Vehicle Trajectory-Based Data Forwarding Schemes for Vehicular Ad Hoc Networks

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Abstract

This paper introduces three vehicle trajectory-based data forwarding schemes, tailored for vehicular ad hoc networks. Nowadays GPS-based navigation systems are popularly used for providing efficient driving paths for drivers. With the driving paths called vehicle trajectories, we can make data forwarding schemes more efficient, considering the micro-scoped mobility of individual vehicles in road networks as well as the macro-scoped mobility of vehicular traffic statistics. This paper shows why the vehicle trajectory is a key ingredient in the design of the vehicle-to-infrastructure, infrastructure-to-vehicle, and vehicle-to-vehicle data forwarding schemes over multihop. Through the mathematical formulation, the key design techniques are shown for three forwarding schemes based on vehicle trajectory, compared with a state-of-the-art data forwarding scheme based on only vehicular traffic statistics.

Ⅰ. Introduction

Recently, Vehicular Ad Hoc Networks (VANETs) have been intensively researched for the safe and efficient driving in road networks [1]-[7]. Especially, Korea was ranked as the third among the OECD countries in terms of the highest death rate [8]. VANET can reduce this fatality rate by helping vehicles communicate with each other to avoid collisions in roadways. Also, in the era of high oil price, VANET can provide individual vehicles with efficient moving paths, considering their final destinations and real-time traffic conditions in road networks [9]. Through vehicular networks, as shown in Fig. 1, a variety of automotive cloud services [10] can be provided to vehicles, such as 1) Automatic update of automotive software, 2) On-Board Diagnostics (OBD) [11] data report for online diagnosis, and 3) Remote control for vehicle by smartphone.

The vehicular networking for the driving safety and efficiency has been feasible through the standardization of Dedicated Short Range Communications (DSRC) as IEEE 802.11p in 2010 [12]-[14]. IEEE 802.11p is an extension of IEEE 802.11a, considering the characteristics of vehicular networks, such as the high-speed mobility and high node density in roadways. As an important trend for the vehicular networking, GPS-based navigation systems (e.g., dedicated GPS navigator [15] and Smartphone navigator [16]) are popularly used by drivers. It was expected that 300 million mobile devices will be equipped with GPS receivers only in 2009 [17]. With these cutting-edge technologies of DSRC and GPS navigation, one natural research question is how to utilize the vehicle trajectories in order to make data forwarding more efficient in vehicular networks.

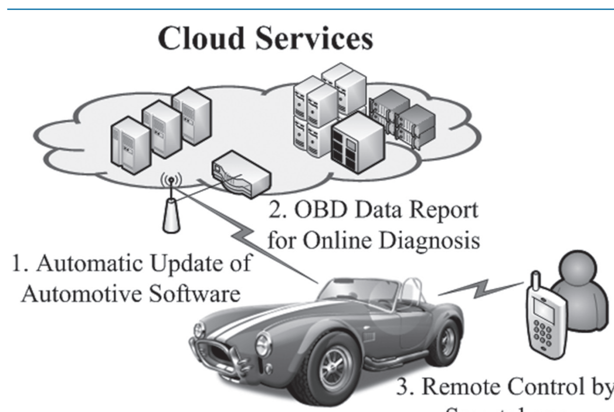


Fig. 1. Automotive Cloud Services through Vehicular Networks

Let us assume the setting of vehicular networks. Traffic Control Center (TCC) [18] is a central node to collect vehicular traffic statistics in road networks and to maintain individual vehicle trajectories. Access Points (APs) are sparsely deployed as Road-Side Units (RSUs) [19] and interconnected to provide vehicles with the connectivity to the wired networks (e.g., the Internet) having the TCC. Since the APs have the limited coverage due to the sparse deployment of APs, the vehicular networks are one of Disruption Tolerant Networks (DTNs) such that vehicles use the forward-and-carry approach for data delivery. 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. These schemes use vehicular traffic statistics (e.g., vehicle arrival rate per road segment) to compute the forwarding metric, such as expected delivery delay.

Given vehicle trajectories as future moving paths available through GPS-based navigation systems, three data forwarding schemes (i.e., TBD [1], TSF [2], and STDFS [3]) have been proposed to take advantage of these vehicle trajectories for 1) the better computation of forwarding metrics and 2) the determination of target points that are the rendezvous positions of the packet and the destination vehicle.

This paper is structured as follows. Section II summarizes the literature review of vehicular networking. Section III describes the modeling of link delay, packet delivery delay, and vehicle travel delay. Section IV describes a vehicular traffic statistics-based data forwarding called VADD [4] and three data forwarding schemes based on vehicle trajectories. Section V analyzes three trajectory-based forwarding schemes along with VADD. Section VI concludes this paper along with future work.

