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TBD: Trajectory-Based Data Forwarding for Light-Traffic Vehicular Networks

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Abstract

This paper proposes a Trajectory-Based Data Forwarding (TBD) scheme, tailored for the data forwarding in light-traffic vehicular ad-hoc networks. We consider the scenarios in which Internet access points are sparsely deployed to receive the road-side reports of time-critical information such as driving accident or hazard. Since the Internet access points have limited communication coverage, a vehicular ad-hoc network is needed to forward data packets to the access points. State-of-the-art schemes have demonstrated the effectiveness of their data forwarding strategies by exploiting known vehicular traffic statistics (e.g., densities and speeds) in such a network. These results are encouraging, however, further improvements can be made by taking advantage of the growing popularity of GPS-based navigation systems. This paper presents the first attempt to investigate how to effectively utilize vehicles' trajectory information in a privacy-preserving manner. In our design, the trajectory information is combined with the traffic statistics to improve the performance of data forwarding in road networks. Through theoretical analysis and extensive simulation, it is shown that our design outperforms the existing scheme in terms of both the data delivery delay and packet delivery ratio, specially under light-traffic situations.

1 Introduction

With the standardization of Dedicated Short Range Communication (DSRC) by IEEE [4], Vehicular Ad Hoc Networks (VANETs) have recently reemerged as one of promising research areas for safety and connectivity in road networks. Currently, most research and development fall into one of two categories: (i) vehicle-to-vehicle (v2v) communications [12, 22] and (ii) vehicle-to-infrastructure (v2i) communications [24, 18, 5, 3]. In the meantime, the GPS technology has be adopted for navigation purposes at an unprecedented rate. It is expected that approximately 300 million GPS devices will be shipped in 2009 alone [23]. It becomes a very timely topic to develop novel applications by integrating the cutting-edge DSRC and GPS technologies.

Specifically, this work is motivated by the observed trend that a large number of vehicles have started to install GPS-receivers for navigation and 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, the nature research question is how to make the most of this trend to improve the performance of vehicular ad hoc networks.

Let's consider the scenario where Internet access points are sparsely deployed along the roadways for the road-side reports, such as the time-critical reports of driving accident or driving hazard. The Internet access points have limited communication coverage, so the vehicles cannot directly transmit their packets to the Internet access points. To support such a scenario, the *carry-and-forward* technique are proposed for use by several opportunistic forwarding schemes [19, 24, 15]. In these schemes, vehicles *carry* or *forward* packets progressively close to an access point by selecting potential shortest path based on traffic statistics. Without considering individual vehicles' trajectories, these forwarding scheme can be inefficient, especially in light-traffic road networks (e.g., rural-area road networks). This is because that the probability to forward packets to other vehicles at intersections is low in light-traffic road networks and it would be the case that vehicles carry packets towards the wrong direction, introducing excessive long delays.

This paper, for the first time, proposes a data forwarding scheme utilizing the vehicles' trajectory information for light-traffic road networks. The first challenge is how to use the trajectory information in a privacy-preserving manner, while improving the data forwarding performance. To resolve this challenge, we design a local algorithm to compute expected data delivery delay (EDD) at individual vehicles to an access point, using private trajectory information and known traffic statistics. Only the computed delay is shared with neighboring vehicles. The vehicle with the shortest expected delivery delay (EDD) is selected as the next packet carrier for its neighboring vehicles. The other challenge is how to model an accurate road *link delay*, a delay defined as the time taken for a packet to travel through a road segment using *carry-and-forward*. To resolve this challenge, we accurately model road link delay, based on traffic density information obtained from the GPS-based navigation system. Our intellectual contributions are as follows:

- An analytical link delay model for packet delivery along a road segment that is much more accurate than that of the state-of-art solutions. Besides serving as a critical building block of our TBD design, this link delay model is useful for other VANET designs, such as data dissemination through network-wide broadcast.
- An expected E2E delivery delay computation based on individual vehicle trajectory. The E2E delivery delay is estimated using both vehicular traffic statistics and individual vehicle trajectory. It turns out that this estimation provides a more accurate delivery delay, so vehicles can make better decision on the packet forwarding.

The rest of this paper is organized as follows: Section 2 describes the problem formulation. Section 3 describes our link delay model. Section 4 explains the design of the trajectory-based forwarding including the computation of the end-to-end delivery delay. Section 5 evaluates our design. We summarize related work in Section 6 and conclude this paper in Section 7.

