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Trajectory-Based Data Forwarding Schemes for Vehicular Networks

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Abstract

This paper explains trajectory-based data forwarding schemes for multihop data delivery in vehicular networks where the trajectory is the GPS navigation path for driving in a road network. Nowadays, GPS-based navigation is popular with drivers either for efficient driving in unfamiliar road networks or for a better route, even in familiar road networks with heavy traffic. In this paper, we describe how to take advantage of vehicle trajectories in order to design data-forwarding schemes for information exchange in vehicular networks. The design of data-forwarding schemes takes into account not only the macro-scoped mobility of vehicular traffic statistics in road networks, but also the micro-scoped mobility of individual vehicle trajectories. This paper addresses the importance of vehicle trajectory in the design of multihop vehicle-to-infrastructure, infrastructure-to-vehicle, and vehicle-to-vehicle data forwarding schemes. First, we explain the modeling of packet delivery delay and vehicle travel delay in both a road segment and an end-to-end path in a road network. Second, we describe a state-of-the-art data forwarding scheme using vehicular traffic statistics for the estimation of the end-to-end delivery delay as a forwarding metric. Last, we describe two data forwarding schemes based on both vehicle trajectory and vehicular traffic statistics in a privacy-preserving manner.

Keywords

VANET; DSRC; vehicular networks; data forwarding; vehicle trajectory

1 Introduction

Vehicular ad hoc networks (VANETs) have been studied intensively in wireless communications between vehicles for the driving safety and efficiency in road networks [1]–[7]. Every year, many South Koreans die in road accidents, and the fatality rate is increasing [8]. VANET can reduce the fatality rate by allowing vehicles to communicate directly with each other and avoid collisions in road networks. Also, in the era of high oil prices, VANET can determine the most efficient route for a car to take according to the final destination and real-time traffic conditions [9]. A variety of automotive cloud services [10] can be envisioned for vehicles and drivers. Such services include intelligent navigation, safe driving, automatic update of automotive software, onboard diagnostics (OBD) [11], reporting for online diagnosis, and smartphone vehicular remote control.

VANET for driving safety and efficiency has been researched in earnest since dedicated short range communications (DSRC) was standardized as IEEE 802.11p in 2010 [12]–[14]. IEEE 802.11p is an extension of IEEE 802.11a and defines the vehicular network characteristics, such as high-speed mobility and high vehicle density in roadways. Another important trend in vehicular networks is GPS-based navigation (e.g., dedicated GPS navigation [15] and smartphone navigation [16]), which is commonly used by drivers to navigate in unfamiliar areas. It was expected that 300 million mobile devices would be equipped with GPS receivers in 2009 [17]. These cutting-edge technologies for DSRC and GPS navigation open the way for research into the utilization of vehicle trajectories to make data forwarding more efficient in vehicular networks.

Let us assume the following setting in a vehicular network: The Traffic Control Center (TCC) [18] is a central node that collects traffic statistics (e.g., vehicle inter-arrival rate and average speed per road segment) in a road network. The TCC also maintains the trajectory, current position, speed, and direction of an individual vehicle to track vehicles registered in the TCC. Access points (APs) are sparsely deployed as roadside units (RSUs) [19] and are interconnected in order to provide vehicles with connectivity to wired networks (e.g., the Internet) that lead to the TCC. APs have limited coverage because of the

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sparse deployment of APs by the deployment cost, so the vehicular networks are Disruption Tolerant Networks (DTNs) such that vehicles adopt the forward-and-carry approach for the multihop data delivery in road networks. Using this forward-and-carry approach, many data forwarding schemes (such as VADD [4], Delay-bounded Routing [5] and SADV [6]) for the vehicular networks have been proposed so far. However, these schemes use only vehicular traffic statistics (e.g., vehicle arrival rate per road segment) to compute a forwarding metric, such as Expected Delivery Delay (EDD) from a packet source to a packet destination. Thus, this EDD is used to select a next-hop vehicle toward the packet destination.

Given vehicle trajectories as future navigation paths available through GPS-based navigation systems, three data forwarding schemes, i.e., Trajectory-Based Forwarding (TBD) [1], Trajectory-Based Statistical Forwarding (TSF) [2], and Trajectory-Based Multi-Anycast Forwarding (TMA) [3] have been proposed to take advantage of these vehicle trajectories for 1) the better computation of a forwarding metric called EDD and 2) the determination of a target point that is the rendezvous position of the packet and the destination vehicle. TMA [3] is an extension of TSF [2] for the multicast data delivery from AP to multicast group vehicles as packet destinations. In this paper, we focus on the unicast data delivery scheme with TBD [1] and TSF [2] rather than the multicast data delivery scheme with TMA [3]. Note that this paper is the refined version of our early magazine article in [20], explaining TBD [1] and TSF [2] from the forwarding design aspect.

The remainder of this paper is structured as follows. Section 2 is a literature review of vehicular networking. Section 3 describes the modeling of link delay, packet delivery delay, and vehicle travel delay. Section 4 describes a data-forwarding scheme called vehicle-assisted data delivery (VADD), which is based on vehicular traffic statistics [4], as well as two data-forwarding schemes, TBD [1] and TSF [2], which are based on vehicle trajectories. Section 5 analyzes these two trajectory-based forwarding schemes along with VADD. Section 6 concludes the paper and describes future work.

