit the packet to another private vehicle $V_b \in V$ and use it as a relay vehicle to deliver the packet to a public vehicle. We note that *anycast* is in consideration and the packet can be delivered to any public vehicle. Fig. 1 shows an example of the operation. Private vehicle $V_b \in V$ will encounter public vehicle $P_b \in P$ on road segment $L_{4,8}$ (between intersections I_4 and I_8) and private vehicle $V_c \in V$ will encounter public vehicle $P_a \in P$ on road segment $L_{5,9}$. If road segment $L_{5,9}$ is crowded (while road segment $L_{4,8}$ is relatively quiet), V_a transmits the packet to V_b, which can reliably deliver the packet to public vehicle P_b.

Motivated by this, we design a novel forwarding scheme that accounts for the vehicle density, and delivers packets in a reliable and timely manner. To this end, we estimate the expected encounter time of two vehicles, and the probability of successful transmission at the encounter place. For the former, we use previous results, which are included for completion. Our main contribution is the estimation of the latter. Once the probability is calculated, the vehicle with the packet can easily decide whether it carries the packet or it transmits to a forwarder for relay.

Ⅳ. ESTIMATION ON THE PROBABILITIES OF VEHICLE ENCOUNTER AND SUCCESSFUL TRANSMISSION

Given a VANET with anycast to public vehicles, our goal is to make a routing decision for reliable and timely packet delivery. In the decision, the key elements to success are accurate estimations of the encounter probability of two vehicles and the probability of successful packet transmission at the encounter place under practical assumptions of CSMA/CA. We use the results of [24] for calculation of the encounter probability and the encounter place, and develop new estimation method of the probability of successful packet transmission, taking into account the backoff behavior of CSMA/CA.

Ⅳ-A. Encounter probability of two vehicles

Given the predetermined paths (or trajectories) of vehicles, we can estimate the encounter probability of the two vehicles traveling in their opposite direction. Suppose that the trajectories of two vehicles overlap on road segment $L_{i,j}$: one vehicle travels from intersection I_i to I_j, and the other travels from intersection I_j to I_i. The probability that two vehicle encounters on road segment $L_{i,j}$ can be estimated by estimating the time when they arrive at intersection I_i. To this end, we start with the travel time of a vehicle on a road segment.

It has been shown that the travel time over a road segment follows the Gamma distribution $\Gamma(\kappa,\theta)$, where κ is the shape parameter and θ is the scale parameter [22], [25]. Thus, the travel time (or link travel delay) $d_{i,j}$ of a vehicle through road segment $L_{i,j}$ is modeled as $\Gamma(\kappa_{i,j},\theta_{i,j})$, where the parameters $\kappa_{i,j}$ and $\theta_{i,j}$ can be estimated by using the mean $\mathrm{E}[d_{i,j}]=\mu_{i,j}$ and the variance $\mathrm{Var}[d_{i,j}]=\sigma_{i,j}^2$ of the link travel delay as follows [26]:

$$\theta_{i,j}=\frac{Var[d_{i,j}]}{E[d_{i,j}]}=\frac{\sigma_{i,j}^2}{\mu_{i,j}}, \tag{1}$$

$$\kappa_{i,j}=\frac{E[d_{i,j}]}{\theta_{i,j}}=\frac{\mu_{i,j}^2}{\sigma_{i,j}^2}. \tag{2}$$

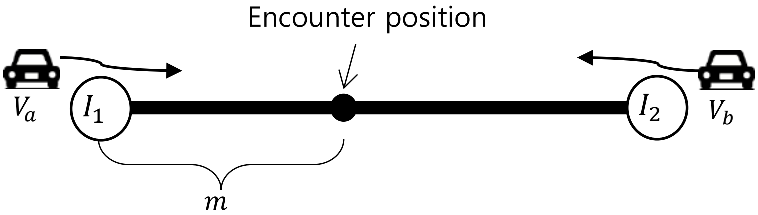


Fig. 2. Two vehicles encountering on road segment $L_{1,2}$.

The traffic statistics of μ_i and σ_i^2 are assumed to be available through the navigation system or the digital map [27].