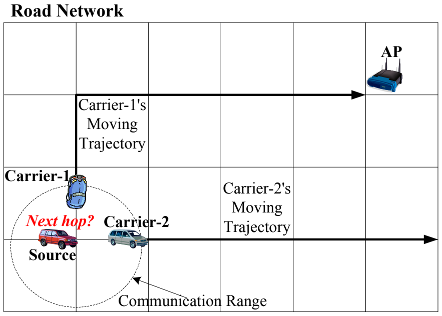
2 Problem Formulation

Given a road network with an Internet access point, the research problem is to minimize the end-to-end delivery delay of packets to the Internet access point. In this paper, we focus on one-way data delivery which is useful for the time-critical reports, such as vehicle accidents, road surface monitoring and driving hazards reports [6]. We leave two-way delivery as future work. In this paper, we refer (i) *Vehicle trajectory* as the moving path from the vehicle's starting position to its destination position in a road network; (ii) *Expected Delivery Delay (EDD)* as the expected time taken to deliver a packet generated by a vehicle to an Internet access point via the VANET; (iii) *Carry delay* as a part of the delivery delay introduced while a packet is carried by a moving vehicle; (iv) *Communication delay* as a part of the delivery delay introduced while a packet is forwarded among vehicles. Our work is based on the following four assumptions:

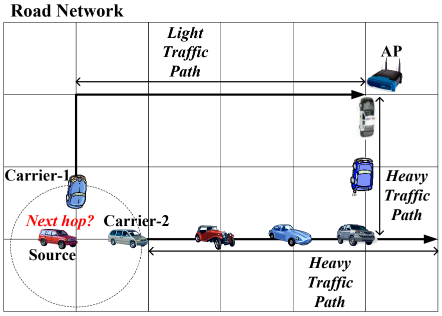
- The geographical location information of packet destinations, such as Internet access points (APs), is available to vehicles. A couple of studies have been done to utilize the Internet access points available on the road-sides [3, 5].
- Vehicles participating in VANET have a wireless communication device, such as the Dedicated Short Range Communications (DSRC) device [4]. Nowadays many vehicle vendors, such as GM and Toyota, are planning to install DSRC devices at vehicles [1].
- Vehicles are installed with a GPS-based navigation system and digital road maps. 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 [10].
- Vehicles know their trajectory by themselves. However, vehicles do not release their trajectory to other vehicles for privacy concerns.

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 [1] to forward a packet over the same road segment, even after considering the retransmission due to wireless link noise or packet collision. Therefore, since the carry delay is the dominating part of the total delivery delay, in the rest of the paper we focus on the carry delay for the sake of clarity, although the small communication delay does exist in our design.

Let's consider the following packet forwarding scenarios in Figure 1. The first scenario, as shown in Figure 1(a), is that three vehicles, denoted as *Source*, *Carrier-1* and *Carrier-2*, are moving in a road network. The *Source* wants to send its packet to the access point. *Carrier-1* and *Carrier-2* are within *Source*'s communication range. If trajectories are known, it is clear that *Source* will decide to forward its packets to *Carrier-1*, since *Carrier-1* moves towards the access point. The first challenging problem is how to make such a decision when privacy-sensitive trajectories are not shared directly.



(a) A Light-Traffic Road Network



(b) A Road Network with Unbalanced Traffic Density

Figure 1. Packet Delivery Scenarios

The second scenario, as shown in Figure 1(b), is that *Carrier-1*'s trajectory is on the light road traffic path and *Carrier-2*'s trajectory is on the heavy road traffic path. In this case, *Source* can select *Carrier-2* as next carrier and forward its packet to *Carrier-2* since *Carrier-2* has a high probability that it can forward *Source*'s packets to the access point via a communication path consisting of other vehicles. The second challenging problem is how to combine the road traffic statistics (e.g., density) information with the vehicle trajectory information for better forwarding decision making. In the next sections, we will deal with the two challenges raised in this section through the Link delay modeling and the Trajectory-based forwarding.

3 The Link Delay Model

This section 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. We leave the link delay for a two-way road segment as future work. Three terms for the link delay model are defined as follows:

Definition 1 (Connected Component). *Let Connected Component be a group of vehicles that can communicate with each other via either one-hop or multi-hop communication. Figure 2 shows a connected component consisting of vehicles* n_1,..., n_k.