2 Related Work

Much research has been done on multihop Vehicle-to-Infrastructure (V2I) [1], [4], [5], Infrastructure-to-Vehicle (I2V) [2], and Vehicle-to-Vehicle (V2V) [2] data-forwarding for safety and efficiency in vehicular networks. For these networks, VANETs are used for data forwarding over multihop toward the packet destination. VANET is different from traditional mobile ad hoc networks (MANETs) [20] because it supports the networking in road networks with layout rather than in two-dimensional open space assumed by MANETs. VANET is designed to take into account 1) high-speed vehicular mobility on roadways, 2) confined vehicular mobility on roadways, and 3) predictable vehicle mobility through roadmaps. Because of the first characteristic, there is frequent network partitioning and merging, so the forward-and-carry approach [1] is required instead of connection-oriented route usually used in MANET [21]. Because of the second characteristic, vehicular traffic statistics, such as vehicle arrival rate and average speed per road segment and vehicle branch probability at each intersection, can be collected [1]. The third characteristic is due to vehicle trajectory provided by GPS navigator [2].

Many data-forwarding schemes have been proposed with digital roadmaps and vehicular traffic statistics [4]–[6]. VADD [4] formulates the data-forwarding process as a stochastic process in road segments or at intersections, and is designed to minimize delivery delay. Delay-bounded routing [5] is designed to minimize communication cost in terms of the number of packet transmissions for better channel utilization. SADV [6] is a stable forwarding structure in road networks. It is based on relay nodes and reduces deviation in the delivery delay. These three schemes are for the multihop V2I data delivery, and the packet destination is a static node. Also, they utilize only vehicular traffic statistics to 1) estimate a link delay that is the delivery delay for a packet to be forwarded or carried over a road segment and 2) estimate a forwarding metric of end-to-end (E2E) delivery delay. Thus, these vehicular traffic statistics are macro-scoped vehicular information that describes the overall patterns of vehicle mobility in road networks.

Besides the forwarding schemes based on macroscoped vehicular information, the following three data-forwarding schemes have been proposed: TBD [1], TSF [2], and TMA [3]. These are based on microscoped vehicular information, such as vehicle trajectory. Based on vehicle trajectory information, TBD, TSF, and TMA are designed for the multihop V2I, I2V, and V2V data delivery, respectively. In this paper, we show how useful vehicle trajectory is in the design of data-forwarding schemes for vehicular networks. Because TMA [3] is an extension of TSF [2] for multicasting in vehicular networks, we focus on TSF along with TBD in this paper. Thus, the main ideas of TBD and TSF will be discussed to provide insight into the design of data-forwarding schemes with vehicle trajectory.

Machine-to-machine (M2M) communications have recently received a lot of attention within the networking community [22]. In a road network setting, M2M needs to allow drivers, passengers, and pedestrians to communicate with vehicles, infrastructure nodes, and Internet servers. This M2M is very important to realize vehicular cloud services that have been identified for next-generation vehicles [10]. Nowadays, most vehicles have more than 50 embedded computer components [11] including OBD systems. When vehicles connect to vehicular cloud via the infrastructure nodes, they can access the following vehicular cloud services: 1) automatic update of software related to systems embedded in the vehicle, 2) intelligent navigation for congested road networks, 3) automatic vehicle control to mitigate the damage in a road accident, 4) accident avoidance to prevent road accidents, and 5) the remote control of vehicles through mobile devices (e.g., smartphones and tablets). With these vehicular cloud services, DSRC-based data forwarding schemes provide vehicles with the network connectivity to the vehicular cloud through VANET at a lower cost by minimizing the usage of cellular networks such as 4G-LTE [23].

3 Delay Modeling

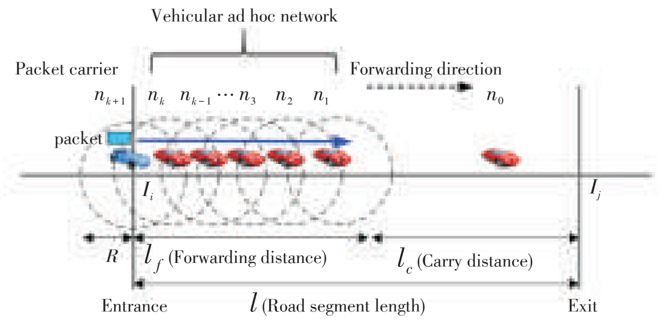
In this section, we describe link delay, E2E packet delivery delay, and E2E vehicle travel delay. We assume that vehicular traffic is one-way traffic to simplify delay modeling. Link delay modeling based on two-way traffic is not covered here.

3.1 Link Delay

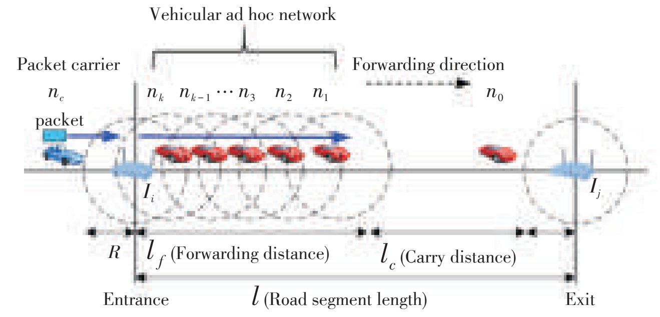
In this subsection, we define link delay as the delay of a packet to be delivered over a road segment from its entrance intersection to its exit intersection using forward-and-carry. We consider link delay in the following two cases: 1) No relay node exists at each intersection, and 2) A relay node exists at each intersection as a temporary packet holder.

3.1.1 Link Delay for a Road Segment without Relay Nodes

We model link delay for a road segment without relay nodes at its intersections that are the end-points of the road segment. As shown in **Fig. 1a**, Packet Carrier n_{k+1} arrives at the entrance of road segment (I_i, I_j). The link delay over the road segment length l is the sum of the communication delay over the forwarding distance l_f and the carry delay over the carry distance l_c. For simplicity, we represent the link delay as the carry delay because the forwarding delay in milliseconds is negligible compared with the carry delay in seconds. That is, the carry delay is the dominant factor in the link delay.



