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Department of Computer Science
and Engineering
University of Minnesota
4-192 EECS Building
200 Union Street SE
Minneapolis, MN 55455-0159 USA

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TSF: Trajectory-based Statistical Forwarding for Infrastructure-to-Vehicle Data Delivery in Vehicular Networks

Jaehoon Jeong, Shuo Guo, Yu Gu, Tian He, and David Du

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Jaehoon Jeong, Shuo Guo, Yu Gu, Tian He and David H.C. Du
Department of Computer Science & Engineering, University of Minnesota
Email: $\{$*jjeong,sguo,yugu,tianhe,du*$\}$*@cs.umn.edu*

Abstract

We consider the scenarios where Internet access points are sparsely deployed in road networks to provide individual vehicles with customized road condition information for the driving safety, such as holes and bumps along their trajectories. Due to the limited communication coverage, vehicular ad-hoc networks are used to support the multi-hop data forwarding. State-of-the-art schemes have demonstrated their effectiveness in the data forwarding from vehicles to stationary points (e.g., Internet access points). However, they are not designed for the reverse data forwarding from Internet access points to vehicles, a much more challenging problem because of the mobility of the packet destination.

This paper proposes a data forwarding scheme called Trajectory-based Statistical Forwarding (TSF), tailored for the infrastructure-to-vehicle data delivery in vehicular networks. TSF forwards packets over multi-hop to a selected target point *where the vehicle is expected to pass by. Such a target point is selected optimally to minimize the packet delivery delay while satisfying the required packet delivery probability. The optimality is achieved analytically by utilizing the packet's delivery delay distribution and the destination vehicle's travel delay distribution. To our knowledge, this paper presents the first attempt to investigate how to effectively utilize the destination vehicle's trajectory to compute such an optimal target point. Through theoretical analysis and extensive simulation, it is shown that our design provides an efficient data forwarding under a variety of vehicular traffic conditions.*

1. Introduction

Vehicular Ad Hoc Networks (VANETs) have recently emerged as one of promising research areas for the driving safety in road networks [1]–[6]. As a result, the IEEE standards association has been working for wireless access in vehicular environments, standardizing Dedicated Short Range Communication (DSRC), such as IEEE 802.11p [7]. In the meantime, the GPS technology has been adopted for navigation purposes at an unprecedented rate. It is expected that approximately 300 million GPS devices will be shipped in 2009 alone [8]. It seems a very timely topic to develop the vehicular networking by integrating the cutting-edge DSRC and GPS technologies. Especially, our work is inspired by this current trend that a huge number of vehicles have started to install GPS-receivers for navigation and are considering DSRC devices for driving safety. The drivers are guided by these GPS-based navigation systems to select better driving paths in terms of the physically shortest path or the vehicular low-density traffic path. Therefore, one natural research question is *how to make the most of these GPS-guided driving paths to improve the performance of vehicular networks*.

Let's consider the scenario where Internet Access Points (APs) are sparsely deployed along the roadways in order to provide individual vehicles with customized driving safety information, such as the road condition information (e.g., holes and bumps) and the road prewarning (e.g., accidents). Since the APs have the limited communication coverage, the infrastructure-to-vehicle data delivery is supported using vehicular ad-hoc networks to bridge the APs and the packet destination vehicles. However, due to the dynamic mobility in the road networks, the Disruption Tolerant Networking (DTN) is required for data delivery in vehicular networks [9]. For vehicular DTN, state-of-the-art schemes [3], [10]–[13] have adopted the *carry-and-forward* approach and have demonstrated their effectiveness in the data forwarding from a moving source (e.g., vehicle) to a stationary destination (e.g., AP). However, these schemes are not designed for the reverse data forwarding. This reverse data forwarding is more challenging because the packet destination is moving during the packet delivery. For infrastructure-to-vehicle data delivery, the packet destination position needs to be accurately estimated considering the temporal-and-spatial rendezvous of the packet and the destination vehicle.

To the best of our knowledge, our Trajectory-based Statistical Forwarding (TSF) is *the first work to investigate the reverse data forwarding based on the vehicle trajectory guided by GPS-based navigation systems* [14]. To ensure the rendezvous of a packet and a destination vehicle, an optimal target point is identified as packet destination position in the road network *in order to minimize the packet delivery delay while satisfying the user-required packet delivery probability*. In order to search such an optimal target point, our key idea is to use the two delay distributions: (i) the packet delivery delay distribution from the AP to the target point and (ii) the vehicle travel delay distribution from the destination vehicle's current position to the target point. Once the target point is decided, TSF adopts the source routing technique, i.e., forwards the packet using a shortest-delay forwarding path specified by multiple intersections in the target road network.

Our intellectual contributions are as follows:

- A reverse forwarding architecture. We propose a data forwarding architecture for the infrastructure-to-vehicle data delivery. The architecture adopts the stationary nodes (i.e., roadside units) for the reliable delivery.
- The delay modeling for packet and vehicle. With the vehicular traffic statistics, we model the distributions of the link delay and the E2E packet delay. With the destination vehicle's trajectory, we model the distribution of the vehicle travel delay. These models are used for computing an optimal target point.
- An optimal target point selection algorithm. With the packet delay distribution and the vehicle delay distribution, an optimal target point is selected to minimize the packet delivery delay while satisfying the user-required packet delivery probability.

The rest of this paper is organized as follows: Section 2 describes the problem formulation along with the stationary-node-based forwarding architecture. Section 3 explains our optimal target point selection. Section 4 explains the packet delay model and the vehicle delay model for target point computation. Section 5 explains the TSF forwarding protocol. Section 6 evaluates our design. We summarize related work in Section 7 and conclude this paper in Section 8.

2. Problem Formulation

In this section, we formulate the data forwarding in vehicular networks as follows: *Given a road network with APs, our goal is to deliver packets reliably from the APs to a moving destination vehicle with a minimum End-to-End delay*.

2.1. Assumptions

This work is based on the following set of assumptions on the road network and vehicle settings.

- Stationary nodes are installed as Roadside Unit (RSU) at intersections at the road networks. Intelligent Transportation Systems (ITS) are trying to make it mandatory install RSUs (i) at intersections for the driving safety or (ii) at tollgates for the electronic fee collection through the DSRC communications between RSUs and vehicles called On-Board Unit (OBUs) [15], [16].
- Vehicles as OBUs participating in VANET have a wireless communication device, such as the DSRC device [7]. Nowadays many vehicle vendors, such as GM and Toyota, are planning to release vehicles with DSRC devices [16], [17].
- Target vehicles and stationary nodes are installed with GPS-based navigation systems and digital road maps [14], [18]. Traffic statistics, such as vehicle arrival rate λ and average vehicle speed v per road segment, are available via a commercial navigation service, similar to the one currently provided by Garmin Ltd [14].
- Target vehicles know their trajectory by themselves and provide it for Internet access points. Such vehicles regularly report their trajectory information to the APs. This report from vehicles to the APs can be performed by the state-of-the-art schemes, such as VADD [3], TBD [11], and SADV [12].