Definition 2 (Forwarding Distance). *Let Forwarding Distance (denoted as* l_f*) be the physical distance a packet travels via wireless communication within a road segment starting from the entrance. Figure 2 shows the forwarding distance* l_f *for the connected component.*

Definition 3 (Carry Distance). *Let Carry Distance (denoted as* l_c*) be the physical distance a packet is carried by a vehicle within a road segment. Figure 2 shows the carry distance* l_c *of vehicle* n_1.

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[1] Note that the data rate in DSRC [4] is from 6∼27 Mbps and transmission range can extend to almost 1,000 meters.

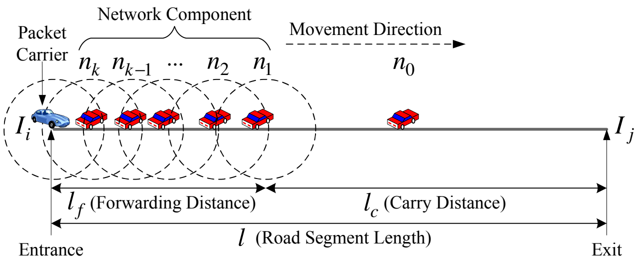
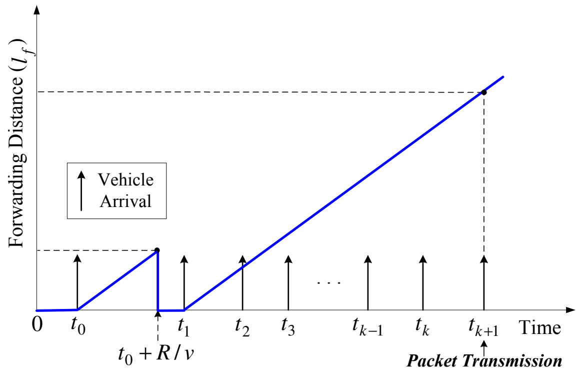
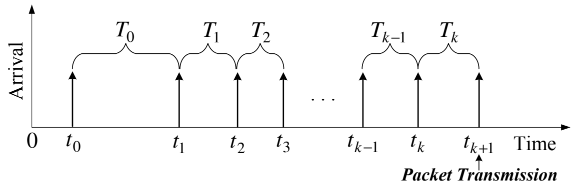


Figure 2. Forwarding Distance l_f and Carry Distance l_c



(a) Forwarding Distance (l_f) over Time



(b) Vehicle Arrival Sequence on One-way Road Segment

Figure 3. Forwarding Distance (l_f) over Time

Let v be the vehicle speed. By ignoring the small communication delay, the link delay d_{ij} along a road with the length of l is the corresponding carry delay. We have,

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

Therefore, the expected link delay $E[d_{ij}]$ is:

$$E[d_{ij}] = (l - E[l_f])/v. \tag{2}$$

In Equation 2, in order to obtain the expected link delay $E[d_{ij}]$, we need to derive the expected forwarding distance $E[l_f]$ first. Clearly the forwarding distance l_f equals the communication length of the connected component that is near the entrance as shown in Figure 2. To illustrate our modeling approach, we use Figure 3(a) to explain how the forwarding distance l_f change over time under different traffic arrival patterns.

- At time t_0, vehicle n_0 arrives. Since n_0 moves at the constant speed v, the forwarding distance l_f increases linearly at the rate of v. During the time interval $[t_0, t_0 + R/v]$, no other vehicle arrives, forcing n_0 to move out of the communication range of I_i. As a result, l_f reduces to zero after $t_0 + R/v$.
- At time t_1, vehicle n_1 arrives. Similarly, the forwarding distance l_f increases linearly at the rate of v. In this case, vehicles n_2,..., n_k arrive at I_i with the inter-arrival time less than R/v, forming a connected component of k vehicles.

To formally derive $E[l_f]$, we model the forwarding distance l_f as the sum of the inter-vehicle distance of vehicles within the component at any time. Figure 3(b) shows the corresponding vehicle arrival times as in Figure 3(a). Let t_h be the arrival time of the h-th vehicle. Let T_h be the inter-arrival interval of the h-th vehicle and the $(h+1)$-th vehicle. T_h is assumed to be an exponential random variable with arrival rate λ. This assumption has been shown valid in [20], because the *Kolmogorov-Smirnov test* can accurately approximate the statistics of vehicle inter-arrival time based on the empirical data for a real roadway into an *exponential distribution*.