Ⅱ. Related Work

For vehicular networks, many researchers have researched on the multihop vehicle-to-infrastructure (V2I) [1][4][5], infrastructure-to-vehicle (I2V) [2], and vehicle-to-vehicle (V2V) [3] communications for the driving safety and efficiency. For these vehicular networks, Vehicular Ad Hoc Networks (VANETs) have been designed, different from the traditional Mobile Ad Hoc Networks (MANETs) [20]. This is because VANETs should consider the networking in road networks rather than two-dimensional open space in MANETs with the following three characteristics: 1) High-speed vehicle mobility in roadways, 2) Confined mobility within roadways, and 3) Predicted mobility through roadmaps. Due to the first characteristic, the frequent network partition and mergence happens, so the forward-and-carry approach is required [1]. With the second characteristic, the vehicular traffic statistics can be collected, such as vehicle arrival rate and average speed per road segment and vehicle branch probability at each intersection [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 and at intersections, aiming at the minimal delivery delay. Delay-bounded Routing [5] aims at the minimization of communication cost in terms of the number of packet transmissions for better channel utilization. SADV [6] proposes a stable forwarding structure in road networks based on relay nodes to reduce the deviation of the delivery delay. All of these three schemes are for the multihop V2I data delivery such that the packet destination is 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 and 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 to describe the overall patterns of vehicle mobility in road networks.

In addition to the forwarding schemes based on the macro-scoped vehicular information, the following three data forwarding schemes have been proposed, based on micro-scoped vehicular information, such as vehicle trajectory: 1) Trajectory-Based Forwarding (TBD) [1], 2) Trajectory-based Statistical Forwarding (TSF) [2], and 3) Shared-Trajectory-based Data Forwarding Scheme (STDFS) [3]. Based on vehicle trajectory information, TBD, TSF, and STDFS are designed for the multihop V2I, I2V and V2V data delivery, respectively. In this paper, it will be shown how much useful the vehicle trajectory is in the design of the data forwarding schemes for vehicular networks. Also, the main ideas of TBD, TSF, and STDFS will be discussed to let the audience get some insights for the design of data forwarding schemes.

Machine-to-Machine (M2M) communications have recently received a lot of attention from the networking community [24]. In the 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 automotive cloud services (as shown in Fig. 1) that have been spotlighted for next-generation vehicles [10]. Nowadays most of vehicles have more than 50 embedded computer components [11] including On-Board Diagnostics (OBD) Systems. When vehicles can connect to the infrastructure nodes, they can support 1) the auto-update of software related to their embedded systems, 2) intelligent navigation services even in damaged roads after earthquake, 3) passive safety to mitigate the damage in an accident, 4) active safety to avoid an accident, and 5) the remote control of vehicles through mobile devices and smartphones. For these automotive cloud services, DSRC-based data forwarding schemes can provide vehicles with the network connectivity through vehicular ad hoc networks at a lower cost than cellular networks.

Ⅲ. Delay Modeling

In this section, we describe link delay, E2E packet delivery delay, and E2E vehicle travel delay. We assume that the vehicular traffic is one-way traffic for simplicity in delay modeling. The link delay modeling based on two-way traffic is left as future work.

Ⅲ.1 Link Delay

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.

Ⅲ.1.1 Link Delay for Road Segment without Relay Nodes

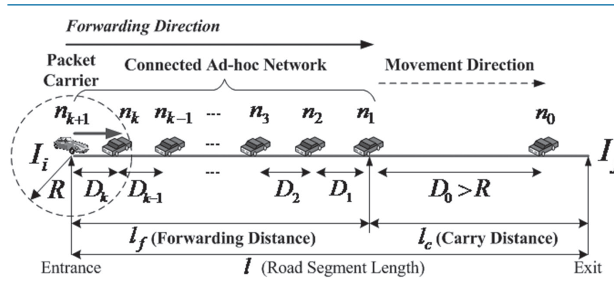


Fig. 2. Link Delay Modeling for Road Segment

In this section, we model link delay for a road segment without relay nodes at intersections that are the end-points of the road segment. As shown in Fig. 2, 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.

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

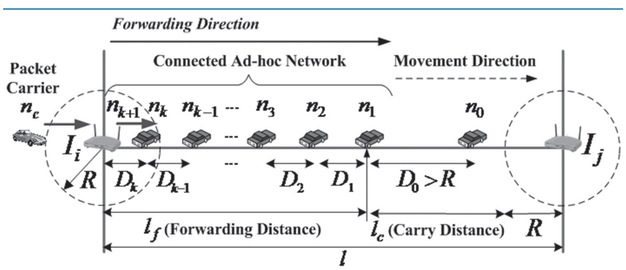
$$E[d_{ij}] = E\left[\frac{l_c}{v}\right] = E\left[\frac{l - l_f}{v}\right] = \frac{l}{v} - \frac{E[l_f]}{v}. \tag{2}$$