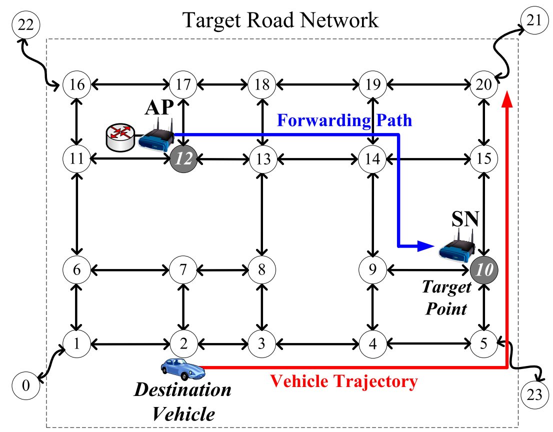


Figure 1. Data Forwarding from AP to Target Point in Road Network

2.2. About Stationary-Node-Assisted Forwarding

The data forwarding from vehicle to AP (i.e., fixed destination) has already been researched with a *stochastic model*, such as VADD [3] and TBD [11]. The stochastic model tries to forward packets opportunistically towards the packet destination using *in-situ next carriers* without stationary nodes at intersections. Both VADD [3] and TBD [11] demonstrate the effectiveness of their approaches, mainly because the final destination is a fixed access point. However, forwarding from the AP to the vehicle is a completely different story. The success ratio of reverse data forwarding highly depends on the accuracy of delay estimation, because only *just-in-time* packets can be delivered to a moving vehicle.

To investigate whether we can apply existing infrastructure-free forwarding technique such as VADD [3], we conduct simulations in the road network. As shown in Figure 1, the AP is placed at intersection n_{12} and the target point is intersection n_{10}. The AP at n_{12} generates 5000 packets with the exponential distribution of 1-second interval towards the stationary node at n_{10}. As shown in the figure, one of the packet forwarding paths is $n_{12} \to n_{13} \to n_{14} \to n_9 \to n_{10}$.

Figure 2 shows the delivery delay distributions of VADD with the estimated mean and deviation of E2E delay of VADD shown in Table 1 and 2, respectively. Clearly, VADD has a very large delay estimation error in that the mean of the expected delivery delay is much different from that of the actual delivery delay. More noticeably, VADD has a standard deviation (STD) estimation error of 1277.1%, a value that makes just-in-time delivery difficulty, if not possible. Such a large uncertainty is introduced by stochastic forwarding at the intersection, where a vehicle has to carry the packet along a wrong direction if no vehicle at intersection moves toward the right direction. In the rest of the paper, we demonstrate such a large uncertainty should and can be removed by requiring stationary nodes at the intersections. Such a requirement can be met by modifying existing roadside units, which have already been mandatory at intersections for driving safety and at tollgates for the electronic fee collection. Note that SADV [12] is an early work to investigate the stationary-node-assisted forwarding in vehicular networks, however, it does not consider the reverse forwarding from APs to moving vehicles.

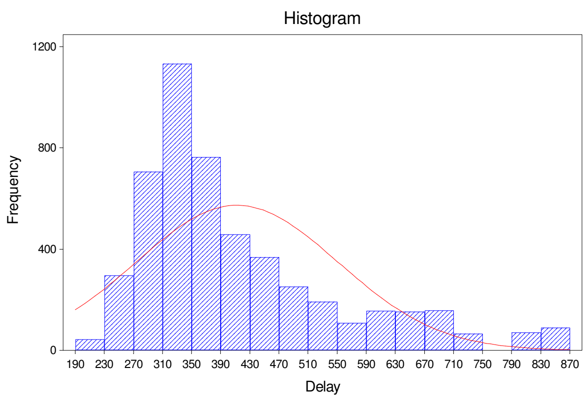


Figure 2. Delay Histogram for VADD

Table 1. Delay Average Estimation of VADD

Protocol	Expected Delay	Actual Delay	Error
VADD	489.1sec	412.5sec	15.7%

Table 2. Delay Standard Deviation (STD) of VADD

Protocol	Expected STD	Actual STD	Error
VADD	10.1sec	139.2sec	1277.1%

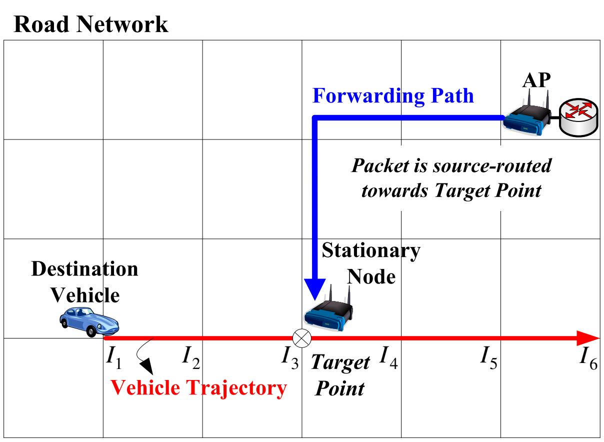


Figure 3. Data Forwarding for Infrastructure-to-Vehicle Data Delivery

2.3. Concept of Operation in TSF

Figure 3 shows the data packet forwarding from an AP to a destination vehicle. Suppose that the destination vehicle has its vehicle trajectory consisting of six intersections, that is, $I_1 \rightarrow I_2 \rightarrow \cdots \rightarrow I_6$ and has registered its vehicle trajectory into the AP. Our goal is to deliver packets from the AP to the destination vehicle with a short delay. As shown in Figure 3, our delivery strategy is to let the packets arrive earlier at a target point (i.e., intersection I_3 on the destination vehicle's trajectory) than the destination vehicle. Since there exists a stationary node at the target point, the packets earlier arrived can wait for the destination vehicle. Thus, a target point is determined as *rendezvous point* where the packet is highly expected to meet the destination vehicle with the shortest packet delay. In the next section, we will explain how to determine an optimal target point on the vehicle trajectory.

3. Target Point Selection for Data Delivery

In this section, we explain how to select an optimal target point for the data delivery from an AP to a destination vehicle with the packet delay and vehicle delay distributions. The target point selection is based on the *delivery probability* that the packet will arrive earlier than the destination vehicle at the target point. This delivery probability can be computed with the packet delivery delay's distribution and the destination vehicle movement delay's distribution as follows. Let T be the set of intersections consisting of the destination vehicle's trajectory. Let i be a target point where $i \in T$. Let α be the user-required delivery probability. Let P_i be the packet delay that a packet will be delivered from AP to target point i. Let V_i be the vehicle delay that the destination vehicle will move from its current position to target point i. For example, in Figure 3, P_3 is the packet delay that a packet will be delivered from AP to target point I_3 and V_3 is the expected vehicle delay that Destination Vehicle will move from its current position I_1 to target point I_3. Thus, we can compute the delivery probability as $P[P_i \leq V_i]$.

Given a user-required delivery probability threshold α, we select a target point intersection i with the minimum vehicle movement delay as optimal target point such that $P[P_i \leq V_i] \geq \alpha$. Note that the minimum vehicle movement delay determines the destination vehicle's packet reception delay. More formally, we can select an optimal target point with a minimum delivery delay while satisfying the delivery probability as follows:

$$i^* \leftarrow \arg\min_{i \in T} E[V_i] \quad \text{subject to } P[P_i \leq V_i] \geq \alpha. \tag{1}$$

In (1), the delivery probability $P[P_i \leq V_i]$ is the probability that the packet will arrive earlier at target point i than the destination vehicle. Figure 4 shows the distribution of packet delay P and the distribution of vehicle delay V.