The result can be extended to the travel delay over a sequence of road segments, i.e., a path. Consider a set N of road segments that is a partial sequence of the vehicle's trajectory. Under the assumption that the travel times across multiple road segments are independent, the end-to-end delay D (over path N) also follows the Gamma distribution $\Gamma(\kappa_D, \theta_D)$ where the parameters κ_D and θ_D are calculated using the mean $E[D]$ and the variance $Var[D]$ as in (1) and (2). From the independency of the travel times over the road segments, $E[D]$ and $Var[D]$ can be obtained by summing the means and the variances of each link's travel time along the path as

$$E[D] = \sum_{i \in N} E[d_i] = \sum_{i \in N} \mu_i, \tag{3}$$

$$Var[D] = \sum_{i \in N} Var[d_i] = \sum_{i \in N} \sigma_i^2. \tag{4}$$

We now estimate the encounter probability from the expected travel time over path. We consider two private vehicles V_a and V_b, both of which travel through road segment $L_{1,2}$ between two intersections I_1 and I_2 as shown in Fig. 2. They could be also a public vehicle. Suppose that the current time is time 0, and let $T_{a,1}$ and $T_{a,2}$ be the time when V_a arrives at I_1 and at I_2, respectively. Similarly let $T_{b,1}$ and $T_{b,2}$ be the time when V_b arrives at I_1 and at I_2, respectively. Then, the probability that the two vehicles encounter on $L_{1,2}$ can be written as

$$P(V_a \text{ and } V_b \text{ encounter on road segment } L_{1,2}) = P(T_{a,1} \leq T_{b,1} \cap T_{a,2} \geq T_{b,2}). \tag{5}$$

Let $d_{1,2}$ be the link travel delay for $L_{1,2}$. Then, the link arrival time $T_{a,1}$ and the link departure time $T_{a,2}$ satisfy that

$$T_{a,2} = T_{a,1} + d_{1,2}. \tag{6}$$

Similarly, letting $d_{2,1}$ be the link travel delay for $L_{2,1}$, we also have

$$T_{b,1} = T_{b,2} + d_{2,1}. \tag{7}$$

Note that $d_{1,2}$ and $d_{2,1}$ follow the Gamma distribution, and the summation of two independent processes with the Gamma distribution is another Gamma distribution with the sum of their means and variances. Thus, we approximate the departure time $T_{a,2}$ and $T_{b,1}$ as

$$T_{a,2} = T_{a,1} + t_{1,2}, \tag{8}$$

$$T_{b,1} = T_{b,2} + t_{2,1}. \tag{9}$$

where $t_{1,2} = E[d_{1,2}]$ and $t_{2,1} = E[d_{2,1}]$. From (5), we obtain:

$$P(V_a \; and \; V_b \; encounter \; on \; road \; segment \; L_{1,2}) = P(T_{a,1} \leq T_{b,1} \leq T_{a,1} + t_{1,2} + t_{2,1}). \tag{10}$$

Let $f(x)$ and $g(y)$ denote the probability density function (PDF) of Gamma random variables for $T_{a,1}$ and $T_{b,1}$, respectively [26]. Then (10) can be calculated as

$$P(V_a \; and \; V_b \; encounter \; on \; road \; segment \; L_{1,2}) = \int_0^\infty \int_x^{x+t_{1,2}+t_{2,1}} f(x)g(y)dydx. \tag{11}$$

We can also calculate the expectation of the encounter time between two vehicles. From Fig. 2, suppose that the encounter position is m meters away from I_1, the mean travel speed from I_1 to I_2 is $v_{1,2}$, and the mean travel speed from I_2 to I_1 is $v_{2,1}$, we have the encounter time T_e as

$$m = (T_e - T_{a,1})v_{1,2} = (T_{b,1} - T_e)v_{2,1}. \tag{12}$$

Therefore:

$$T_e = \frac{T_{a,1}v_{1,2} + T_{b,1}v_{2,1}}{v_{1,2} + v_{2,1}}. \tag{13}$$

In addition to the encounter probability (11) and the expected encounter time (13), we need to calculate the probability of successful packet transmission, which will be directly used to make the routing decision.

Ⅳ-B. Probability of successful packet transmission

We assume that each vehicle should "periodically" broadcast a beacon message to disseminate its location and other information. Once a vehicle successfully identifies the other through the beacon, the two vehicles can exchange the data packet through a separate high-rate channel. Therefore, we focus on the probability of successful transmission of the beacon messages. The DSRC protocol that is standardized as the IEEE 802.11p uses the distributed coordinated function (DCF) of IEEE 802.11 for the medium access. Let σ denote the slot time for the carrier sensing and the timer granularity (e.g., $\sigma = 13\, us$ for IEEE 802.11p) [28]. If multiple vehicles attempt a transmission of beacon message in the same time slot, their signals will collide and none of the transmissions will be successful.