Thus, for $E[d_{ij}]$ in (2), the expected forwarding distance $E[l_f]$ needs to be computed. As shown in Fig. 2, the expected forwarding distance can be computed as the sum of vehicle interdistances D_h for $h = 1..k$ from the entrance intersection I_i, leading to the connected 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. Note that in the light-traffic vehicular network that is our target setting, this assumption is validated from traffic measurements [25]. The expected forwarding distance is computed as the conditional expectation of the length of the connected ad-hoc network, consisting of vehicle interdistances D_h interconnected by the communication range R. Note that 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:

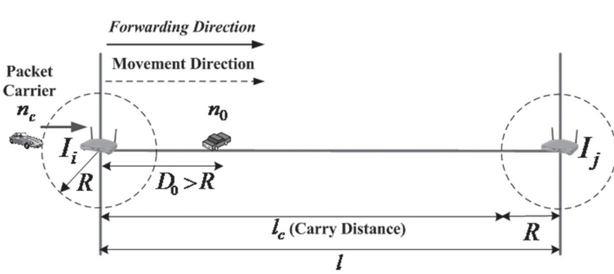
$$E[l_f] = E[D_h | D_h \leq R] \times \frac{P[D_h \leq R]}{P[D_h > R]}. \tag{3}$$

In (3), it can be seen that $E[l_f]$ is the product of 1) the average interdistance of two vehicles within the same connected ad-hoc network and 2) the ratio of the probability that the interdistance is not greater than the communication range to the probability that the interdistance is greater than the communication range.

Ⅲ.1.2 Link Delay for Road Segment with Relay Nodes



(a) Case 1: Immediate Forward



(b) Case 2: Wait and Carry

Fig. 3. Link Delay Modeling for Road Segment with Relay Nodes

In this section, we model link delay for a road segment with relay nodes at intersections that are the end-points of the road segment. In this case, we consider that a relay node is placed at each intersection as a temporary packet holder for the reliable I2V data delivery [2]. Fig. 3 shows the link delay modeling for road segment (I_i, I_j) with relay nodes at intersections I_i and I_j. For the case with relay nodes, we consider two cases of 1) Immediate Forward and 2) Wait and Carry. As shown in Fig. 3(a), the first case is that Packet Carrier n_c can forward its packets to the head vehicle n_1 of the connected ad-hoc network (consisting of k vehicles from n_1 to n_k) via the relay node (denoted as n_{k+1}) at the entrance I_i. As shown in Fig. 3(b), the second case is that Packet Carrier n_c forwards its packets to the relay node at the entrance I_i and the relay node will hold 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. 3 is represented as follows:

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

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 $P[\text{wait}] = 1 - \beta = e^{-\frac{\lambda R}{v}}$. Refer to Appendix in [2] for the detailed derivation of $E[d]$. In the similar way, the variance of the link delay can be computed as follows:

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

where $E[d^2] = \frac{(l-R)^2 - 2(l-R)E[l_f] + E[l_f^2]}{v^2} \times \beta + \left(\frac{1}{\lambda} + \frac{l-R}{v}\right)^2 \times (1 - \beta)$ and $E[d]$ is (5). Refer to Appendix in [2] for the detailed derivation of $E[d^2]$.

Finally, we model the link delay as a Gamma distribution with the mean $E[d]$ in (5) and the variance $Var[d]$ in (6). This is because the link delay is a positive continuous random variable. Though 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 $e_i \in E(G)$ for the road network graph G is $d_i \sim \Gamma(\kappa_i, \theta_i)$ such that $\theta_i = \frac{Var[d_i]}{E[d_i]}$ and $\kappa_i = \frac{E[d_i]}{\theta_i}$. Refer to [26] 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. With this link delay, we will model End-to-End (E2E) packet delivery delay.

Ⅲ.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 E2E packet delivery delay as the sum of the link delays of the road segments on the forwarding path. In the same way with Section Ⅲ.1.2, the E2E packet delivery delay 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 $\theta_p = \frac{Var[P]}{E[P]}$ and $\kappa_p = \frac{E[P]}{\theta_p}$.

Ⅲ.3 E2E Vehicle Travel Delay

We define E2E vehicle travel delay as the travel time for a vehicle to take from its current position to its future position along its vehicle trajectory that is the driving path in the road network, provided by GPS navigator. It is known that the travel delay for a road segment in a light-traffic road network follows a Gamma distribution [27]. 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 $\theta_i = \frac{Var[t_i]}{E[t_i]}$ and $\kappa_i = \frac{E[t_i]}{\theta_i}$. Note that even for a heavy-traffic road network, our design can use an appropriate distribution from a mathematical model or travel measurement.