As shown in Figure 3(b), when the vehicle n_{k+1} carrier arrives at t_{k+1} with an outgoing packet, the forwarding distance l_f is zero if $T_k = t_{k+1} - t_k > R/v$, otherwise l_f is the communication length of the connected component $\sum_{h=1}^{k} T_h v$ if $T_k = t_{k+1} - t_k < R/v$. We note the expected number of vehicle inter-distances (i.e., vT_h) within a connected component is the ratio between $P[vT_h \leq R]$ and $P[vT_h > R]$, according to detailed derivation in Appendix A. Therefore, we obtain $E[l_f]$ for the road segment (I_i, I_j) as follows:

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

From (3), we can see that $E[l_f]$ is the multiplication of (i) the *average inter-distance* of two adjacent vehicles within the same component and (ii) the *ratio* of the probability that the inter-distance is not greater than the communication range *to* the probability that the inter-distance is greater than the communication range. As the inter-arrival time decreases, this ratio increases, leading to the longer average forwarding distance; note that as the inter-arrival time decreases, the average inter-distance decreases, but the increasing rate of the ratio is much faster. Therefore, this fits well our intuition that the shorter inter-arrival time, the shorter inter-distance for communication, leading to the longer average forwarding distance.

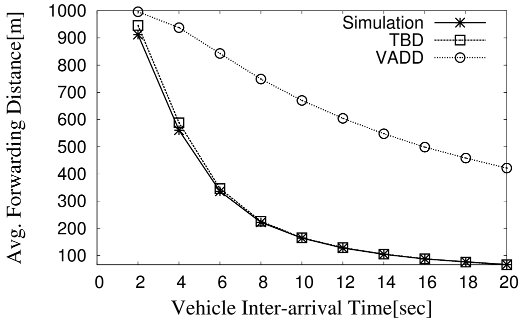
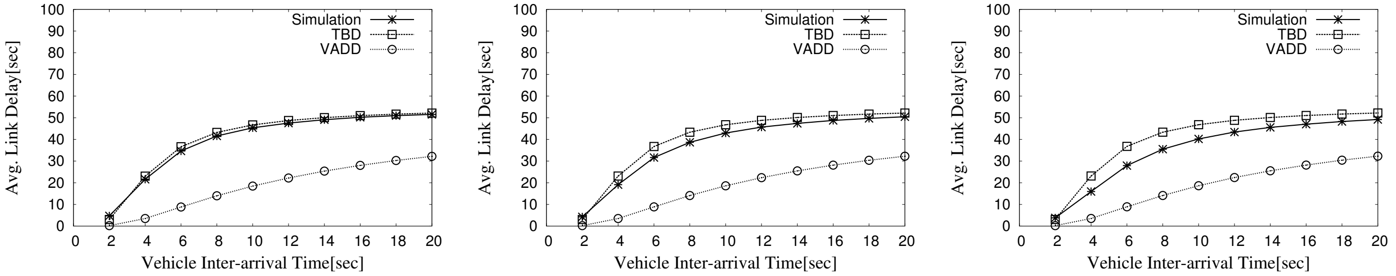


Figure 5. Validation and Comparison of Analytical Models

Figure 5 shows the average forwarding distance l_f comparison among simulation model and two analytical models for one-way roadway: (i) Our *TBD* link model for finite road length in Appendix A and (ii) *VADD* link model proposed by Zhao and Cao [24]. As shown in Figure 5, our link model gives very accurate average forwarding distance l_f estimates under different inter-arrival intervals. The reason *VADD* is not accurate is that *VADD* considers the sum of the lengths of all connected vehicles, while missing the fact that only the connected component starting from the entrance can actually be used for data forwarding.