If the traffic in road networks follows the Poisson arrival model, the distributions of packet delay and vehicle delay follow the Gamma distributions such that $P \sim \Gamma(\kappa_p, \theta_p)$ and $V \sim \Gamma(\kappa_v, \theta_v)$ [19]. Note that our model is not restricted to the Poisson arrival model and can accommodate any empirical distributions. That is, if more accurate distributions are available, our model can use them for the computation of the delivery probability. Given the packet delay distribution

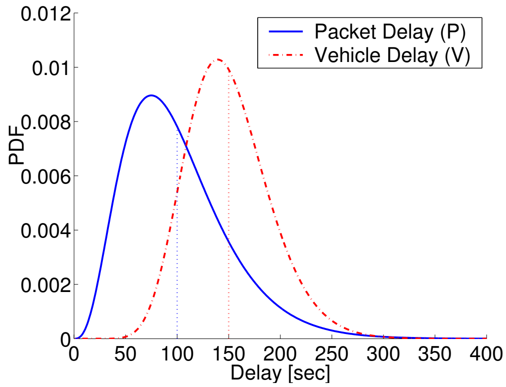


Figure 4. Packet Delay Distribution and Vehicle Delay Distribution

and the vehicle delay distribution are independent of each other, the delivery probability $P[P_i \leq V_i]$ is computed as follows:

$$P[P_i \leq V_i] = \int_0^{TTL} \int_0^{v} f(p)g(v)dpdv. \tag{2}$$

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); TTL is determined as the destination vehicle trajectory's lifetime that is the destination vehicle's travel time from its current position to its last position on the trajectory. Note that the delivery probability is computed considering the packet's lifetime TTL; that is, since the packet is discarded after TTL, the probability portion is zero after TTL.

Clearly, optimal target point selection depends on the packet delay model P and the vehicle delay model V which are described in the next section.

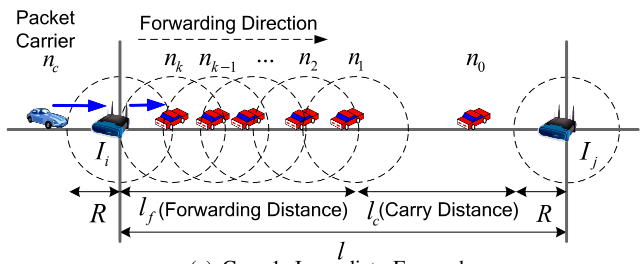
4. Delay Models

In this section, we describe two types of delay models: (i) Packet delay model and (ii) Vehicle delay model. For the packet delay model, we first describe the link delay taken for the packet to be delivered over a road segment in Section 4.1 and then the End-to-End (E2E) packet delay from one position to another position on the road network in Section 4.2. For the vehicle delay model, we explain how to construct the vehicle delay distribution from the vehicle's current position to a target point in Section 4.3.

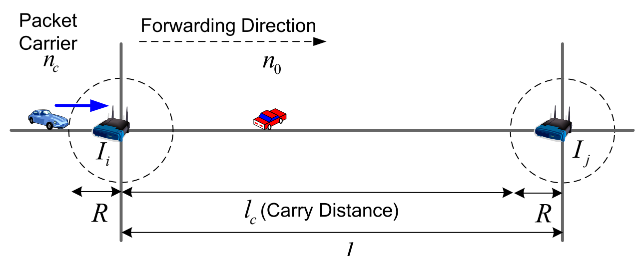
4.1. Link Delay Model

This subsection analyzes the link delay for one road segment with one-way vehicular traffic given the vehicle inter-arrival time, the vehicle speed and the communication range. It is supposed that one stationary node for packet buffering is placed at each end-point (i.e., intersection) of the road segment. We leave the link delay for a two-way road segment as future work.

It should be noted that in the VANET scenarios, the carry delay is *several orders-of-magnitude* longer than the communication delay. For example, a vehicle takes 90 seconds to travel along a road segment of 1 mile with a speed of 40 MPH, however, it takes *only ten of milliseconds* to forward a packet over the same road segment, even after considering the retransmission due to wireless link noise or packet collision; this short retransmission time is because the data rate in DSRC [7] is 6∼27 Mbps and transmission range can extend to almost 1,000 meters. Thus, since the carry delay is the dominating part of the total delivery delay, in our analytical model for the link delay we focus on the carry delay for the sake of clarity, although the small communication delay does exist in our design.



(a) Case 1: Immediate Forward



(b) Case 2: Wait and Carry

Figure 5. Link Delay Modeling for Road Segment

The link delay for one road segment is computed considering the following two cases:

- **Case 1: Immediate Forward**: There is at least one vehicle (i.e., $k > 0$) moving towards the intended next intersection along the packet's forwarding path. The current *packet carrier* n_c forwards its packets to the stationary node at Intersection I_i. As shown in Figure 5(a), The stationary node forwards the packets to vehicle n_k right away and the packets are forwarded up to vehicle n_1, that is, by the forwarding distance l_f, which is the length of the connected ad-hoc network consisting of vehicles n_i for $i = 1..k$. Vehicle n_1 will carry the packets up to the communication range of the stationary node at I_j, that is, by the carry distance l_c. Note that the link delay for this case is analyzed in our previous work called *TBD* [11].
- **Case 2: Wait and Carry**: There is no vehicle (i.e., $k = 0$) moving towards the intended next intersection along the packet's forwarding path. As shown in Figure 5(b), the current *packet carrier* n_c forwards its packets to the stationary node at Intersection I_i. The stationary node stores the packets in its local storage until a vehicle moves on the road segment (I_i, I_j). The average waiting time is $1/\lambda$ where the vehicle arrival rate on the road segment (I_i, I_j) is λ. After this average waiting, the

new packet carrier will carry the packets by the carry distance $l_c (= l - R)$.

Thus, we can compute the expectation of the link delay with the link delays of these two cases as follows:

$$d = \begin{cases} \frac{l-l_f-R}{v} & \text{for case 1: immediate forward,} \\ \frac{1}{\lambda} + \frac{l-R}{v} & \text{for case 2: wait and carry.} \end{cases} \quad (3)$$

$$\begin{aligned} E[d] &= E[\text{link delay} \mid \text{forward}] \times P[\text{forward}] \\ &\quad + E[\text{link delay} \mid \text{wait}] \times P[\text{wait}] \\ &= \frac{l - R - E[l_f]}{v}\beta + (\frac{1}{\lambda} + \frac{l-R}{v})(1-\beta) \end{aligned} \quad (4)$$

where $P[\text{forward}] = \beta = 1 - e^{-\frac{\lambda R}{v}}$ and $P[\text{wait}] = 1 - \beta = e^{-\frac{\lambda R}{v}}$. Please, refer to Appendix A for the detailed derivation. Also, in the similar way, we can compute the variance of the link delay as follows:

$$\begin{aligned} Var[d] &= E[d^2] - (E[d])^2 \\ &= \frac{(l-R)^2 - 2(l-R)E[l_f] + E[l_f^2]}{v^2}\beta \\ &\quad + (\frac{1}{\lambda} + \frac{l-R}{v})^2(1-\beta) \\ &\quad - (\frac{l-R-E[l_f]}{v}\beta + (\frac{1}{\lambda} + \frac{l-R}{v})(1-\beta))^2. \end{aligned} \quad (5)$$

Please, refer to Appendix B for the detailed derivation.

Finally, with the mean $E[d]$ and variance $Var[d]$ of the link delay, we model the link delay d as the Gamma distribution. Note that the Gamma distribution is usually used to model the positive continuous random variable, such as the waiting time and lifetime [19]. Thus, the distribution of the link delay d_i for the edge $e_i \in E[G]$ is $d_i \sim \Gamma(\kappa_i, \theta_i)$ such that $E[d_i] = \kappa_i\theta_i$ and $Var[d_i] = \kappa_i\theta_i^2$ for $d_i, \kappa_i, \theta_i > 0$ [19]. Since we have the mean and variance of the link delay, that is, $E[d_i] = \mu_i$ in (4) and $Var[d_i] = \sigma_i^2$ in (5), we can compute the parameters θ_i and κ_i of the Gamma distribution as follows:

$$\theta_i = \frac{Var[d_i]}{E[d_i]} = \frac{\sigma_i^2}{\mu_i}. \quad (6)$$

In (6), the parameter θ_i is computed by dividing the link delay variance by the mean link delay.

$$\kappa_i = \frac{E[d_i]}{\theta_i} = \frac{\mu_i}{\theta_i} = \frac{\mu_i^2}{\sigma_i^2}. \quad (7)$$

In (7), the parameter κ_i is computed by dividing the mean link delay by the parameter θ_i in (6).