We start with a brief overview the operation of the IEEE802.11p CSMA/CA medium access control protocol. Before transmitting a packet, vehicles ensure idle medium through the carrier-sensing functionality. To elaborate, a backoff timer is used, which sets to a random integer value in [0, W]. It counts down only when the channel is idle, and a vehicle attempts to transmit when the timer becomes 0. We do not consider the exponential backoff that is widely used in the case of multiple collisions. The timer counts down by one per time slot, only when the medium is idle. If the medium is busy, the timer freezes. When the timer expires, the vehicle occupies the channel by transmitting the beacon. Once the vehicle grabs the channel and transmits the beacon, the other vehicles will freeze their backoff timer during the transmission time. Let L denote the fixed time duration for a beacon transmission. Under the MAC protocol, a beacon will wait until the backoff timer expires. We denote the beacon waiting in the buffer by *pending beacon*, and denote the vehicles with a pending beacon by *contending vehicle*. All contending vehicles listen to the medium for idle channel, and will transmit its beacon when their time expire. Hence, to calculate the probability of success transmission, estimating the number of contending vehicles is crucial since it directly impacts the probability of simultaneous beacon transmissions. Let N_c denote the expected number of contending vehicles while a vehicle holds a pending beacon. We note that estimating the expected number N_c of contending vehicles is difficult because the time that holds a pending beacon is also a function of N_c, and it is not proportional to the number of neighboring vehicles as we will see in the following.

Given that each vehicle generates its beacon at rate B, we estimate average N_c by considering the contending time or the *active time* $g(N_c)$ of a contending vehicle. We consider an *average vehicle* and its behavior under the assumption that all the vehicles behave statistically the same, e.g., all the vehicles have the same contending time $g(N_c)$. Note that before a successful beacon transmission, a vehicle will observe average $\frac{N_c}{2}$ beacon broadcasts from other contending vehicles and freezes its backoff timer during their transmission times $\frac{N_c \cdot L}{2}$. Further it will wait on average for $\frac{W \cdot \sigma}{2}$ time to count down the backoff timer. Thus, a vehicle that has a pending beacon waits for $\frac{N_c \cdot L}{2} + \frac{W \cdot \sigma}{2}$ and occupies the channel for L time. We obtain

$$g(N_c) = \frac{N_c \cdot L}{2} + \frac{W \cdot \sigma}{2} + L. \tag{14}$$

Note that the start of the active times of neighboring vehicles will be uniformly distributed over a beacon period $1/_B$, and average number of vehicles whose active time partially overlaps with the vehicle of our interest is N_c. Suppose there are N_n vehicles in the road within a transmission range. Fig. 3 shows distributions of each vehicle's active time. Let t_1 and t_2 denote the start and the end of active time of the vehicle of our interest (vehicle 1). For given a beacon period $1/_B$, there exist N_n neighboring vehicles which start their active time, and during $g(N_c)$ time, there exist $N_c/_2$ contending vehicles which start their active time, because at t_2, we have $N_c/_2$ contending vehicles which start their active time during $[t_1, t_2]$. Therefore, the ratio of the active time to the beacon period should equal to the ratio of the expected number of contending vehicles to the expected number of vehicles in the road within a transmission range, i.e.,

$$\frac{g(N_c)}{1/_B} = \frac{N_c/_2}{N_n}. \tag{15}$$

Combining (14) and (15), we obtain,

$$N_c = \frac{(B \cdot W \cdot \sigma + 2 \cdot B \cdot L) \cdot N_n}{1 - B \cdot L \cdot N_n}. \tag{16}$$