(a) Link delay modeling without relay nodes



(b) Link delay modeling with relay nodes

▲**Figure 1. Link delay modeling for road segment.**

To compute the link delay, we first need to compute the forwarding distance l_f over road segment l and then compute the carry distance l_c as $l - l_f$. Let v be the average vehicle speed over the road segment. The road segment (I_i,I_j), the link delay d_{ij} can be computed as the carry delay as follows:

$$d_{ij} = \frac{l_c}{v} = \frac{l - l_f}{v}. \tag{1}$$

The expected link delay $E[d_{ij}]$ is computed as follows:

$$E[d_{ij}] = E\left[\frac{l_c}{v}\right] = E\left[\frac{l - l_f}{v}\right] = \frac{l}{v} - \frac{E[l_f]}{v}. \tag{2}$$

Thus, for $E[d_{ij}]$ in (2), the expected forwarding distance $E[l_f]$ needs to be computed. As shown in Fig. 1a, $E[l_f]$ can be computed as the sum of vehicle interdistances D_h for $h = 1 \ldots k$ from the entrance intersection I_i, leading to the connected vehicular ad hoc network. We assume that the vehicles arrive at the entrance intersection I_i of road segment (I_i, I_j) by the Poisson process of the arrival rate λ. In light-traffic vehicular networks that are our target settings, this assumption is validated from traffic measurements [24]. $E[l_f]$ is computed as the conditional expectation of the length of the connected vehicular ad hoc network, consisting of vehicle interdistances D_h (for $h = 1 \ldots k$) interconnected by the communication range R. The vehicle interdistance D_h is the product of vehicle interarrival time T_h and average vehicle speed v that is, $D_h = vT_h$. In [1], the expected forwarding distance $E[l_f]$ is computed as follows:

$$E\left[l_f\right] = E\left[D_h | D_h \le R\right] \times \frac{P\left[D_h \le R\right]}{P\left[D_h > R\right]}. \tag{3}$$

In (3), $E[l_f]$ is the product of 1) the average interdistance, denoted $E\left[D_h | D_h \le R\right]$, of two consecutive vehicles within the same connected vehicular ad hoc network, and 2) the ratio of the probability, denoted $P\left[D_h \le R\right]$, that the interdistance D_h is less than or equal to the communication range R to the probability, denoted $P\left[D_h > R\right]$, that the interdistance D_h is greater than the communication range R.

3.1.2 Link Delay for Road Segment with Relay Nodes

We model link delay for a road segment with relay nodes at its intersections. These nodes are end-points of the road segment. A relay node is placed at each intersection as a temporary packet holder for reliable I2V data delivery [2]. **Fig. 1b** shows link-delay modeling for a road segment (I_i, I_j) with relay nodes at its intersections I_i and I_j. For the case with relay nodes, we consider the following two cases: 1) immediate forwarding and 2) wait and carry. The first case is that packet carrier n_c forwards its packets to the head vehicle n_1 of the connected vehicular ad hoc network (comprising k vehicles from n_1 to n_k) via the relay node (denoted n_{k+1}) at the entrance I_i. The second case is that there are no vehicles within the communication range R of the entrance I_i moving toward exit I_j. In this case, packet carrier n_c forwards its packets to the relay node at entrance I_i, and the relay node holds the packets until a vehicle arrives at I_i and moves from I_i to I_j.

The link delay d for the two cases in Fig. 1b is given by

$$d=\begin{cases}\dfrac{l-l_f-R}{v} & \textit{for case } 1\text{: immediate forward,}\\[2ex] \dfrac{1}{\lambda}+\dfrac{l-R}{v} & \textit{for case } 2\text{: wait and carry.}\end{cases} \tag{4}$$

The expected link delay is computed as the conditional expectation of the link delay for the two cases as follows:

$$\begin{aligned}E[d]&=E[\text{link delay}|\text{forward}]\times P[\text{forward}]+\\&\quad E[\text{link delay}|\text{wait}]\times P[\text{wait}]\\&=\frac{l-R-E[l_f]}{v}\beta+\left(\frac{1}{\lambda}+\frac{l-R}{v}\right)(1-\beta),\end{aligned} \tag{5}$$

where $P[\text{forward}]=\beta=1-e^{-\frac{\lambda R}{v}}$ and $P[\text{wait}]=1-\beta=e^{-\frac{\lambda R}{v}}$. The detailed derivation of $E[d]$ is given in [2, Appendix]. Similarly, the variance of the link delay is given by

$$Var[d]=E[d^2]-(E[d])^2, \tag{6}$$

where $E[d^2]=\dfrac{(l-R)^2-2(l-R)E[l_f]+E[l_f^2]}{v^2}\times\beta+\left(\dfrac{1}{\lambda}+\dfrac{l-R}{v}\right)^2\times(1-\beta)$ and $E[d]$ is (5).

The detailed derivation of $E[d^2]$ is given in [2, Appendix].

Finally, we can model the link delay as a Gamma distribution with mean $E[d]$ in (5) and variance $Var[d]$ in (6) because the link delay is a positive continuous random variable. Although we use this approximated distribution for the link delay, our forwarding design can accommodate any better distribution if available. Thus, the distribution of the link delay d_i for the directed edge $e_i \in E(G)$ in the road network graph G is $d_i \sim \Gamma(\kappa_i,\theta_i)$ such that $\theta_i=\dfrac{Var[d_i]}{E[d_i]}$ and $\kappa_i=\dfrac{E[d_i]}{\theta_i}$. Refer to [25] for the detailed the derivation of the parameters θ_i and κ_i. So far, the link delay over a road segment with relay nodes has been modeled. In next subsection, with this link delay, we will model E2E packet delivery delay.