Up to now, we have modeled the link delay for a directed edge corresponding to a road segment. Next, with the distribution of the link delay for each edge, we can compute the E2E packet delay from the AP to the target point assuming the independence of the link delays for the road segments consisting of the E2E path from the AP to the target point. In the next section, we will construct the distribution of the packet delay from the AP to a target point as the Gamma distribution.

4.2. E2E Packet Delay Model

In this subsection, we model the End-to-End Packet Delay from one position to another position in a given road network. As discussed in Section 4.1, the link delay is modeled as the Gamma distribution of $d_i \sim \Gamma(\kappa_i, \theta_i)$ for edge $e_i \in E(G)$ in the road network graph G. Given a forwarding path from AP to a target point, we assume that the link delays of edges consisting of the path are independent. From this assumption, the mean and variance of the E2E packet delay are computed as the sum of the means and the sum of the variances of the link delays consisting of the E2E path, respectively. Assuming that the forwarding path consists of N edges, the mean and variance of the E2E packet delay distribution can be computed as follows:

$$E[P] = \sum_{i=1}^{N} E[d_i] = \sum_{i=1}^{N} \mu_i. \quad (8)$$

$$Var[P] = \sum_{i=1}^{N} Var[d_i] = \sum_{i=1}^{N} \sigma_i^2. \quad (9)$$

With (8) and (9), the E2E packet delay distribution can be modeled as $P \sim \Gamma(\kappa_p, \theta_p)$ such that $E[P] = \kappa_p\theta_p$ and $Var[P] = \kappa_p\theta_p^2$ for $P, \kappa_p, \theta_p > 0$ [19].

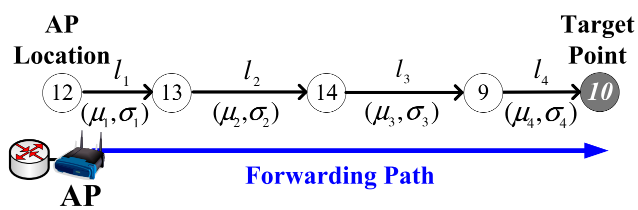


Figure 6. Packet Delay Model from AP to Target Point

For example, as shown in Figure 6, the packet forwarding path is $n_{12} \rightarrow n_{13} \rightarrow n_{14} \rightarrow n_9 \rightarrow n_{10}$. The mean and variance for the packet delay distribution can be computed as $\mu_p = \sum_{i=1}^{4} \mu_i$ and $\sigma_p^2 = \sum_{i=1}^{4} \sigma_i^2$. From these mean μ_p and variance σ_p^2, we can compute the parameters θ_p and κ_p of the Gamma distribution with Equations (6) and (7).

4.3. Vehicle Delay Model

In this subsection, we model the Vehicle Delay from one position to another position in a given road network. Give the road network graph G, the travel time for edge $e_i \in E(G)$ is modeled as the Gamma distribution of $t_i \sim \Gamma(\kappa_i, \theta_i)$; note that the travel time distribution for each road segment can be obtained through vehicular traffic measurement and is usually considered the Gamma distribution [20], [21]. The parameters κ_i and θ_i of the Gamma distribution are computed with the mean travel time μ_i and the travel time variance σ_i^2 using the relationship among the mean $E[t_i]$, the variance $Var[t_i]$, κ_i, and θ_i such that $E[t_i] = \kappa_i\theta_i$ and $Var[t_i] = \kappa_i\theta_i^2$ for $t_i, \kappa_i, \theta_i > 0$ [19] as follows:

$$\theta_i = \frac{Var[t_i]}{E[t_i]} = \frac{\sigma_i^2}{\mu_i}. \quad (10)$$

In (10), the parameter θ_i is computed by dividing the travel time variance by the mean travel time.

$$\kappa_i = \frac{E[t_i]}{\theta_i} = \frac{\mu_i}{\theta_i} = \frac{\mu_i^2}{\sigma_i^2}. \tag{11}$$

In (11), the parameter κ_i is computed by dividing the mean travel time by the parameter θ_i in (10).

Given a vehicle trajectory from the vehicle's current position to a target point, we suppose that the travel times of edges consisting of the trajectory are independent. Assuming that the trajectory consists of M edges, in the same way with the Packet Delay Model in Section 4.2, the mean and variance of the vehicle delay distribution can be computed as follows:

$$E[V] = \sum_{i=1}^{M} E[t_i] = \sum_{i=1}^{M} \mu_i. \tag{12}$$

$$Var[V] = \sum_{i=1}^{M} Var[t_i] = \sum_{i=1}^{M} \sigma_i^2. \tag{13}$$

With (12) and (13), the E2E vehicle delay distribution can be modeled as $V \sim \Gamma(\kappa_v, \theta_v)$ such that $E[V] = \kappa_v \theta_v$ and $Var[V] = \kappa_v \theta_v^2$ for $V, \kappa_v, \theta_v > 0$ [19].

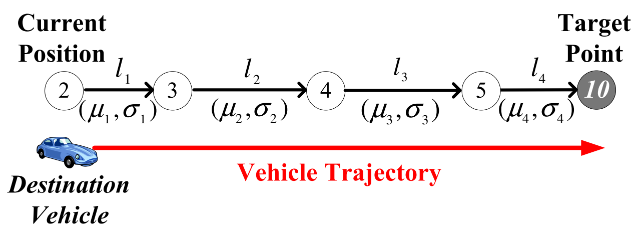


Figure 7. Vehicle Delay Model from Current Position to Target Point

For example, as shown in Figure 7, the vehicle trajectory is $n_2 \rightarrow n_3 \rightarrow n_4 \rightarrow n_5 \rightarrow n_{10}$. The mean and variance for the vehicle delay distribution can be computed as $\mu_v = \sum_{i=1}^{4} \mu_i$ and $\sigma_v^2 = \sum_{i=1}^{4} \sigma_i^2$. From these mean μ_v and variance σ_v^2, we can compute the parameters θ_v and κ_v of the Gamma distribution with Equations (10) and (11).

So far, we have explained our forwarding design and delay models. In the next section, based on these design and delay models, we will explain our forwarding protocol considering the scenarios with multiple APs.

5. TSF Protocol

In this section, we explain the protocol of our Trajectory-based Statistical Forwarding (TSF). First, we will explain our TSF forwarding protocol in the road network with one AP in Section 5.1. Second, we will consider how to extend our forwarding protocol in the road network with multiple APs in Section 5.2.

5.1. Forwarding Protocol

In this subsection, we describe our design of *the TSF forwarding protocol* for the infrastructure-to-vehicle data delivery in the given road network.

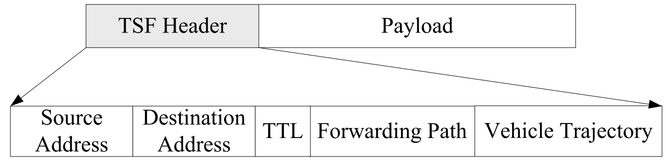


Figure 8. TSF Packet Format

For the TSF forwarding protocol, we use the TSF packet format as shown in Figure 8. Especially, the field of *Forwarding Path* contains the list of the intersections for the source routing from AP to the target point and the field of *Vehicle Trajectory* is the destination vehicle's trajectory, that is, the series of intersections on the destination vehicle's trajectory. With this TSF packet, the data packets will be forwarded towards the destination vehicle. Our forwarding protocol consists of the following two steps.