Given the expected number of contending vehicles, we can obtain the probability of successful transmission of a beacon at a time. Let P_s denote the probability of successful transmission of a beacon. A vehicle can successfully transmit a beacon at a time when no one has same contention window size with its own among contending vehicles in its communication range. Thus, P_s is expressed as

$$P_s = \left(1 - \frac{1}{W}\right)^{N_c}. \tag{17}$$

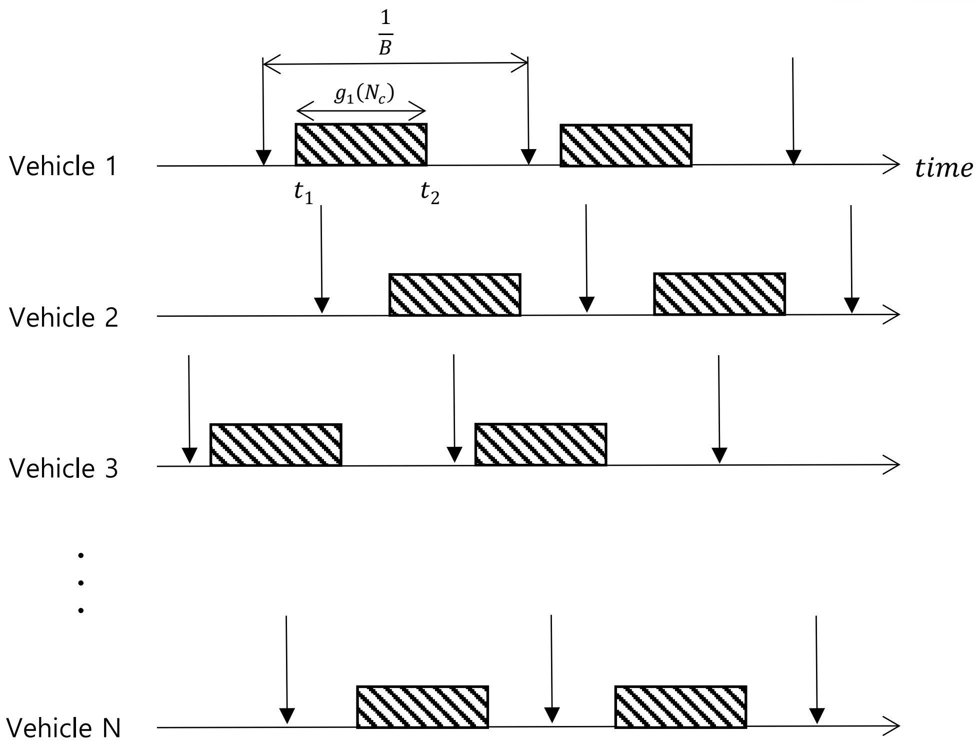


Fig. 3. Distributions of active time.

Note that if two vehicles encounter with each other, they can exchange the beacons within the transmission range. Let T denote the time, for which two vehicles are within the transmission range (i.e., encounter duration), then the probability P_s^T that a packet can be successfully delivered during the encounter can be obtained as

$$P_s^T = 1 - (1 - P_s)^{\frac{T}{1/B}}. \tag{18}$$

IV-C. Packet Delivery Prediction based Data forwarding (PDPD)

We now develop the forwarding decision scheme with the estimated successful transmission probability. When there are a number of contending vehicles within a transmission range, a transmission attempt of the beacon will be likely to fail due to collision with other vehicles. Hence, it would be better to avoid the public vehicle that passes through a highly congested road.

Given a vehicle network with the public vehicles that can provide the Internet connection, our goal is to make a decision of carry-on or transmit for relay to satisfy reliable packet delivery from a packet source (private vehicle) to a packet destination (public vehicle). In this network, each vehicle has the following information: the smallest expected time T_e^a for vehicle V_a to encounter a public vehicle, the probability P_e^a of encounter the public vehicle, and the successful transmission probability $P_s^{T,a}$ during the encounter. The forwarding algorithm is shown in Algorithm 1.

When a private vehicle $V_a \in V$ has a data packet to forward, it collects information from neighboring vehicles within its communication range, and among the neighboring vehicles $V_b \in V$ (including itself $V_a \in V$) such that $P_e^b \cdot P_s^{T,b} \geq p$ for some threshold p, it forward the packet to the vehicle $V_b \in V$ with minimum T_e^b as the next-hop. If there is no candidate vehicle in its neighborhood, it carries the packet until it meets another vehicle.