3.2 E2E Packet Delivery Delay

We define E2E packet delivery delay as the packet delivery delay along a forwarding path from a source position to a destination position in the road network. We model this delay as the sum of the link delays of the road segments on the forwarding path. As in section 3.1.2, the E2E packet delivery delay, denoted P, can be modeled as a Gamma distribution with the mean and variance of the E2E packet delivery delay as follows, assuming that the forwarding path consists of n edges:

$$E[P]=\sum_{i=1}^{n}E[d_i]. \tag{7}$$

$$Var[P]=\sum_{i=1}^{n}Var[d_i]. \tag{8}$$

With the mean in (7) and the variance in (8), the E2E packet delay distribution can be modeled as $P \sim \Gamma(\kappa_p,\theta_p)$ such that $\theta_p=\dfrac{Var[P]}{E[P]}$ and $\kappa_p=\dfrac{E[P]}{\theta_p}$, as derived in [25].

3.3 E2E Vehicle Travel Delay

We define E2E vehicle travel delay as the time taken for a vehicle to move from its current position to its future position along its vehicle trajectory, which is the navigation path in the road network provided by a GPS navigator. It is known that the travel delay for a road segment in a light-traffic road network follows a Gamma distribution [26]. Thus, for a road segment $e_i \in E(G)$, the travel delay distribution is $t_i \sim \Gamma(\kappa_i,\theta_i)$ such that $\theta_i=\dfrac{Var[t_i]}{E[t_i]}$ and $\kappa_i=\dfrac{E[t_i]}{\theta_i}$, as derived in [25]. Note that even for a heavy-traffic road network, our design can accommodate any appropriate distribution from a mathematical model or empirical measurement.

For E2E vehicle travel delay, we take the same approach with the E2E packet delivery delay in section 3.2. Assuming that the vehicle trajectory consists of n edges, we have the mean and variance of the E2E vehicle delay distribution, denoted V, as follows:

$$E[V]=\sum_{i=1}^{n}E[t_i]. \tag{9}$$

$$Var[V]=\sum_{i=1}^{n}Var[t_i]. \tag{10}$$

With the mean in (9) and the variance in (10), the E2E vehicle delay distribution can be modeled as $V \sim \Gamma(\kappa_v,\theta_v)$ such that $\theta_v=\dfrac{Var[V]}{E[V]}$ and $\kappa_v=\dfrac{E[V]}{\theta_v}$, as derived in [25].

In next section, we describe three data forwarding schemes, VADD [4], TBD [1], and TSF [2]. Also, we model the packet delivery delay and vehicle travel delay.

4 Data-Forwarding Schemes

VADD enables us to invent TBD and TSF with vehicle trajectory for the V2I data delivery and the I2V data delivery, respectively. First, we explain how VADD computes a forwarding metric called EDD with only vehicular traffic statistics, used to select a next-hop vehicle in the V2I data delivery. Second, we describe how TBD plugs in vehicle trajectory in the computation of a forwarding metric EDD for the V2I data delivery. Last, we explain how TSF works for the I2V data delivery with our target point selection algorithm using the distributions of the destination vehicle's trajectory.

4.1 Vehicle-Assisted Data Delivery for V2I Data Delivery (VADD)

VADD [4] is a data-forwarding scheme for V2I data delivery. It is based on vehicular traffic statistics, such as the vehicle arrival rate and average speed per road segment along with the digital roadmaps provided by GPS navigation systems [15]. VADD is explained at first because TBD [1], as one of vehicle trajectory-based forwarding schemes, enhances the stochastic model of VADD with individual vehicle trajectory.

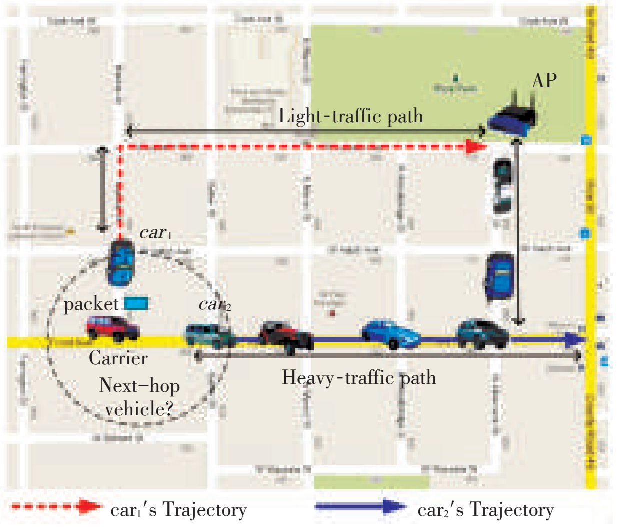
VADD aims to minimize delivery delay from vehicle to infrastructure node (e.g., AP). For example, the current packet carrier (denoted *carrier*) wants to deliver its packet to AP in the road network (**Fig. 2a**). *Carrier* has two neighboring vehicles, car_1 and car_2, within its communication range. The future trajectories of these cars are shown by solid or dotted arrows. Assume that the trajectory of car_1 passes through a light traffic path where a few vehicles are expected to move. On the other hand, the trajectory of car_2 passes through heavy traffic, and many vehicles are expected to move. Therefore, data forwarding over communication has a high chance using intermediate vehicles as packet forwarders during the packet's forward-and-carry process. In this case, definitely, Carrier needs to forward its packets to car_2 as a next-hop carrier rather than car_1, as shown in **Fig. 2b**. In VADD, to support this selection of a next-hop carrier based on vehicular traffic statistics, an EDD is computed as a forwarding metric by vehicles adjacent to the current packet carrier. A minimum-EDD vehicle will be selected as the next-hop carrier. Thus, the EDD computation is a key contribution in VADD.