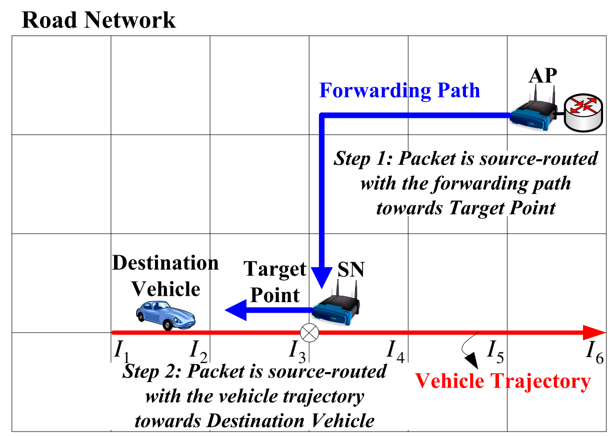


Figure 9. TSF Forwarding Protocol

5.1.1. The First-Step Forwarding to Target Point. The first-step forwarding is to forward a packet through the source routing with the forwarding path (specified in Figure 8). As shown in Figure 9, the forwarding path is the *shortest packet delay path* from AP to the target point I_3 determined by AP with the optimization in (1). For example, as shown in Figure 6, the forwarding path is $n_{12} \rightarrow n_{13} \rightarrow n_{14} \rightarrow n_9 \rightarrow n_{10}$. The stationary nodes on the forwarding path are trying to forward the packets to carriers moving towards their neighboring stationary nodes along the forwarding path. In Figure 6, the stationary node at n_{12} is trying to forward the packets towards the neighboring node n_{13} on the forwarding path. In this way, the packet will be delivered to the target point, for example, n_{10} in Figure 6.

5.1.2. The Second-Step Forwarding to Destination Vehicle. The second-step forwarding is to forward a packet through the source routing with the reverse path of the vehicle trajectory (specified in Figure 8) from the target point towards the destination vehicle along the reverse path of the vehicle trajectory. As shown in Figure 9, when the packet arrives at the stationary node corresponding to the target point I_3, the stationary node will hold the packet until a vehicle passes it. If the vehicle is heading for the next intersection I_2 on the reverse path of $I_3 \rightarrow I_2 \rightarrow I_1$, the stationary node at I_3 will forward its packet to the vehicle. For example, in Figure 10, if the stationary node corresponding to the target point n_{10} finds a vehicle moving reversely on the destination vehicle's trajectory (i.e., on $n_{10} \rightarrow n_5$), it will forward its packet to the vehicle as next packet carrier. The packet carrier carries and forwards the packet towards the destination vehicle. If the carrier goes out of the vehicle trajectory at n_5, it forwards its packet to the stationary node at n_5 on the vehicle trajectory before its leaving from the vehicle trajectory. The stationary node n_5 that takes over the packet will be trying to forward the packet to another carrier moving towards the destination vehicle along the reverse path of the vehicle trajectory. This process is repeated until the packet can be delivered to the destination vehicle.

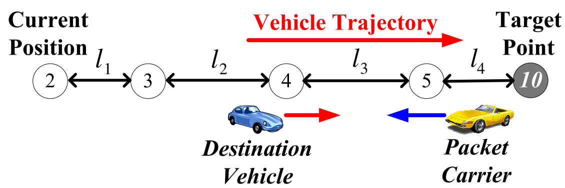


Figure 10. Reverse Path Forwarding for Vehicle Trajectory

The rationale of the reverse-path forwarding is that the optimization for a target point in (1) provides an optimal target point with the minimum packet delivery delay while satisfying the required delivery probability. This indicates that the packet will hit the destination vehicle along the destination vehicle's trajectory if the packet follows the reverse path of the vehicle trajectory. Of course, there is some probability that the packet arrives at the target point later than the destination vehicle. In this case, the packet will not hit the destination vehicle, so will be discarded after its TTL expiration. In the performance evaluation in Section 6, we will show the trade-off between the delivery delay and the delivery ratio according to the user-required delivery probability threshold α.

5.2. Data Forwarding with Multiple APs

In a large-scale road network, multiple Internet Access Points (APs) are usually required to accommodate the infrastructure-to-vehicle data delivery. In this case, an AP with the minimum delivery delay can send the packets to a destination vehicle among the multiple APs; note that the multiple APs are connected with each other via the Internet, so the communication delay among the APs are negligible compared with the carry delay at the second level. We can easily extend our data forwarding framework for this multiple-AP road network. We can determine *the Expected Vehicle Delay (EVD) of the destination vehicle for the multiple APs* as *the minimum among the EVDs for the APs* as follows:

$$\mathrm{EVD}^* \leftarrow \min_{k \in AP} \mathrm{EVD}_k \qquad (14)$$

where AP is the set of APs and EVD_k is the EVD of the destination vehicle for access point AP_k; note that the

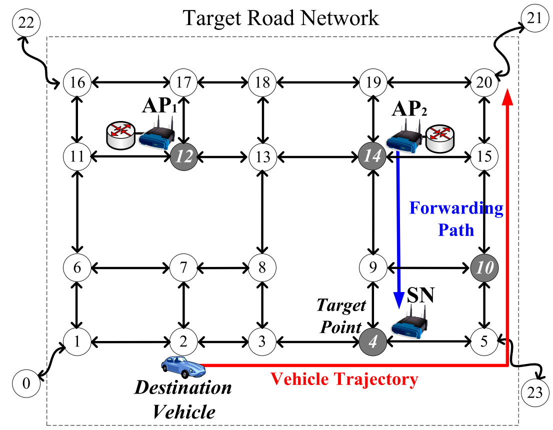


Figure 11. Data Forwarding with Multiple APs

AP with the minimum EVD will try to send packets to the destination vehicle.

For example, Figure 11 shows the road network graph with two access points AP_1 and AP_2. The EVD^* is $\min\{\mathrm{EVD}_1, \mathrm{EVD}_2\}$ where EVD_1 and EVD_2 are computed using (1) to satisfy the required delivery probability α, respectively. In this figure, since $\mathrm{EVD}_2 < \mathrm{EVD}_1$, AP_2 will send the packet towards its target point n_4.

6. Performance Evaluation

In this section, we evaluate the performance of *TSF*, focusing on our optimal target point selection algorithm. The evaluation setting is as follows:

- **Performance Metrics:** We use (i) *average delivery delay* and (ii) *packet delivery ratio* as the performance metrics.
- **Baselines:** Our work is the first attempt for the reverse data forwarding based on the vehicle trajectory, so we have no other state-of-the-art schemes for comparison. To evaluate our target point selection algorithm, we compare the following two target point selection algorithms: (i) Random Trajectory Point (RTP) and (ii) Last Trajectory Point (LTP). In RTP, an intersection is randomly selected among the intersections consisting of the destination vehicle's trajectory. In LTP, the last intersection on the destination vehicle's trajectory is selected as target point.
- **Parameters:** In the performance evaluation, we investigate the impacts of (i) *Vehicular traffic density* N, (ii) *Vehicle speed* μ_v, (iii) *Vehicle speed deviation* σ_v, (iv) *Delivery probability threshold* α, and (v) *Internet access point density* M.