Algorithm 1: PDPD Algorithm.

```
If V_a ∈ V has a packet to send
    Set T_min = T_e^a
    For V_b ∈ V
        If V_b is in the communication range of V_a
            If P_e^b · P_s^{T,b} ≥ p for some threshold p
                If T_e^b < T_min
                    T_min = T_e^b
                    Next forwarder is V_b
                Else
                    Next forwarder is V_a
```

Ⅴ. PERFORMANCE EVALUATION

This section evaluates the performance of PDPD through simulations. The evaluation is based on the following wireless communication setting:

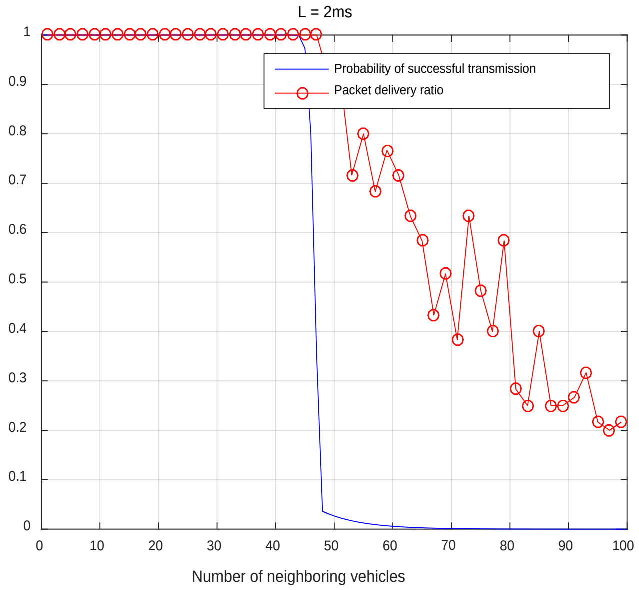
- *Wireless communication setting*: In the network, each vehicle periodically broadcast a beacon at rate 10. The distributed coordinated function (DCF) of IEEE 802.11 is used for medium access. Each vehicle has backoff timer, and randomly chooses an integer with range [0, 7] and decreases the integer value for every 13*us* slot time of idle channel. For simplicity, we do not consider exponential backoff in the case of multiple collisions. We assume that packet length is very small and two vehicles can quickly exchange (i.e., a packet takes 4*ms* to be transmitted). The communication range is 200*m*.

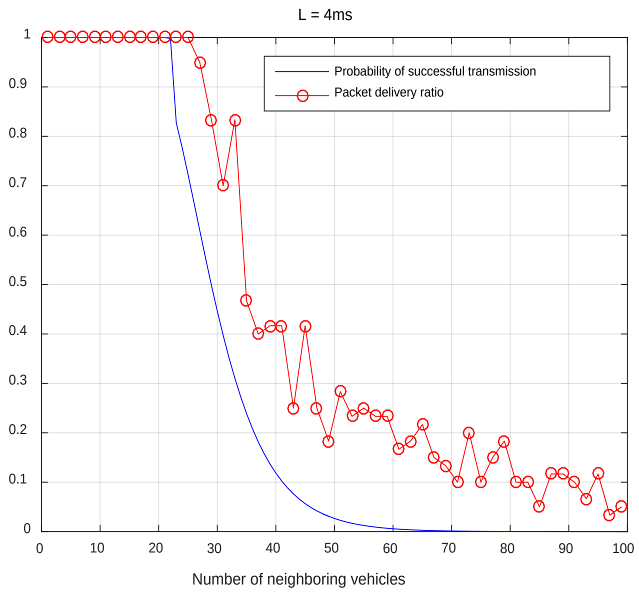
During the simulation, unless otherwise specified, we use the default values in Table 1.

Table 1. Default parameters.

Parameter	Description
Vehicle beacon interval	$^{1}/_{B} = 0.1sec$
Contention window size	$W = 7$
Contention slot time	$\sigma = 13us$
Time for a beacon transmission	$L = 4ms$
Communication range	$R = 200m$

We first verify the estimation of probability of successful transmission. Each vehicle generates its beacon over a beacon period, and when generating a beacon, it tries to transmit the beacon under the medium access control (e.g., CSMA/CA). Since two vehicles, traveling in opposite direction, can communicate with each other for approximately 6 seconds with 60*km/h* vehicle speed. We assume that the time for two vehicles can exchange the beacons is 6 seconds. During 6 seconds, we observe the attempt to transmit the beacon, the occurrence of collision and successful transmission for a vehicle, and measure the delivery ratio (i.e., the ratio of the number of successful transmission to the number of attempt). The simulation is repeated with increased number of neighboring vehicles. Fig. 4 shows the successful transmission probability as a function of the number of neighboring vehicles and compares the packet delivery ratio under different beacon length. As shown in the Fig. 4, our probability of successful packet transmission is well estimated.