Here, we explain how to compute EDD given the packet's destination (i.e., the location of the infrastructure node) along with the vehicular traffic statistics. Fig. 2b shows the road network graph as an abstract representation for the road network in Fig. 2a. This road network graph is a directed graph $G=(V,E)$, where V is the vertex set of intersections and E is the directed edge set of road segments. The EDD is computed on the basis of a stochastic model proposed by VADD [4]. Let d_{ij} be the expected link delay for edge e_{ij} in (2), discussed in section 3.1.1. Note that d_{ij} means $E[d_{ij}]$ in (2) for the simplicity of notation. Let D_{ij} be the EDD at the intersection i when a packet is delivered over the edge e_{ij}. The EDD D_{ij} is formulated recursively as follows:

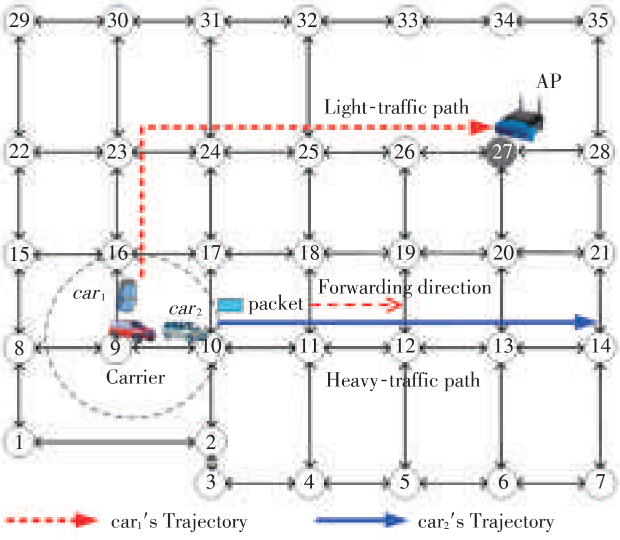
$$\begin{aligned} D_{ij} &= d_{ij} + E\left[\text{delivery delay at } j \text{ by forward or carry}\right] \\ &= d_{ij} + \sum_{k \in N(j)} P_{jk} D_{jk}, \end{aligned} \tag{11}$$

where $N(j)$ is the set of j's adjacent intersections. This recursive formation is reasonable because the packet delivered over edge e_{ij} arrives at intersection j and it is is forwarded to one of j's adjacent intersections, denoted k, with probability P_{jk} and the EDD D_{jk}. Refer to TBD in [1] for the detailed computation of the average forwarding probability P_{jk}.

Fig. 3 shows the EDD computation for edge $e_{9,10}$ where Packet Carrier Candidate is currently moving. The EDD $D_{9,10}$ is computed using (11) as follows: $D_{9,10} = d_{9,10} + P_{10,9}D_{10,9} + P_{10,2}D_{10,2} + P_{10,11}D_{10,11} + P_{10,17}D_{10,17}$. Even though VADD solves the data forwarding problem through the linear systems

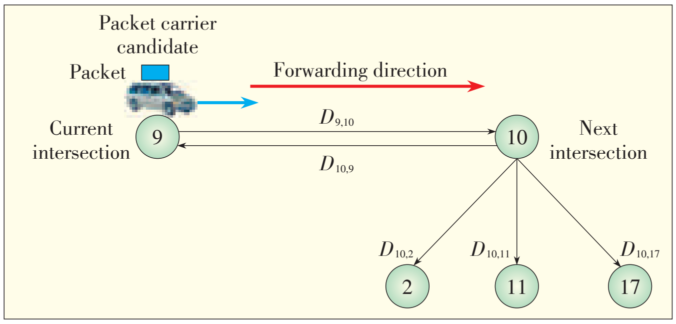


(a) V2I data forwarding considering vehicle density



(b) Next-hop vehicle selection for V2I data forwarding

▲**Figure 2. V2I data forwarding in road network.**



▲**Figure 3. EDD computation for Edge $e_{9,10}$.**

of recursive equations in (11), the limitation of VADD does not use the vehicle trajectory available for a better forwarding metric computation. In the next subsection, TBD [1] is used to take advantage of vehicle trajectory and improve VADD.

4.2 Trajectory-Based Data Forwarding for V2I Data Delivery (TBD)

TBD [1] is a data forwarding scheme to improve VADD for the V2I data delivery, using not only vehicular traffic statistics but also vehicle trajectory in the privacy-preserving manner. As an extreme example, assume that Fig. 2b describes the data forwarding in an extremely light-traffic vehicular network so that *carrier* has only car_1 and car_2 as the possible next-hop carriers in this road network. That is, we assume that only these three vehicles exist in the road network. The next-hop carrier candidates car_1 and car_2 are moving toward intersection 16 and intersection 10, respectively. One difference is that the trajectory of car_1 passes through AP, and the trajectory of car_2 is far away from the communication range of AP. In this case, car_1 should be selected by *carrier* as a next-hop carrier because car_1 will be able to deliver *carrier's* packets to AP with a shorter EDD than car_2. In this subsection, we explain how individual vehicles compute their EDD with their own trajectory in order to allow for this next-hop selection while they do not expose their own trajectory to other vehicles because of privacy concerns.

The main idea of TBD is to divide the data delivery process into the following two steps: 1) The packet carry process at the current carrier and 2) the delivery process after the packet leaves the current carrier. Note that in the case of light-traffic vehicular networks, a vehicle could carry a packet continuously over multiple edges along its trajectory until it meets a better next-hop carrier.