(a) Constant Vehicle Speed with $\mu_v = 40$MPH (b) Vehicle Speed with $N(40, 3.5)$MPH (c) Vehicle Speed with $N(40, 7)$MPH

Figure 4. Link Delay Comparison among Simulation and Analytical Models

The above modeling process assumes the speed v of vehicles is constant. Clearly it does not hold well in practice, because for four-lane roadways, the vehicle speed deviation is 6.2 MPH (i.e., 9.98 km/h), according to field study conducted by Victor Muchuruza [11]. To investigate how robust our link delay model is, we test the accuracy of our model under three different settings: (i) a constant vehicle speed of 40 MPH, (ii) a normal speed distribution of $N(40, 3.5)$ and (iii) a normal speed distribution of $N(40, 7)$. Our model is compared with simulation, which approximates the ground truth, and VADD [24]. Figure 4 illustrates that as the vehicle speed deviation is within the realistic bound, the *TBD*'s link delay is closer to the simulation result than that of *VADD*.

4 TBD: E2E Delay Model and Protocol

In this section, we explain the design of our trajectory-based forwarding with two steps: We will first explain how to compute the Expected Delivery Delay (EDD) considering both *vehicular traffic statistics* and *individual vehicle trajectory* in section 4.1 and then describe how vehicles perform the data forwarding based on EDD in section 4.2.

4.1 End-to-End Delay Model

In this section, we model the EDD with a *stochastic model* [24] for a given road network. We define the road network graph for the EDD computation as follows:

Definition 4 (Road Network Graph). *Let a road network graph be the directed graph of* $G = (V, E)$, *where* $V = \{v_1, v_2, ..., v_n\}$ *is a set of intersections in the road network and* $E = [e_{ij}]$ *is a matrix of edge* e_{ij} *for vertices* v_i *and* v_j *such that* $e_{ij} \neq e_{ji}$. *Figure 6 shows a road network graph.*

To estimate end-to-end delay, we cannot use the traditional shortest path algorithms, such as Dijkstra's shortest path algorithm. This is because when the packet carrier arrives at an intersection, it is not guaranteed that it can meet another vehicle moving towards the most preferred direction. In this case, the packet carrier needs to determine whether it can forward its packet to another vehicle moving towards other preferred directions or has to carry it with itself to the next intersection on its trajectory. In order to consider all of the possible cases in the forwarding at each intersection, we formulate the data delivery based on this carry-and-forward as the *stochastic model*.

4.1.1 Expected Delivery Delay at Intersection

In this section, we explain how to compute the EDD at an intersection, using a stochastic model. Suppose that a packet at intersection i is delivered towards intersection j. Let d_{ij} be the link delay for edge e_{ij} in Equation 1. We note the expected delay EDD at an intersection depends on the forwarding direction (i.e., edge). Therefore, we use D_{ij} denote the EDD at the intersection i when the edge e_{ij} is used as the forwarding edge. We formulate D_{ij} recursively as follows:

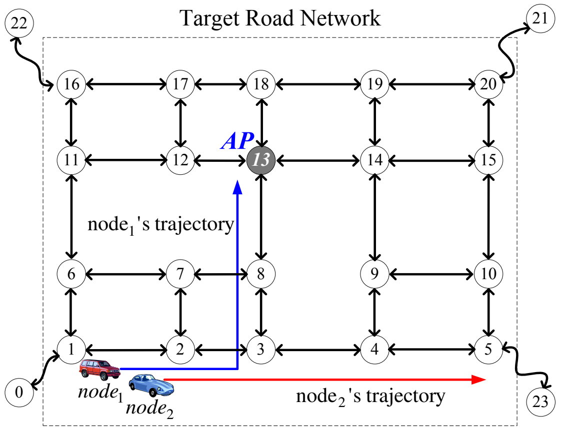


Figure 6. Road Network Graph for Data Forwarding Scenario in VANET.

$$\begin{aligned} D_{ij} &= d_{ij} + E[\text{delivery delay at } j \text{ by forwarding or carry}] \\ &= d_{ij} + \sum_{k \in N(j)} P_{jk} D_{jk} \end{aligned} \tag{4}$$

where $N(j)$ is the set of neighboring intersections of intersection j. We use this stochastic model to compute the EDD at intersection i because the packet will be delivered with some probability to one of outgoing edges at intersection j. This means that when the carrier of this packet arrives at intersection j, the next carrier on each outgoing edge towards intersection k will be met with probability P_{jk}. We will explain how to compute the probability P_{jk} later.