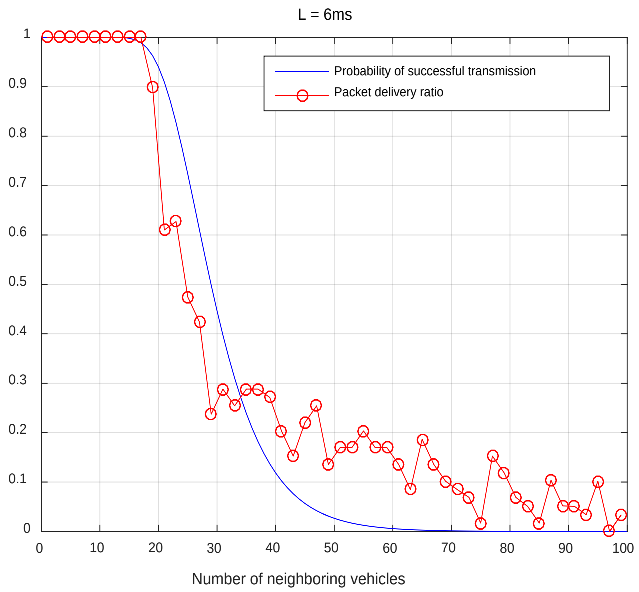


Fig. 4. The probability of successful transmission and delivery ratio comparison for different deacon transmission time (*L= 2ms, 4ms, 6ms*).

We now verify whether the PDPD can provide a reliable and timely data forwarding when considering the probability of successful transmission on forwarding decision. To do this, we simulate with two different forwarding scheme: One only uses the encounter probability on forwarding decision, and the other uses both encounter probability and probability of successful transmission on forwarding decision. In each simulation, the threshold value is 0.5.

We consider a road network with 36 intersections, which forms a rectangular road network topology. We place 300 private vehicles on the top of the road network and 50 private vehicles on the bottom of the road network. We define the top of the road network as high vehicle density area and the bottom of the road network as low vehicle density area. Each private vehicle randomly chooses one of the intersections in each area as its start position, and randomly chooses another intersection as its destination position, and moved along the road. Once it arrives at the destination position, the private vehicle repeats the random selection of next destination and moving. We also place 100 private vehicles in the perimeter of our road network, where they circulate to help the packet forwarding. Two public vehicle pass through one road segment in the top of the road network, and another two public vehicle pass through one road segment in the bottom of the road network.

We conduct 100 rounds of each simulation with different random seeds. Fig. 5 shows the impact of the probability of successful transmission on packet delivery ratio and packet delivery delay. As we consider probability of successful transmission on forwarding decision, a packet is delivered in low vehicle density area rather than high vehicle density area, so the packet delivery ratio is improved. We also find that the average delivery delay of the packet is lower than the case of considering only the