Suppose the current carrier has the trajectory T (i.e., a sequence of intersections to visit) as $T{:}1 \rightarrow 2 \rightarrow \cdots \rightarrow M$. Let C_{ij} be the total packet carry delay (i.e., travel delay) from intersection i to intersection j along the trajectory ($1 \leqslant i \leqslant j \leqslant M$). That is, C_{ij} is the sum of the carry delays of the road segments between intersections i and j such that $C_{ij} = \sum_{k=i}^{j-1} l_{k,k+1}/v$. The EDD for the trajectory T is given by

$$D = \sum_{j=1}^{M} \Big(P[\text{packet is carried from node 1 to } j] \times \big(C_{1j} + E[\text{delivery delay at } j] \big) \Big)$$
$$= \sum_{j=1}^{M} \left(\left(\prod_{h=1}^{j-1} P^{c}_{h,h+1} \right) \times \left(C_{1j} + \sum_{k \in N(j)} P'_{jk} D_{jk} \right) \right), \tag{12}$$

where P'_{jk} is the forwarding probability to forward a packet at intersection j to another vehicle moving toward intersection k (computed in (6) in [1]), $P^{c}_{h,h+1}$ is the carry probability to carry a packet from intersection h to $h+1$ such that $P^{c}_{h,h+1} = 1 - \prod_{k \in N(h)} P'_{h,h+1}$, and D_{jk} is the EDD at edge e_{jk} in (11).

For example, **Fig. 4** shows the EDD computation for a packet carrier candidate with the trajectory ($T{:}10 \rightarrow 11 \rightarrow 12$). The EDD D is computed by (12) as follows:

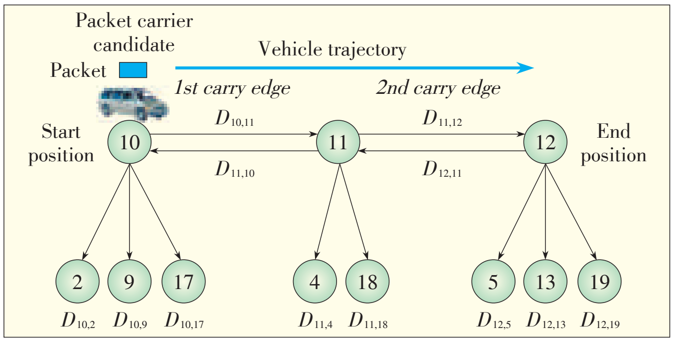
$$\begin{aligned} D = {} & P'_{10,2} D_{10,2} + P'_{10,9} D_{10,9} + P'_{10,11} D_{10,11} + P'_{10,17} D_{10,17} + \\ & P^{c}_{10,11} (C_{10,11} + P'_{11,4} D_{11,4} + P'_{11,10} D_{11,10} + P'_{11,12} D_{11,12} + P'_{11,18} D_{11,18}) + \\ & P^{c}_{10,11} P^{c}_{11,12} (C_{10,12} + P'_{12,5} D_{12,5} + P'_{12,11} D_{12,11} + P'_{12,13} D_{12,13} + P'_{12,19} D_{12,19}). \end{aligned} \tag{13}$$

Therefore, TBD allows individual vehicles to calculate their own EDD based on their own trajectory so that the packet carrier can select the best next-hop carrier among its neighboring vehicles. However, TBD is designed for the static packet destination. Thus, when the destination is moving in the I2V data delivery, we need a totally different approach that takes into account the mobility of the destination vehicle. In the next subsection, we introduce TSF [2] for multihop I2V data delivery.

4.3 Trajectory-Based Statistical Data Forwarding for I2V Data Delivery (TSF)

TSF [2] is a data-forwarding scheme for multihop I2V data delivery, which involves the packet destination vehicle trajectory. **Fig. 5** shows I2V data delivery from AP_1 to Destination Vehicle. TSF for I2V has one significant difference from VADD and TBD for V2I in that TSF requires relay nodes at intersections as temporary packet holders that are not directly connected to the wired network for the deployment cost reduction. The relay nodes are required for the reliable I2V data delivery from AP to a destination vehicle so that the delivery delay standard deviation is bounded to deliver packets from AP to the moving destination vehicle in a timely manner [2], [6].

The challenge for I2V is in selecting a target point that corresponds to a relay node in order to guarantee the rendezvous



▲**Figure 4. EDD computation for vehicle trajectory.**

of the packet from AP and the moving destination vehicle. In Fig. 5, AP$_1$ selects intersection 13, denoted n_{13}, as a target point through the current position and trajectory of Destination Vehicle. The current positions and trajectories of vehicles are available to APs via TCC [18] because the vehicles regularly report their current position and trajectory to TCC for the location management in TCC for the mobile vehicles like in Mobile IPv6 [27]. Thus, TCC is a home agent in managing the location of vehicles in the similar way with Mobile IPv6 so that APs can get the estimated current position and vehicle trajectory of a destination vehicle from TCC.

In TSF, the target point selection is performed with the following two delay distributions: 1) Vehicle delay distribution from Destination Vehicle's current position to a Target Point and 2) Packet delay distribution from AP to a Target Point. **Fig. 6** shows the packet delay distribution from AP$_1$ to target point candidate n_{13} and the vehicle delay distribution from Destination Vehicle's current position n_{10} to target point candidate n_{13}. For each intersection as a target point candidate along Destination Vehicle's trajectory, we can draw a pair of delay distributions, as in Fig. 6.