For example, suppose that as shown in Figure 7, a packet carried by a vehicle arrives at intersection 1 and is sent towards intersection 2. The EDD of $D_{1,2}$ denotes the end-to-end delivery delay when the carrier sends its packet to the AP via the edge $e_{1,2}$. First, it will take $d_{1,2}$ seconds to deliver a packet to the intersection 2 via $e_{1,2}$. Once the packet arrives at intersection 2, there are three possible cases to deliver the packet. In other words, the packet can be forwarded to one of three neighboring intersections (i.e., intersection 1, 3 or 7) of intersection 2 with some probability. Let $D_{2,1}$, $D_{2,3}$ and $D_{2,7}$ be the EDDs for three edges $e_{2,1}$, $e_{2,3}$ and $e_{2,7}$, respectively. We can compute $D_{1,2}$

using the stochastic model in (4) as follows:

$$D_{1,2} = d_{1,2} + P_{2,1}D_{2,1} + P_{2,3}D_{2,3} + P_{2,7}D_{2,7}.$$

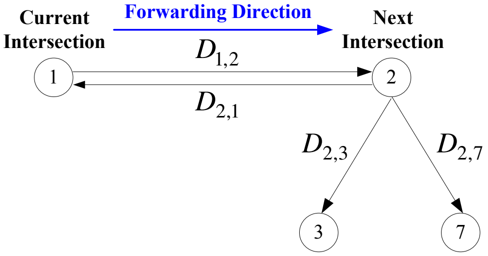


Figure 7. EDD Computation at Intersection 1 for Intersection 2

Let n be the number of directed edges in the road network graph $G = (V, E)$, as shown in Figure 6. We have n variables of D_{ij} for directed edge $e_{ij} \in E(G)$. Since we have n variables and n linear equations of (4), we can solve this linear system using the *Gaussian Elimination* algorithm.

We start to explain how to compute the probability P_{jk} in (4). P_{ij} is defined as the *average forwarding probability* that a packet at intersection i will be delivered to a vehicle moving towards the neighboring intersection j.

Contact Probability: Contact Probability is defined as the chance a vehicle can encounter another vehicle at an intersection. Let R be communication range. Let v_{ij} be the mean vehicle speed on the directed edge e_{ij}. Let T_{ij} be the duration during which a vehicle is able to communicate with the vehicles around the intersection i. Clearly, T_{ij} is affected by the vehicle speed, the communication range, the traffic signal pattern and the queueing delay. In practice, average T_{ij} can be obtained through empirical measurements. In this study, we use a simplifying model to calculate T_{ij} by assuming the nominal communication range is R and a constant speed is v. Therefore, $T_{ij} = 2R/v_{ij}$. We note our design can use empirical T_{ij} measurements if available. Let CP_{ij} be the contact probability that a packet carrier in the intersection area of i will meet at least one vehicle moving towards j for during T_{ij}. Suppose that the vehicle arrival at the directed edge e_{ij} is Poisson process with vehicle arrival rate λ_{ij}. Thus, CP_{ij} is computed using the Poisson Process probability as follows:

$$CP_{ij} = 1 - e^{-\lambda_{ij}T_{ij}}. \quad (5)$$

Forwarding Probability: At an intersection, forwarding is probabilistic in nature, therefore a packet is forwarded with best-effort. Let's define the *forwarding probability* as the chance that a packet carrier at intersection i can forward a packet to another vehicle moving towards one of the neighboring intersections j_k for $k = 1..m$. We note there is a clear distinction between the *contact probability* and *forwarding probability*, because a packet will not be forwarded to a contacted vehicle that moves to a wrong direction.

To calculate forwarding probability, we need to sort edges based on the forward priority. For an intersection i with m forwarding edges e_{ij_k} $(k = 1...m)$, we can sort them in non-decreasing order, based on their *geographically shortest path length* from intersection i to a packet destination (i.e., *AP*) via the edge e_{ij_k}. This heuristic is based on the observation that the edge on the geographically shortest path tends to provide the shortest delivery path; note that the intersection model of [24] uses the angle between the packet destination and the edge for the enumeration, but the smallest angle does not always give the shortest path in the road networks of non-grid topology. Therefore, the forwarding probability P'_{ij_k} for each edge e_{ij_k} is computed as follows:

$$P'_{ij_k} = \begin{cases} CP_{ij_1} & \text{for } k = 1, \\ \left(\prod_{s=1}^{k-1}(1 - CP_{ij_s})\right)CP_{ij_k} & \text{for } k = 2..m. \end{cases} \quad (6)$$