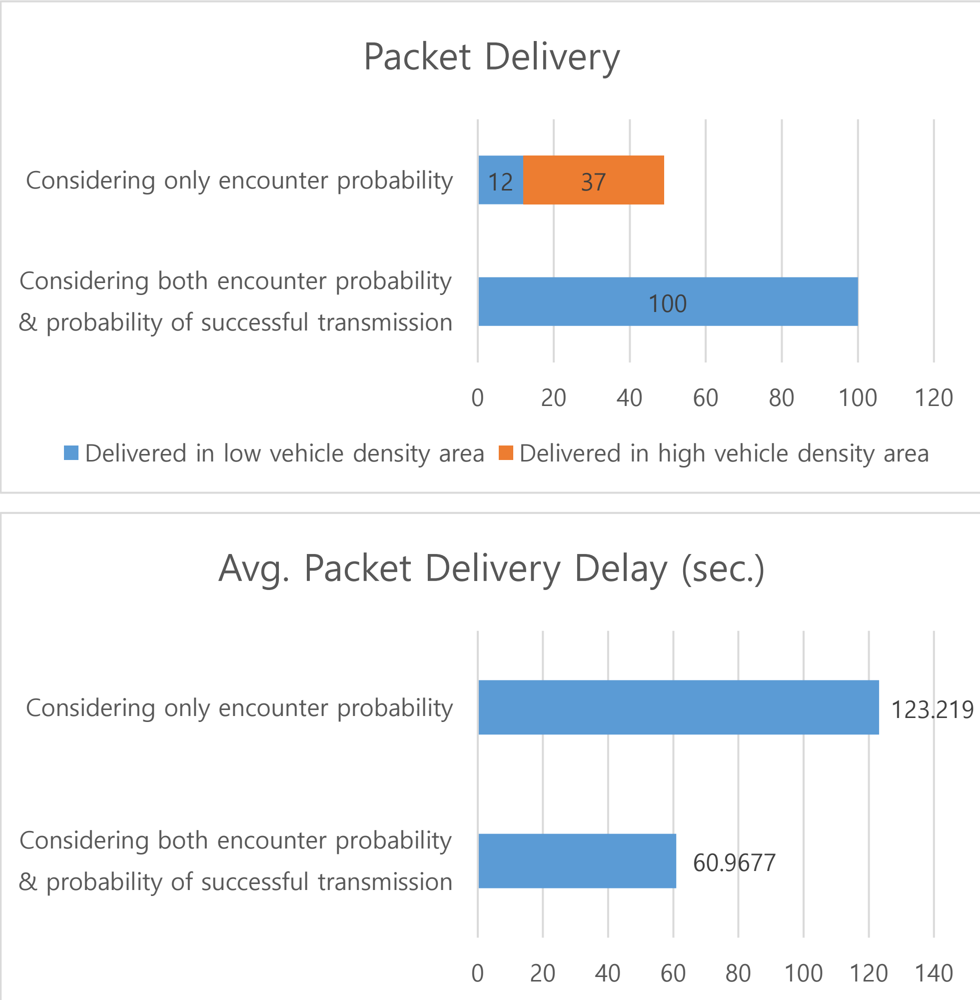


Fig. 5. The impact of the probability of successful transmission on packet delivery ratio and packet delivery delay.

encounter probability on forwarding decision. The reason is that, since there are few chances to grab the channel in high vehicle density area, the packet is often carried by the vehicle rather than forwarding through wireless communications. It results in slow propagation of the packet.

Now we compare performance of our PDPD with GPCR in terms of packet delivery ratio and average packet delivery delay. In our simulation, we use a road network with 25 intersections. We change the number of vehicles. Each vehicle has a random starting point at one of the intersections, and sets its ending point of another intersection at random. For routing between the starting point to the ending point, we apply the standard Dijkstra's algorithm. The movement of the vehicle is then constrained along the shortest route. When a vehicle arrives at its ending point, it repeats the movement procedure by setting another ending point at random.

The speed of each vehicle follows the normal distribution of $N(\mu_v, \sigma_v)$ where $\mu_v = 60km/h$ and $\sigma_v = 20km/h$ [29]. We set the vehicle speed at the entrance of a road segment so that a vehicle may have a different speed at each road segment. Two public vehicles are used as packet destination. Each public vehicle moves around in the perimeter of center of the road network, which is fixed. During the simulation, 100 packets are dynamically generated from a specific private vehicle in the road network, which circulate in the perimeter of whole road network. We continue each simulation run until all of these packets are delivered or dropped (when current packet carrier arrives at its destination, then the packet is dropped).

We investigate the performance of PDPD with different vehicular densities. We vary the vehicle number from 100 to 1000 (the vehicular density can be expressed by the number of vehicles in the network). As shown in Fig. 6, with different densities, PDPD always outperforms GPCR in terms of packet delivery ratio. This is because (1) the trajectory information provides more accurate knowledge for forwarding decision and (2) with the probability of successful transmission, PDPD can avoid delivering a packet to a public vehicle which passes through high density area where the transmission will be likely to fail due to collision with other vehicles.

As the number of vehicles in the road network increases up to 400, the delivery delays of both schemes seem to decrease due to a higher chance of meeting vehicles with a smaller delay. However, as the number of vehicle increases beyond a certain threshold, the delivery delays increase, which is due to the fact that there are few chances to use wireless communications (due to collisions). Because GPCR does not consider this problem when making forwarding decisions, it shows a much longer delivery delay in high vehicular density.