A road network with 49 intersections is used in the simulation and one Internet access point is deployed in the center of the network. Each vehicle's movement pattern is determined by a *Hybrid Mobility model* of City Section Mobility model [22] and Manhattan Mobility model [23]. From the characteristics of City Section Mobility, the vehicles are randomly placed at one intersection as *start position* among the intersections on the road network and randomly

Table 3. Simulation Configuration

Parameter	Description
Road network	The number of intersections is 49. The area of the road map is 8.25km×9km (i.e., 5.1263miles×5.5923miles).
Communication range	$R = 200$ meters (i.e., 656 feet).
Number of vehicles (N)	The number N of vehicles moving within the road network. The default of N is 250.
Time-To-Live (TTL)	The expiration time of a packet. The default TTL is the vehicle trajectory's lifetime, that is, the vehicle's travel time for the trajectory, i.e., 2,086 seconds.
Vehicle speed (v)	$v \sim N(\mu_v, \sigma_v)$ where $\mu_v = \{20, 25, ..., 60\}$ MPH and $\sigma_v = \{1, 2, ..., 10\}$ MPH. The maximum and minimum speeds are $\mu_v + 3\sigma_v$ and $\mu_v - 3\sigma_v$, respectively. The default of (μ_v, σ_v) is $(40, 5)$ MPH.
Vehicle travel path length (l)	Let $d_{u,v}$ be the shortest path distance from start position u to end position v in the road network. $l \sim N(\mu_l, \sigma_l)$ where $\mu_l = d_{u,v}$ km and $\sigma_l = 3$ km (1.86miles).

select another intersection as *end position*. The vehicles move according to the roadways from their start position to their end position. Also, the vehicles wait for a random waiting time (e.g., uniformly distributed from 0 to 10 seconds) at intersections in order to allow the impact of stop sign or traffic signal. From the characteristics of Manhattan Mobility, as shown in Table 3, the vehicle travel path length l from start position u to end position v is selected from a normal distribution $N(\mu_l, \sigma_l)$ where μ_l is the shortest path distance between these two positions and σ_l determines a random detour distance; this random detour distance reflects that all of the vehicles do not necessarily take the shortest path from their start position and their end position. Once the vehicle arrives at its end position, it pauses during a random waiting time and randomly selects another end position. Thus, this vehicle travel process is repeated during the simulation time, based on the hybrid mobility model. On the other hand, among the vehicles, one vehicle is the destination vehicle, moving around the perimeter of the road network according to its vehicle trajectory. The destination vehicle registers its vehicle trajectory into the APs in the road network, so the APs know the destination vehicle's trajectory all the time.

The vehicle speed is generated from a normal distribution of $N(\mu_v, \sigma_v)$ [21], [24], as shown in Table 3. The *average vehicle speeds* are used in the vehicle speed distribution to generate vehicle speeds for every two directions per two-way road segment; that is, these two average speeds per road segment can be measured from vehicular traffic by dividing the *road segment length* by the *average travel time* over the road segment. For simplicity, we let all of the road segments have the same speed distribution of $N(\mu_v, \sigma_v)$ in the road network for the simulation; note that our design can easily extend this simulation setting to having the variety of vehicle speed distributions for road segments.

During the simulation, following an exponential distribution with a mean of 5 seconds, packets are dynamically generated from AP in the road network. Note that this data traffic is low because our target application is the delivery of customized road condition information. The total number of generated packets is 2,000 and the simulation is continued until all of these packets are either delivered or dropped due to TTL expiration. The system parameters are selected based on a typical DSRC scenario [7]. Unless otherwise specified, the default values in Table 3 are used.

6.1. Forwarding Behavior Comparison

We compare the forwarding behaviors of *TSF*, *RTP* and *LTP* with the cumulative distribution function (CDF) of the actual packet delivery delays; note that for *TSF*, the delivery probability threshold α is 95%. From Figure 12, it is very clear that *TSF* has much smaller packet delivery delay than *RTP* and *LTP*. For any given packet delivery delay, *TSF* always has a larger CDF value than both of them before they both reach 100% CDF. For example, *TSF* reaches 75% CDF with a delivery delay of about 765 seconds while the value for *RTP* is about 2,005 seconds and the value for *LTP* is about 2,035 seconds. In other words, on average, the packet delivery delay for *TSF* is much smaller (i.e., 1/3) than that for *RTP* and *LTP*. Especially, the CDF of *LTP* starts to increase from 1% at 1,880 seconds and becomes 99% at 2,015 seconds. This CDF is sharply increasing close to the packet TTL (i.e., 2,086 seconds) because the *LTP* chooses the last point on the vehicle trajectory as target point, leading to the long delivery delay. We will show this quantitatively in the following subsections.

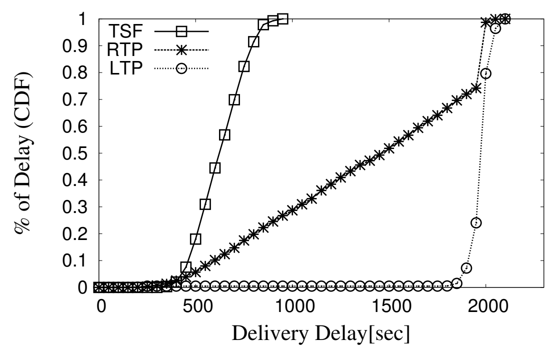
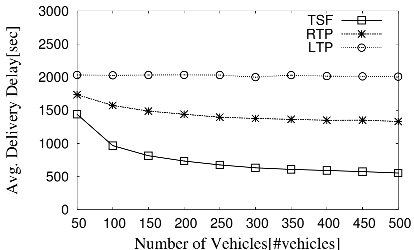


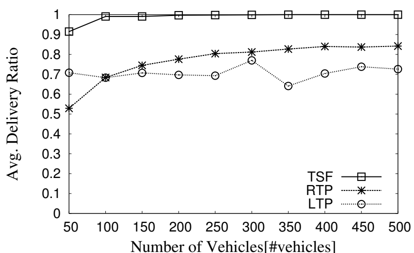
Figure 12. CDF Comparison for Delivery Delay

6.2. Impact of Vehicle Number N

The number of vehicles in the road network determines the vehicular traffic density in a road network. In this subsection, we intend to study how effectively *TSF* can forward packets from AP towards the destination vehicle using the destination vehicle's trajectory. Through our extensive simulations, we observe that under *any vehicular traffic density*, *TSF* significantly outperforms *RTP* and *LTP* in terms of the packet delivery delay and the packet delivery ratio. Figure 13(a) shows the packet delivery delay comparison among *TSF*, *RTP* and *LTP* with varying the number of vehicles, that is, from 50 to 500. As shown in Figure 13(a), *TSF* has much smaller packet delivery delay than *RTP* and *LTP* at all vehicular densities. As expected, one trend is that the delivery delays