For the E2E vehicle travel delay, we take the same approach with the E2E packet delivery delay in Section Ⅲ.2. Assuming that the vehicle trajectory consists of N edges, we have the mean and variance of the E2E vehicle delay distribution 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 $\theta_v = \frac{Var[V]}{E[V]}$ and $\kappa_v = \frac{E[V]}{\theta_v}$.

In the next section, we will describe four data forwarding schemes with the modeling of the packet delay and the vehicle delay.

Ⅳ. Data Forwarding Schemes

In this section, we describe four data forwarding schemes, such as VADD [4], TBD [1], TSF [2], and STDFS [3].

Ⅳ.1 VADD: Vehicle-Assisted Data Delivery for V2I Data Delivery

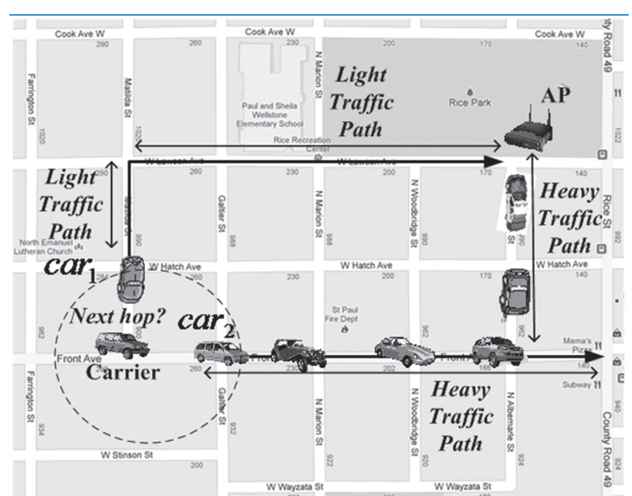


Fig. 4. VADD Data Forwarding in Road Network

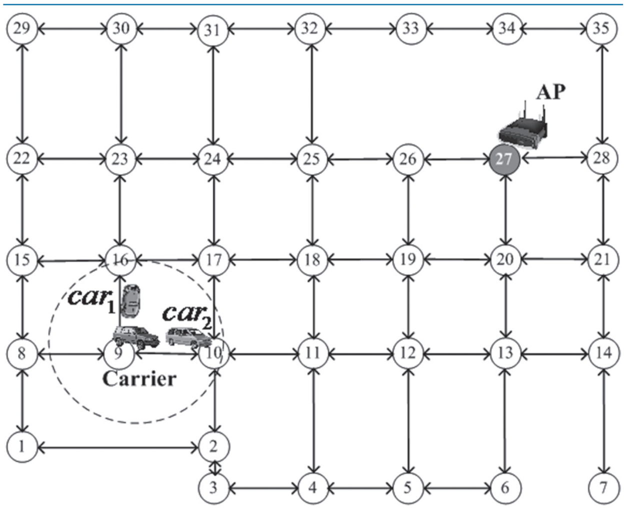


Fig 5. Road Network Graph for Data Forwarding

VADD [4] is a data forwarding scheme for the V2I data delivery, 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 here at first because TBD [1] (as one of vehicle trajectory–based forwarding schemes) is based on the stochastic model of VADD.

VADD aims at the minimization of the delivery delay from vehicle to infrastructure node (e.g., AP). For example, as shown in Fig. 4, the current packet carrier (denoted as Carrier) wants to deliver its packet to AP in the road network. It has two neighboring vehicles (denoted as Car_1 and Car_2) within its communication range; note that their future trajectories are denoted as solid arrows. Car_1's trajectory passes through a light traffic path where a few vehicles are moving statistically. On the other hand, Car_2's trajectory passes through a heavy traffic path where a lot of vehicles are moving statistically, so the data forwarding over communication has a high chance by using intermediate vehicles 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. In VADD, to support this selection of next–hop carrier based on vehicular traffic statistics, an Expected Delivery Delay (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.

Now we will explain how to compute EDD value given the packet's destination (i.e., the location of the infrastructure node) along with the vehicular traffic statistics. Fig. 5 shows the road network graph as a representation for the road network in Fig. 4. 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 as follows. Let d_{ij} be the expected link delay for edge e_{ij} in (2), discussed in Section Ⅲ.1.1. 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:

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

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

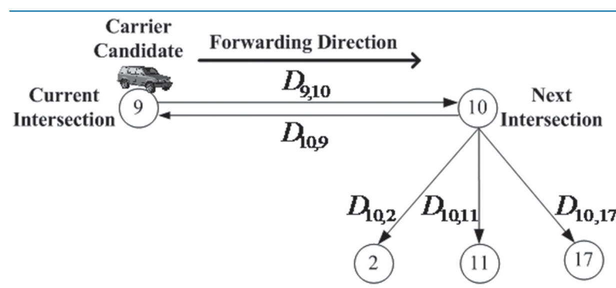


Fig 6. EDD Computation for Edge $e_{9,10}$

For example, Fig. 6 shows the EDD computation for edge $e_{9,10}$ where Carrier Candidate is currently moving. The EDD $D_{9,10}$ is computed by (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 nicely through the linear systems 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] takes advantage of vehicle trajectory to improve VADD.