Conditional Forwarding Probability: Clearly, a packet should not be forwarded to the edge that is worse than the edge the carrier moves toward, therefore, we need to compute the *conditional forwarding probability* that a packet carrier moving on edge e_{ij_h} can forward its packet to another vehicle moving on e_{ij_k}, that is, $P_{ij_k|ij_h} = P[\text{packet is forwarded to } e_{ij_k} | \text{carrier moves from } e_{ij_h}]$. The conditional forwarding probability $P_{ij_k|ij_h}$ is computed as follows:

$$P_{ij_k|ij_h} = \begin{cases} P'_{ij_k} & \text{for } k < h, \\ 1 - \sum_{s=1}^{k-1} P'_{ij_s} & \text{for } k = h, \\ 0 & \text{for } k > h. \end{cases} \quad (7)$$

Average Forwarding Probability: Finally, we can compute the average forwarding probability P_{ij_k} that a packet arriving at intersection i will be delivered to the neighboring intersection j_k by either forwarding or carry. In order to compute P_{ij_k} for the packet-delivered intersection j_k, we need the branch probability B_{ij_h} that a packet carrier arriving at intersection i will move to intersection j_h for $j_h \in N(i)$. This branch probability can be obtained from the vehicular traffic statistics on the edge e_{ij_k}. Therefore, P_{ij_k} is calculated as follows:

$$P_{ij_k} = \sum_{j_h \in N(i)} B_{ij_h} P_{ij_k|ij_h}. \quad (8)$$

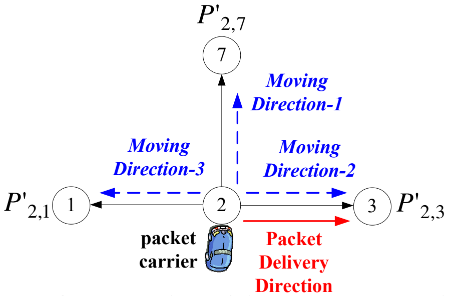


Figure 8. The Computation of Average Forwarding Probability $P_{2,3}$ at Intersection 2

For example, as shown in Figure 8, suppose that a packet carrier is placed at intersection 2 in Figure 6 and moves to one of the neighboring intersections with the corresponding branch probability $B_{2,j}$ for $j = \{1, 3, 7\}$; that is, there are three directions for the packet carrier to take, such as *Moving Direction-1*, *Moving Direction-2* and *Moving Direction-3*. We want to compute the average forwarding probability $P_{2,3}$ that the packet carrier will deliver its packet onto edge $e_{2,3}$. We assume that the ascending order of the shortest path length from intersection 2 towards the AP via the three edges is $e_{2,7}$, $e_{2,3}$ and $e_{2,1}$. According to this assumption, the contacting order for packet forwarding is the same (i.e., $e_{2,7}$, $e_{2,3}$ and $e_{2,1}$) and the forwarding probabilities for these three edges are $P'_{2,7}$, $P'_{2,3}$ and $P'_{2,1}$, respectively. Therefore, the average forwarding probability $P_{2,3}$ is computed from (8) as follows:

$$\begin{aligned} P_{2,3} &= B_{2,1}P_{2,3|2,1} + B_{2,3}P_{2,3|2,3} + B_{2,7}P_{2,3|2,7} \\ &= B_{2,1}P'_{2,3} + B_{2,3}(1 - P'_{2,7}). \end{aligned}$$

Note that (a) $P_{2,3|2,1} = P'_{2,3}$ since the shortest path length for the carrier's moving edge $e_{2,1}$ is longer than that for the forwarding edge $e_{2,3}$, so the carrier tries to forward its packets onto $e_{2,3}$; (b) $P_{2,3|2,3} = 1 - P'_{2,7}$ since the shortest path length for the edge $e_{2,7}$ has the shortest among the three edges; (c) $P_{2,3|2,7} = 0$ since the shortest path length for the carrier's moving edge $e_{2,7}$ is shorter than that for the forwarding edge $e_{2,3}$, so the carrier does not try to forward its packets onto $e_{2,3}$.