To optimize delivery, we formulate the target point selection as follows. Let I be a set of intersections along Destination Vehicle's trajectory. Let P_i be the packet delay from AP to target point candidate i. Let V_i be the vehicle delay from Destination Vehicle's current position to target point candidate i. As a target point, TSF selects an intersection to minimize the packet delivery from AP to Destination Vehicle, while satisfying the user-defined delivery probability threshold α (e.g., 95%) as follows:

$$i^* \leftarrow \arg\min_{i\in I} E[V_i] \quad \text{subject to } P[P_i \le V_i] \ge \alpha. \tag{14}$$

In (14), $P[P_i \le V_i]$ is the delivery probability that the packet will arrive at intersection i earlier than Destination Vehicle. In (14), $E[V_i]$ is the actual packet delivery delay from AP to Destination Vehicle. This is because the packet held by the relay node at intersection i is forwarded to Destination Vehicle when Destination Vehicle passes through intersection i after $E[V_i]$.

We model the packet delay distribution and the vehicle delay distribution in Fig. 6 as Gamma distributions so that $P \sim \Gamma(\kappa_p, \theta_p)$ and $V \sim \Gamma(\kappa_v, \theta_v)$. These are discussed in section 3.2 and section 3.3, respectively. If more accurate delay distributions are available, our TSF design can accommodate those better distributions for a better target point selection.

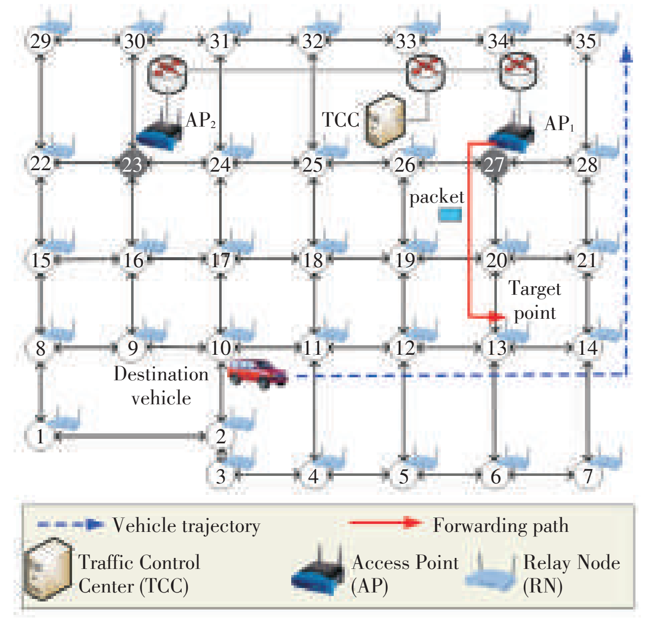
Given the packet delay distribution and the vehicle delay distribution, the delivery probability $P[P_i \le V_i]$ is given by

$$P[P_i \le V_i] = \int_0^{TTL}\int_0^{v} f(p)g(v)\,dp\,dv, \tag{15}$$

where $f(p)$ is the probability density function (PDF) of packet delay p, $g(v)$ is the truncated PDF of vehicle delay v with the integration upper bound TTL that is the packet's Time-To-Live (TTL). Note that since the packet is discarded after TTL, the portion of the delivery probability for vehicle delay v becomes zero after TTL.

TSF can be used for the multihop V2V data delivery in the combination of V2I and I2V. That is, Source Vehicle sends a packet to a nearby AP using TSF (or TBD) for V2I data delivery. Source Vehicle regards AP's intersection as a target point (destination). The AP contacts TCC to locate Destination Vehicle and obtains the corresponding trajectory to compute a target point. With the target point, AP sends the packet toward the target point for I2V data delivery to Destination Vehicle.

TSF can be extended to support multicast from AP to a multicast group vehicles moving in a road network. As a multicast version of TSF, we propose TMA [3]. TMA computes the multiple target points of multicast group vehicles in the same way



PDF: probability density function

Figure 5. I2V data forwarding in road network.

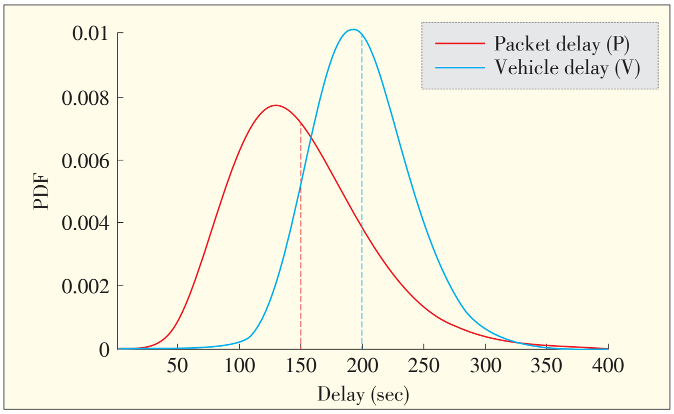


Figure 6. Packet delay distribution and vehicle delay distribution.

that TSF does. With these multiple target points, TMA constructs a minimum Steiner Tree for multicast data delivery so that multicast delivery cost can be minimized and multicast data can be more efficiently shared between vehicles in a multicast group.

One limitation of TSF is that relay nodes need to be deployed as infrastructure nodes for reliable I2V data delivery. In future work, we will develop a data-forwarding scheme that supports both I2V and V2V data delivery without relay nodes and fully utilize the trajectories of vehicles moving in a target road network. In the next section, we analyze three forwarding schemes discussed in this section.