Ⅳ.2 TBD: Trajectory-Based Data Forwarding for V2I Data Delivery

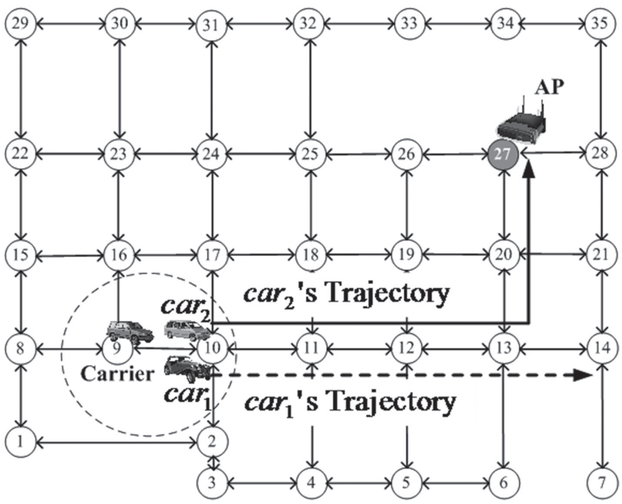


Fig. 7. TBD Data Forwarding in Road Network

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, Fig. 7 shows the data forwarding in an extremely light-traffic vehicular network. The current packet carrier (denoted as Carrier) has only two neighboring vehicles (denoted as car_1 and car_2) for the next-hop carrier in this road network. We assume that only these three vehicles exist in the road network. The next-hop carrier candidates car_1 and car_2 are moving at the same coordinate and in the same direction toward intersection 11. One difference is that car_1's trajectory is far away from the communication range with AP and car_2's trajectory passes through AP. In this case, car_2 should be selected by Carrier as a next-hop carrier because car_2 has a high chance to deliver Carrier's packets to AP. In this section, we will 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 due to privacy concerns.

The main idea of TBD is to divide the data delivery process into 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 time (i.e., travel time) from intersection i to intersection j along the trajectory ($1 \leq i \leq j \leq M$). 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 computed as follows:

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

where 1) P'_{jk} is the forwarding probability to forward packet at intersection j to another vehicle moving toward intersection k (computed in (6) in [1]), 2) $P^{c}_{h,h+1}$ is the carry probability to carry 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 3) D_{jk} is the EDD at edge e_{jk} in (11).

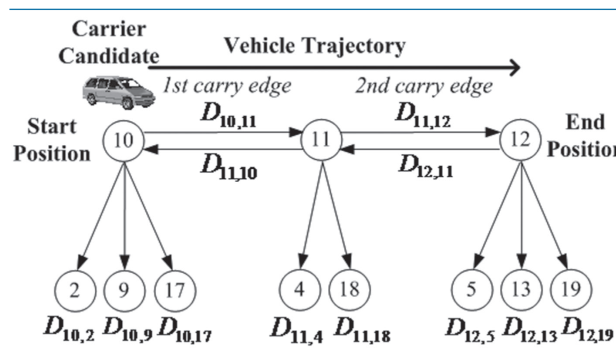


Fig. 8. EDD Computation for Vehicle Trajectory

For example, Fig. 8 shows the EDD computation for carrier candidate with the trajectory ($T: 10 \rightarrow 11 \rightarrow 12$). The EDD D is computed by (12) as follows:

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

Therefore, TBD can allow 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 infrastructure-to-vehicle data delivery, we need a totally different approach considering the mobility of the destination vehicle. In the next subsection, we will introduce TSF [2] for the multihop infrastructure-to-vehicle data delivery.