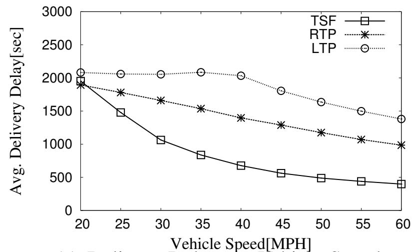


(a) Delivery Delay vs. Vehicle Number

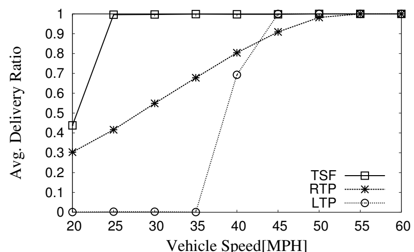


(b) Delivery Ratio vs. Vehicle Number

Figure 13. Impact of Vehicle Number N

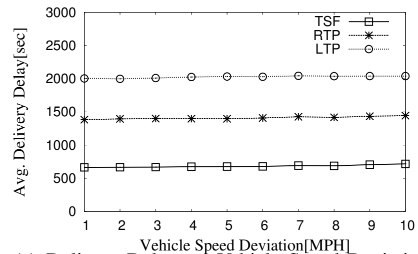


(a) Delivery Delay vs. Vehicle Speed

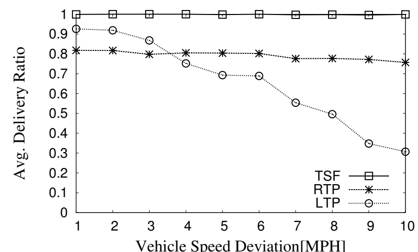


(b) Delivery Ratio vs. Vehicle Speed

Figure 14. Impact of Vehicle Speed μ_v



(a) Delivery Delay vs. Vehicle Speed Deviation



(b) Delivery Ratio vs. Vehicle Speed Deviation

Figure 15. Impact of Vehicle Speed Deviation σ_v

in *TSF*, *RTP* and *LTP* decrease as the number of vehicles increases. This is because the more vehicles increase the forwarding probability among vehicles, so this reduces the carry delay, leading to the overall shorter delivery delay. The smallest delay reduction of *TSF* is 17% at $N = 50$ for *RTP* and 29% at $N = 50$ for *LTP*, respectively. On the other hand, the largest delay reduction is 58% at $N = 500$ for *RTP* and 72% at $N = 500$ for *LTP*, respectively. From this figure, it can be seen that as the road traffic increases, the trajectory in *TSF* has more contribution in the delivery delay. However, as the traffic density reaches a certain point (e.g., $N = 400$), the delay of *TSF* does not decrease much. This is because due to the high delivery probability threshold (i.e., $\alpha = 95\%$), *TSF* selects a target point in a conservative way to satisfy the required delivery probability, leading to a small delay improvement.

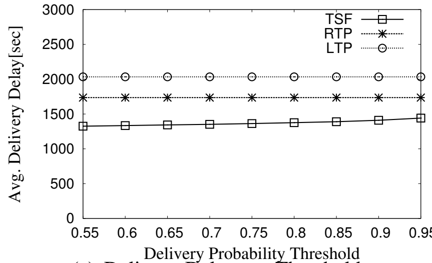
Let us compare the delivery ratios among these three schemes. Figure 13(b) shows the delivery ratio for the vehicle number. *TSF* has the highest delivery ratio (i.e., above 91%) at all the range of the vehicle numbers. One thing to note is that *LTP* does not necessarily have a high delivery ratio (i.e., 71% average ratio). As a reminder, *LTP* sends the packet towards the last trajectory point. However, the path from AP to this last point may not be able to deliver the packet to the last point before the destination vehicle arrives at the last point. This is because the path to the target point is selected without considering the delivery probability, so the packet delivery delay to the target point can be longer than the destination vehicle's travel delay. Therefore, with the optimal target point, *TSF* has better performance than *RTP* and *LTP* in terms of two performance metrics. This indicates the importance of an optimal target point selection for the data delivery.

6.3. Impact of Vehicle Speed μ_v

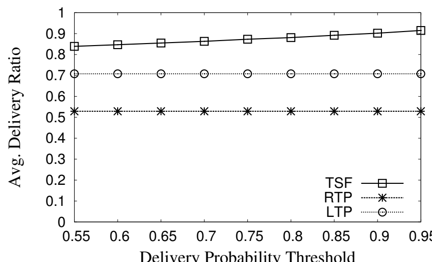
In this subsection, we investigate how the change of mean vehicle speed affects the delivery delay. Figure 14(a) shows the delivery delay under different mean vehicle speeds. As shown in the Figure 14(a), for *TSF*, *RTP* and *LTP*, the higher vehicle speed leads to the shorter delivery delay. This is because the high vehicle speed yields high vehicle arrival rate at each road segment, leading to the shorter delivery delay. However, at all vehicle speeds, the *TSF* still outperforms both *RTP* and *LTP*. For the delivery ratio, as shown in Figure 14(b), the *TSF* has much better performance than the others.

6.4. Impact of Vehicle Speed Deviation σ_v

In this subsection, we investigate the impact of vehicle speed deviation on the performance. We found that under a variety of vehicle speed deviation, *TSF* provides a shorter delay and a more reliable data delivery than both *RTP* and *LTP*. Figure 15(a) illustrates our observation for the delivery delay according to the vehicle speed deviation when the number of vehicles is $N = 250$. The delay performance gaps among these three schemes are almost constant at all of the vehicle speed deviations from 1 MPH to 10 MPH. However, for the delivery ratio, as shown in Figure 15(b), *TSF* provides a reliable delivery close to 100%, however the others have worse performance. Especially, *LTP*'s delivery ratio degrades sharply as the vehicle speed deviation increases. This is because under a higher speed deviation, *LTP* can provide less timely delivery to the target point. On the other hand, *TSF* supports the timely delivery to the target point with the delivery probability considering this speed deviation.

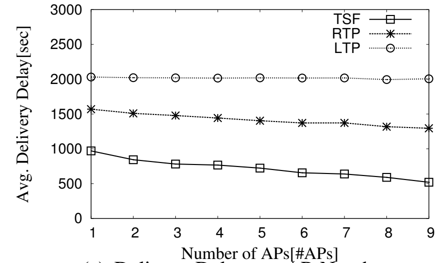


(a) Delivery Delay vs. Threshold α

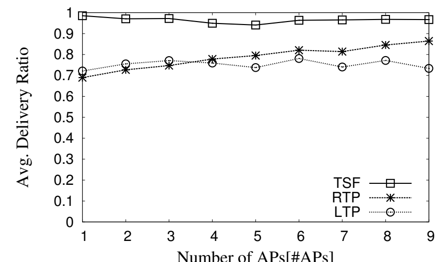


(b) Delivery Ratio vs. Threshold α

Figure 16. Impact of Delivery Probability Threshold α



(a) Delivery Delay vs. AP Number



(b) Delivery Ratio vs. AP Number

Figure 17. Impact of AP Number M

6.5. Impact of Delivery Probability Threshold α

In this subsection, we investigate the impact of the user-required delivery probability threshold α on both the delivery delay and the delivery ratio. For this investigation, we run three schemes under a light-traffic road network where the number of vehicles is $N = 50$.

Figure 16(a) and Figure 16(b) show the delivery delay and the delivery ratio according to α, respectively. First of all, *RTP* and *LTP* are not affected by the threshold α because they do not consider the delivery probability in their target point selection. In the delivery delay, as shown in Figure 16(a), *TSF*'s delivery delay increases slightly as α increases. This is because for a higher α, *TSF* selects a target point in a more conservative way such that the packet will arrive at the target point earlier than the destination vehicle with a higher probability, so the actual delivery to the destination vehicle can be longer. This conservative way leads to the higher delivery ratio as α increases, as shown in Figure 16(b). Therefore, there exists a trade-off between the delivery delay and the delivery ratio according to α. For example, in the interval from $\alpha = 0.85$ to $\alpha = 0.95$ in Figure 16, the delivery ratio is getting better, but the delivery delay is getting worse.

6.6. Impact of AP Number M

In this subsection, we explain how multiple Internet Access Points (APs) have an impact on the performance. Note that multiple APs are uniformly placed in the road network in the simulation. The other parameters are set to the default values in Table 3; that is, the number of vehicles is $N = 100$. In this multiple-AP setting, we need to select an appropriate AP among the set of APs. *TSF* selects an AP with the minimum vehicle delay to the target point satisfying the required delivery probability, as discussed in Section 5.2. Both *RTP* and *LTP* select an AP with the minimum packet delay to the target point.

As shown in Figure 17(a), the delivery delay in both *TSF* and *RTP* decreases as the AP number increases; this is because they select an AP to provide a shorter delivery delay. However, *LTP*'s delay is almost constant regardless of the increase of the AP number; this is because *LTP* selects the last trajectory point as target point, so the packets have to wait for the packet destination at the target points until the destination vehicle arrives at the target point. Actually, the vehicle travel time to this target point will decide the actual delivery delay. For the delivery ratio, as shown in Figure 17(b), *TSF* has a high ratio of at least 95% in most of cases except for $M = 5$ with 94.1%. Note that the required delivery probability α is 95% and the vehicular traffic density $N = 100$ is a light-traffic density. In order to achieve a higher delivery ratio, we need to increase the threshold α under light-traffic conditions, as discussed in Section 6.5.