5 Analysis of Forwarding Schemes

Table 1 shows a comparison of the VANET data-forwarding schemes VADD, TBD and TSF. VADD and TBD only support V2I, and their target application is road condition reports. TSF supports V2I, I2V and V2V, which means there are more target applications, such as road condition sharing and cloud services (e.g., navigation and location-based services). These three forwarding schemes use vehicular traffic statistics for forwarding-metric computation. Except for VADD, the other two schemes TBD and TSF take advantage of vehicle trajectory for more efficient forwarding metric computation. TSF supports the more forwarding types, such as V2I, I2V, and V2V.

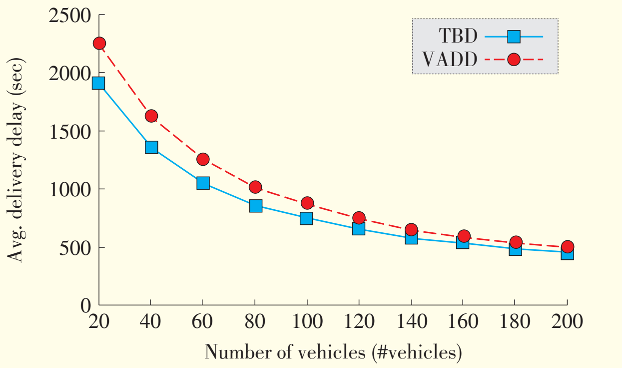
All three forwarding schemes require access points for connectivity to a wired network, such as the Internet. TSF additionally requires relay nodes and traffic control center for reliable multihop I2V (or V2V) data delivery, and protects privacy by not exposing the vehicle trajectories. Thus, for vehicular cloud services through vehicular networks, TSF is recommended because it supports bi-directional data communications between vehicles and infrastructure nodes (e.g., AP).

In the simulations, we evaluated the performance of VADD, TBD, and TSF in an 8.25 km × 9 km road network with 49 intersections. The DSRC communication range is 200 m. The vehicles move in the road network according to a Hybrid Mobility model of City Section Mobility model [28] and Manhattan Mobility model [29]. The simulation configuration can be found in the performance evaluation of TBD [1] and TSF [2].

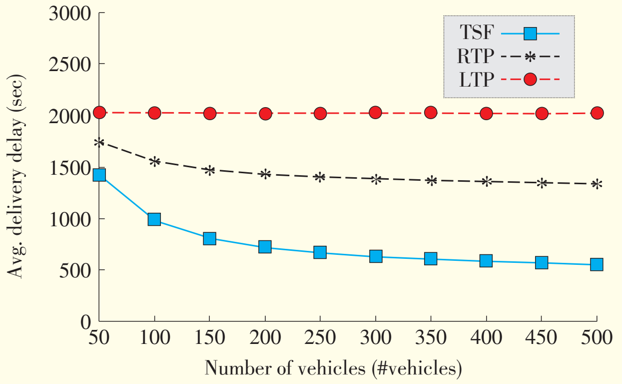
Fig. 7 shows the performance of VANET data-forwarding schemes. For multihop V2I data delivery, Fig. 7a shows the performance of TBD and VADD in average delivery delay by the number of vehicles (i.e., vehicular density) [1]. TBD has a shorter delivery delay than VADD from the lowest vehicular density to the highest vehicular density by a more effective delivery delay estimation using the individual vehicle trajectory. This indicates that TBD provides better V2I data delivery than VADD. For multihop I2V data delivery, Fig. 7b shows TSF, Random Target Point (RTP), and Last Target Point (LTP) [2]. These are different in terms of the target point selection mechanism for a rendezvous point of the packet and destination vehicle. RTP selects a target point as a random intersection among the intersections along the destination vehicle's trajectory. LTP selects a target point as the last intersection of the destination vehicle's trajectory. On the other hand, TSF selects a target point by the optimization in (13) with the packet delay distribution and vehicle delay distribution shown in Fig. 6. TSF has a shorter delivery delay than both RTP and LTP by the optimal target point selection (Fig. 7b). Therefore, the vehicle trajectory is very important information in the design of the data forwarding schemes for either V2I or I2V data delivery.

▼Table 1. The comparison among VANET data forwarding schemes

Scheme	Type	Vehicular Statistics	Vehicle Trajectory	Infrastructure Nodes	Privacy Exposure	Target Application
VADD	V2I	Yes	No	Access points	No	Road condition report
TBD	V2I	Yes	Yes	Access points	No	Road condition report
TSF	V2I, I2V, V2V	Yes	Yes	Access points, relay nodes, traffic control center	No	Road condition sharing, cloud services (e.g., navigation and location-based services)



(a) TBD and VADD comparison for delivery delay by vehicle number for V2I



(b) LTP, RTP, and TSF comparison for delivery delay by vehicle number for I2V

▲Figure 7. The performance evaluation of VANET data forwarding schemes.

6 Conclusions

In this paper, we have described TBD and TSF data-forwarding schemes based on vehicle trajectory in vehicular networks. The vehicle trajectory is a good asset in the design of data-forwarding schemes for multihop V2I or I2V data delivery because it allows for either better forwarding metric computation or better estimation of the location of the packet destination vehicle. In future work, we will investigate more of the characteristics of vehicle trajectory in order to achieve better data forwarding performance, considering the minimization of trajectory sharing overhead and the privacy protection on trajectory. In particular, we will design and implement a new data-forwarding scheme to support multihop V2I, I2V, and V2V data delivery without any relay nodes to reduce deployment cost. For this new data-forwarding scheme, we will investigate how to fully utilize the trajectories of vehicles moving in a target road network. That is, this data forwarding scheme will investigate how to combine packet carrying process and packet forwarding process by predicting the encounter sequence of vehicles as the forwarding chances between the current packet carrier and next-packet carrier candidates with vehicle trajectories.

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