Ⅳ.3 TSF: Trajectory-Based Statistical Forwarding for I2V Data Delivery

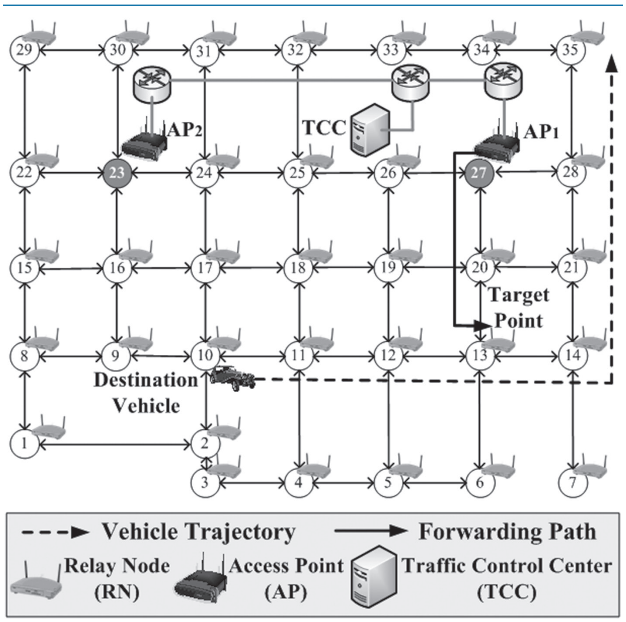


Fig. 9. TSF Data Forwarding in Road Network

TSF [2] is a data forwarding scheme for the multihop infrastructure-to-vehicle (I2V) data delivery, using the trajectory of the packet destination vehicle. Fig. 9 shows the I2V data delivery from AP_1 to Destination Vehicle. One remarkable difference from VADD and TBD for V2I is 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 unlike Access Points (APs) [22]. The relays nodes are necessary for I2V because the delivery delay standard deviation should be bounded to deliver packets from AP to a moving destination vehicle in a timely manner [2][6].

The challenge for I2V is how to select a target point that corresponds to a relay node to guarantee the rendezvous of the packet from AP and the moving destination vehicle. In the figure, AP_1 selects intersection 13 (denoted as n_{13}) as a target point through the current position and trajectory of Destination Vehicle; note that the current positions and trajectories of vehicles are available to APs via Traffic Control Center (TCC) [18] because the vehicles regularly update their current position and trajectory in TCC. Thus, TCC plays a role of a home agent for the location management of vehicles in the similar way with Mobile IPv6 [28].

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 Target Point and 2) Packet delay distribution from AP to Target Point. Fig. 10 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 along Destination Vehicle's trajectory, we can draw a set of delay distributions like Fig. 10.

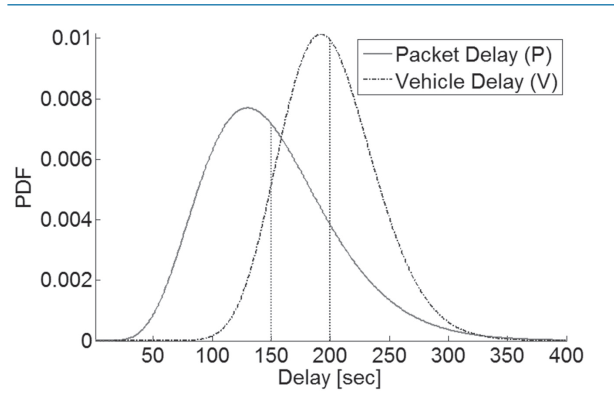


Fig. 10. Packet Delay Distribution and Vehicle Delay Distribution

For the delivery optimization, we formulate the target point selection as follows. Let I be a set of intersections on 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:

$$i^* \leftarrow \arg\min_{i \in I} E[V_i] \quad \text{subject to } P[P_i \leq V_i] \geq \alpha \tag{13}$$

In (13), $P[P_i \leq V_i]$ is the delivery probability that the packet will arrive at intersection i earlier than Destination Vehicle. In (13), $E[V_i]$ is the actual packet delivery delay from AP to Destination Vehicle in that the packet held by the relay node at intersection i will be forwarded to Destination Vehicle when Destination Vehicle passes through intersection i after $E[V_i]$.

For the packet delay distribution and the vehicle delay distribution in Fig. 10, we model those delay distributions as Gamma distributions such that $P \sim \Gamma(\kappa_p, \theta_p)$ and $V \sim \Gamma(\kappa_v, \theta_v)$, discussed in Section Ⅲ.2 and Section Ⅲ.3, respectively. If more accurate delay distributions are available, TSF design can accommodate those better distributions for the target point selection.

Given the packet delay distribution and the vehicle delay distribution, the delivery probability $P[P_i \leq V_i]$ is computed as follows:

$$P[P_i \leq V_i] = \int_0^{TTL} \int_0^{v} f(p) g(v) dp dv, \tag{14}$$

where $f(p)$ is the probability density function (PDF) of packet delay p, $g(v)$ is the PDF of vehicle delay v, and TTL is the packet's Time-To-Live (TTL).

Actually, TSF can be used for the multihop V2V data delivery. That is, Source Vehicle sends a packet to a nearby AP using TSF (or TBD), regarding AP's intersection as a target point (or destination). The AP contacts Traffic Control Center to locate Destination Vehicle and get the corresponding trajectory in order to compute a target point, sending the packet toward the target point for the I2V data delivery to Destination Vehicle.

One limitation of TSF is to require relay nodes as infrastructure nodes for the reliable I2V data delivery. In the next subsection, we will introduce STDFS [3] to support both I2V and V2V data delivery without relay nodes by fully utilizing the trajectories of vehicles existing in a target road network.