Through the performance evaluation, we can conclude (i) that *TSF* is a promising solution for the reliable, efficient infrastructure-to-vehicle data delivery through the optimal target point selection and (ii) that there exists a trade-off between the delivery ratio and the delivery delay according to the user-required delivery probability.

7. Related Work

Recently, the VANET research has put a lot of attentions on the data forwarding and data dissemination for vehicle-to-vehicle or vehicle-to-infrastructure communications [1], [3], [4], [25]–[27]. The data forwarding in VANET is different from that in the traditional mobile ad-hoc networks (MANETs) [28] for the reasons of (i) vehicles are moving on the physically constrained areas (i.e., roadways), (ii) the moving speed of vehicles is also constrained by the speed limit on the roadways and (iii) the communication shortest paths do not always match the physical shortest paths due to heterogeneous traffic conditions on road segments. These unique characteristics of the road networks open the door of research opportunities for the data forwarding in the VANET. Also, the frequent network partition and mergence due to the high mobility of vehicles make the MANET routing protocols [28] ineffective in the VANET settings [29]. Thus, in order to deal with such frequent network partition and mergence, the *carry-and-forward* approaches are necessary. Epidemic Routing [10] is an early work to handle this issue through the random pair-wise exchange of data packets among mobile nodes. However, it is designed for two-dimensional open fields, not optimized for the road networks with the confined routes for vehicles.

Data forwarding schemes investigating the layout of road network and vehicular traffic statistics are proposed in *VADD* [3], Delay-Bounded Routing [4], and *SADV* [12]. *VADD* investigates the data forwarding using a stochastic model based on vehicular traffic statistics in order to achieve the *lowest delivery delay* from a mobile vehicle to a stationary packet destination. Delay-Bounded Routing proposes data forwarding schemes to satisfy the *user-defined delay bound* rather than the *lowest delivery delay*. In addition, it also aims at minimizing the channel utilization in terms of the number of packet transmissions. In *SADV* [12], authors also propose a forwarding strategy which leverages on the stationary nodes in the network. For all those existing approaches, they focus on the data forwarding from vehicles to a fixed destination, such as Internet access point (AP).

With increasingly popular usage of GPS devices, *vehicle trajectory information* has become a new valuable input for effective data forwarding schemes. Our earlier work *TBD* [11] utilizes such vehicle trajectory information along with vehicular traffic statistics to further improve communication delay and delivery probability for vehicle-to-static-destination communications. In this paper, we take a step further and provide an efficient solution for forwarding messages from a fixed destination (i.e., AP) to a mobile node (i.e., vehicle) using the trajectory of the mobile destination.

8. Conclusion

In this paper, we propose a Trajectory-based Statistical Forwarding (TSF) in vehicular networks, where the carry delay is the dominating factor for the End-to-End delivery delay. Our goal is to provide a reliable, efficient infrastructure-to-vehicle data delivery by minimizing the packet delivery delay subject to the required delivery probability. This goal is achieved by computing an optimal target point as *packet-and-vehicle-rendezvous-point* with the vehicle delay distribution and the packet delay distribution, which can be obtained from the vehicle trajectory and the vehicular traffic statistics, respectively. Once an optimal target point is determined, through the shortest-delivery-delay path from the AP to the mobile destination, packets are source-routed towards the packet destination.

With the increasing popularity of GPS-based navigation systems and DSRC communication devices, we believe that our forwarding scheme opens the first door for exploiting the potential benefits of the vehicle trajectory for the infrastructure-to-vehicle data delivery in vehicular networks, such as road environment conditions for the driving safety. As future work, we will explore the impact of the partial deployment of stationary nodes on the performance and develop solutions to deal with such a setting.

Acknowledgment

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Appendix

In this appendix, we derive the mean and variance of the link delay discussed in Section 4.1.

1. Mean Link Delay

In this section, we compute the mean link delay for road segment (I_i, I_j), as shown in Figure 5. We can compute the mean link delay $E[d]$ by combining these two link delays in (3) as follows. Suppose that the vehicles arrive with arrival rate λ. Let $C(k)$ be the condition for the ad-hoc network consisting of k vehicle inter-arrivals. Let $L(k)$ be the length of the connected ad-hoc network of k vehicle inter-arrivals. Therefore, the mean link delay $E[d]$ is computed by the sum of the conditional expectations for the two cases in (3) as follows:

$$\begin{aligned} E[d] &= E[\text{link delay} \mid \text{forward}] \times P[\text{forward}] \\ &\quad + E[\text{link delay} \mid \text{wait}] \times P[\text{wait}] \\ &= (\sum_{k=1}^{\infty} E[\frac{l-R-L(k)}{v} | C(k)] \times P[C(k)]) \\ &\quad \times P[\text{forward}] + (E[\text{waiting time}] + \frac{l-R}{v}) \times P[\text{wait}] \\ &= \frac{l-R-E[l_f]}{v}\beta + (\frac{1}{\lambda} + \frac{l-R}{v})(1-\beta) \end{aligned} \tag{15}$$

where $P[\text{forward}] = \beta = 1 - e^{-\frac{\lambda R}{v}}$, $P[\text{wait}] = 1 - \beta = e^{-\frac{\lambda R}{v}}$, and $E[\text{waiting time}] = \frac{1}{\lambda}$. Please, refer to our previous work called *TBD* [11] for the detailed computation related to $L(k)$, $C(k)$ and $E[l_f]$.

2. Variance of Link Delay

In this section, we compute the variance of the link delay for road segment (I_i, I_j), as shown in Figure 5. For the variance $Var[d]$, we need to compute the second moment of the link delay $E[d^2]$. This second moment $E[d^2]$ can be computed as follows:

$$
\begin{aligned}
E[d^2] = &(\sum_{k=1}^{\infty} E[(\frac{l-R-L(k)}{v})^2 | C(k)] \times P[C(k)]) \\
&\times P[\text{forward}] + (E[\text{waiting time}] + \frac{l-R}{v})^2 \times P[\text{wait}] \\
= &(\sum_{k=1}^{\infty} E[\frac{(l-R)^2 - 2(l-R)L(k) + L(k)^2}{v^2} | C(k)] \\
&\times P[C(k)]) \times P[\text{forward}] + (E[\text{waiting time}] \\
&+ \frac{l-R}{v})^2 \times P[\text{wait}] \\
= &\frac{(l-R)^2 - 2(l-R)E[l_f] + E[l_f^2]}{v^2} \times P[\text{forward}] \\
&+ (E[\text{waiting time}] + \frac{l-R}{v})^2 \times P[\text{wait}] \\
= &\frac{(l-R)^2 - 2(l-R)E[l_f] + E[l_f^2]}{v^2} \beta \\
&+ (\frac{1}{\lambda} + \frac{l-R}{v})^2 (1-\beta).
\end{aligned}
\tag{16}
$$

Therefore, the link delay variance $Var[d]$ is computed from Equations (15) and (16) as follows:

$$
\begin{aligned}
Var[d] = &\frac{(l-R)^2 - 2(l-R)E[l_f] + E[l_f^2]}{v^2} \beta \\
&+ (\frac{1}{\lambda} + \frac{l-R}{v})^2 (1-\beta) \\
&- (\frac{l-R-E[l_f]}{v} \beta + (\frac{1}{\lambda} + \frac{l-R}{v})(1-\beta))^2.
\end{aligned}
\tag{17}
$$