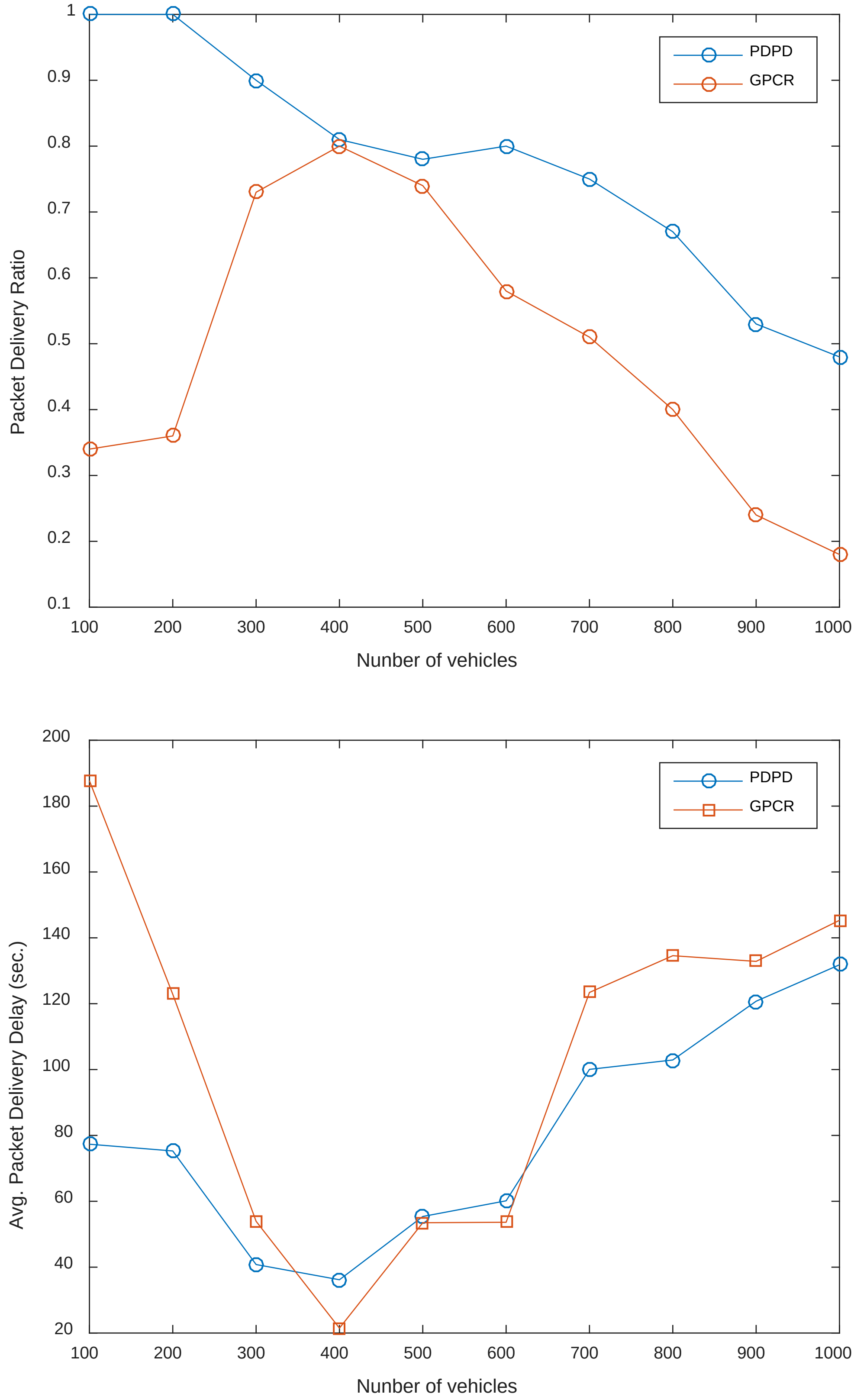


Fig. 6. Comparison with other routing scheme.

VI. CONCLUSION

VANET, one of core technology of ITS for a variety of services, is the essential element to the realization of traffic environments with better safety and efficiency. Routing protocols in VANET have been developed for decades and often designed based on routing protocols in MANET. However, the requirement of high mobility support in VANETs makes it more challenging despite recent advance in communication technology. In this thesis, we propose a reliable vehicle-to-vehicle data delivery called Packet Delivery Prediction-based Data Forwarding (PDPD), accounting for traffic statistics and quality of wireless communications. PDPD uses two probabilities to guide forwarding decision; the encounter probability of two vehicles that is the next forwarder and the destination vehicles, and the probability of successful transmission at the encounter place. We evaluate our proposed schemes through simulations. The results show that packets can be delivered in a more reliable manner under the proposed scheme by considering the probability of successful transmission in vehicular networks.

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