Ⅳ.4 STDFS: Shared-Trajectory-Based Data Forwarding Scheme for V2V Data Delivery

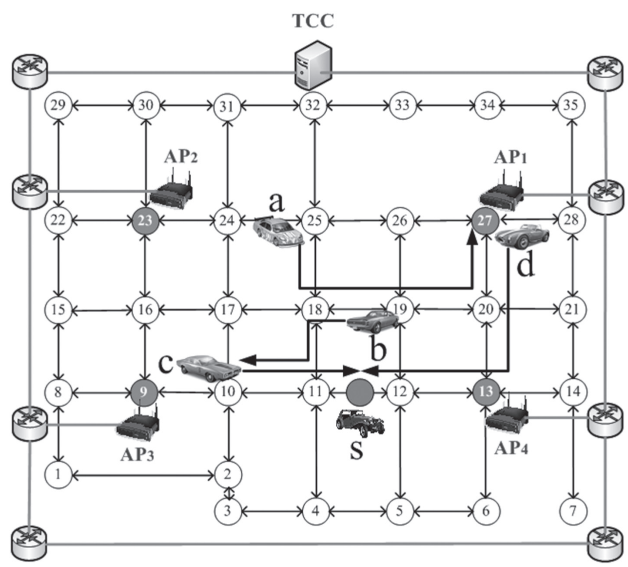


Fig. 11. STDFS Data Forwarding in Road Network

STDFS [3] is a data forwarding scheme for the multihop vehicle-to-vehicle (V2V) data delivery through the sharing of the trajectories of vehicles moving in a target road network; note that V2V can support I2V (or V2I) by regarding infrastructure node as stationary source vehicle (or stationary destination vehicle) staying at the corresponding intersection. Fig. 11 shows the data forwarding from vehicle a (denoted as V_a) to stationary vehicle s (denoted as V_s) via the intermediate vehicles b or d (denoted as V_b or V_d). STDFS assumes that vehicles can periodically download the trajectories of other vehicles from APs sparsely deployed at intersections, as shown in Fig. 11.

In STDFS, source vehicle constructs the predicted encounter graph to determine the next-hop carrier that can guarantee the user-defined delivery probability α like in TSF. In Fig. 11, V_a is the source vehicle and V_s is the destination vehicle. The vehicles V_b, V_c and V_d are intermediate carriers. As shown in Fig. 12, V_a computes a sequence of encounters with other vehicles. In this figure, V_b and V_d may be the next encountered vehicles for V_a for data forwarding. In the expansion of the predicted encounter graph, V_b may encounter V_c and then V_c may finally encounter the destination V_s. In the same way, V_d may finally encounter the destination V_s. Fig. 12(h) is the final predicted encounter graph considering all of encounter events with encounter probability. Refer to [3] for the detailed computation of the encounter probability for two vehicles.

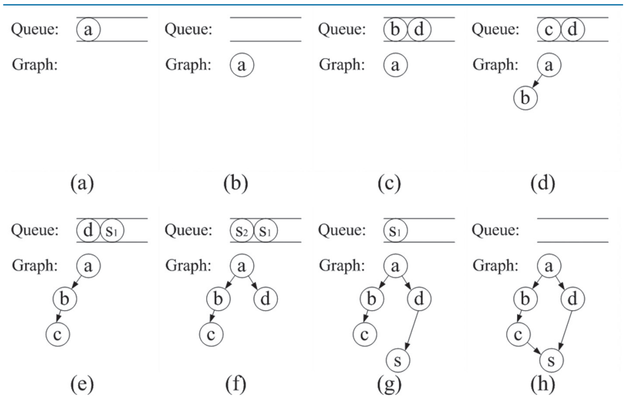


Fig. 12. Predicted Encounter Graph Construction

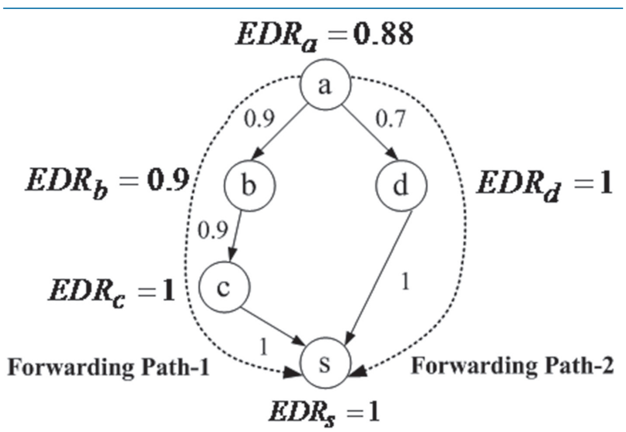


Fig. 13. EDR Calculation of Vehicle V_a

As a forwarding metric, the Expected Delivery Ratio (EDR) is computed from each intermediate carrier to the packet destination with the predicted encounter graph obtained from Fig. 12. To compute the EDR for a given vehicle e (denoted as V_e), first of all, we need to compute the forwarding probability $P_e(i)$ that V_e can forward its packet to the i^{th} forwarder in the predicted encounter graph:

$$P_e(i) = \left(\prod_{j=1}^{i-1}(1-p_{ej})\right)P_{ei}, \qquad (15)$$

where p_{ej} is the encounter probability between V_e and the i^{th} forwarder of V_e in the predicted encounter graph; for example, in Fig. 12, V_b is the 1st forwarder of V_a and V_d is the 2nd forwarder of V_a because V_b and V_d may encounter V_a in the temporal order. Now, the EDR of V_e can be calculated by the following recursive formula:

$$EDR_e = \sum_{i=1}^{n} P_e(i)EDR_i. \qquad (16)$$

For example, given the predicted encounter graph with encounter probability p_{ij} on each directed edge e_{ij} (representing the event of the encounter between vehicles i and j), we can calculate EDR_e for the forwarder candidate V_e. By (16), the EDRs for forwarders can be recursively calculated from the destination V_s up to the source V_e. For the source V_a, the corresponding EDR is calculated as follows: $EDR_a = p_{ab}EDR_b + (1-p_{ab})p_{ad}EDR_d = 0.9 * 0.9 + (1-0.9) * 0.7 * 1 = 0.88$.

Next, we will explain how to compute Expected Delivery Delay (EDD) from V_e to the packet destination V_s. Let $Q_e(i)$ be the conditional probability that V_e's packet is delivered to V_s via V_e's i^{th} forwarder under the condition that V_e's packet is delivered to V_s: that is, $Q_e(i) = \frac{P_e(i)EDR_i}{EDR_e}$. The EDD of V_e can be computed recursively as follows:

$$EDD_e = \sum_{i=1}^{n} Q_e(i)(d_i + EDD_i), \qquad (17)$$

where d_i is the vehicle travel delay (discussed in Section Ⅲ.3) for V_e to carry the packet until V_e encounters its i^{th} forwarder.

For the data forwarding in STDFS, the packet carrier announces the packet destination to neighboring vehicles within the connected ad hoc network. The neighboring vehicles individually calculate their own EDR and EDD by (16) and (17) for the selection of next-hop carrier. The current carrier selects a neighboring vehicle with a minimum EDD so long as the next-hop vehicle's EDR is at least the user-defined delivery probability α.

STDFS requires the sharing of trajectories among vehicles through APs. This means some overhead for the

Table 1. The Comparison among Four Data Forwarding Schemes for Vehicular Ad Hoc Networks

Forwarding Scheme	Forwarding 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 information sharing, Detour guidance, Cloud services
STDFS	V2I, I2V, V2V	Yes	Yes	Access Points, Traffic Control Center	Yes	Road information sharing, Detour guidance, Cloud services

data delivery STDFS. Also, the sharing of trajectories makes concerns about privacy. In the future work, we will design a forwarding protocol to address these two issues. So far we have explained three vehicle trajectory-based data forwarding schemes (i.e., TBD, TSF, and STDFS) as well as one vehicular traffic statistics-based data forwarding (i.e., VADD). In the next section, we will analyze the four forwarding schemes discussed in this section.

Ⅴ. The Analysis of Forwarding Schemes

In this section, we will analyze the four forwarding schemes (i.e., VADD, TBD, TSF, and STDFS) explained in Section Ⅳ. Table 1 shows the comparison among those schemes. VADD and TBD can support only V2I. On the other hand, TSF and STDFS can support all of V2I, I2V and V2V, leading to more target applications, as shown in Table 1. All of four forwarding schemes use vehicular traffic statistics for their forwarding metric computation. Except for VADD, the remaining three schemes take advantage of vehicle trajectory for the more efficient forwarding metric computation (for TBD) and the more forwarding types (for TSF and STDFS).

All of four forwarding schemes require Access Points for the connectivity to the wired network, such as the Internet. TSF additionally requires Relay Nodes and Traffic Control Center for the reliable multihop I2V (or V2V) data delivery without exposing the vehicle trajectories. On the other hand, STDFS does not require Relay Nodes for I2V or V2V, but it needs the exposure of privacy-sensitive vehicle trajectories through the sharing of trajectories among the participant vehicles for STDFS data forwarding.

For the automotive cloud services through vehicular networks as shown in Fig. 1, TSF or STDFS are recommended because they can support bi-directional data communications among vehicles and infrastructure.

Ⅵ. Conclusion

This paper explained three data forwarding schemes based on vehicle trajectory in vehicular networks. The vehicle trajectory is a good asset to the design of data forwarding schemes because it allows for either a better forwarding metric computation or a better location estimation of the packet destination vehicle. As future work, we will investigate more the characteristics of vehicle trajectory to make better data forwarding schemes, considering the minimization of trajectory sharing overhead and the privacy protection on trajectory.

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