We note this EDD model computes D_{ij} without considering the trajectory. If two vehicles $node_1$ and $node_2$ are placed at the same intersection 1 in Figure 6, their EDDs towards the same packet-delivered edge $e_{1,2}$ are the same with each other. Therefore, only with this intersection EDD model, the individual vehicle's trajectory does not affect the computation of EDD, so we cannot determine to choose which one as the best next carrier. In the next section, we explain how the vehicle trajectory can be added in the EDD computation.

4.1.2 *Expected Delivery Delay based on Trajectory*

In this section, we explain how to compute the expected E2E delivery delay (EDD) based on the *vehicle trajectory*. A trajectory is defined as the moving path from a vehicle's starting position to its destination position in a road network;.

The main idea of trajectory-based forwarding is to divide the delivery process recursively into two steps: (i) The packet carry process at the current vehicle and (ii) the delivery process after the packet leaves this vehicle. In the case of light traffic, it is possible that a vehicle could carry a packet continuously over multiple edges.

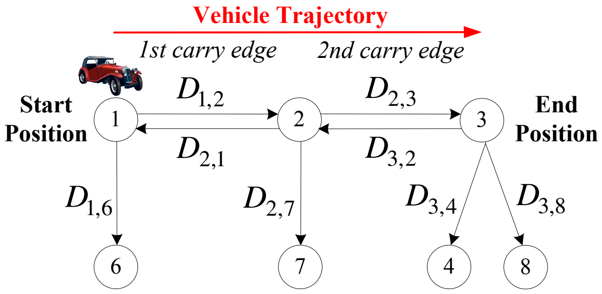


Figure 9. EDD Computation for the Trajectory from Intersection 1 to Intersection 3

Suppose the packet is with the current vehicle. This vehicle will travel along a trajectory denoted by a sequence of intersections: $1 \rightarrow 2 \rightarrow \cdots \rightarrow M$. Let C_{ij} be the total time taken to carry the packet by the vehicle from the intersection i to the intersection j along the trajectory ($1 \leq i \leq j \leq M$). Formally, $C_{ij} = \sum_{k=i}^{j-1} l_{k,k+1}/v$. As a reminder, P'_{mn} is the forwarding probability in (6) that the vehicle at intersection m can forward its packets to another vehicle moving towards the neighboring intersection n. As a reminder, P^c_{mn} be the carry probability that the vehicle cannot forward its packet at intersection m, and so has to carry its packets to the adjacent intersection n. Formally, $P^c_{mn} = 1 - \prod_{k\in N(m)} P'_{mk}$. The expected end-to-end delay D at the vehicle is computed as follows:

$$\begin{aligned} D &= \sum_{j=1}^{M} (P[\text{a packet is carried from intersection 1 to } j] \\ &\quad \times (C_{1j} + E[\text{delivery delay at intersection } j])) \qquad (9) \\ &= \sum_{j=1}^{M} ((\prod_{h=1}^{j-1} P^c_{h,h+1}) \times (C_{1j} + \sum_{k\in N(j)} P'_{jk}D_{jk})) \end{aligned}$$

In (9), $P[\text{a packet is carried from intersection 1 to } j] = \prod_{h=1}^{j-1} P^c_{h,h+1}$ is the carry probability along the trajectory from intersection 1 to the intersection j. $E[\text{delivery delay at intersection } j] = \sum_{k\in N(j)} P^f_{jk}D_{jk}$ is the expected delivery delay after the packet leaves the current vehicle.

For example, as shown in Figure 9, let the trajectory be $1 \rightarrow 2 \rightarrow 3$ in the road network in Figure 6. First, the vehicle at intersection 1 can try to forward the packets to the neighboring intersections 2 and 6. If it cannot forward the packets at the intersection 1, it must carry them by the next intersection 2. When it arrives at intersection 2, it can try to forward again. If it cannot forward again, it will carry the packet to the third intersection 3. At the destination, if the vehicle cannot forward, it discards the packets. With this scenario, the expected delivery delay D is computed as follows:

$$\begin{aligned} D &= P'_{1,6}D_{1,6} + P'_{1,2}D_{1,2} + P^c_{1,2}(C_{1,2} + P'_{2,1}D_{2,1} + P'_{2,3}D_{2,3} \\ &\quad + P'_{2,7}D_{2,7}) + P^c_{1,2}P^c_{2,3}(C_{1,3} + P'_{3,2}D_{3,2} + P'_{3,4}D_{3,4} \\ &\quad + P'_{3,8}D_{3,8}). \end{aligned}$$

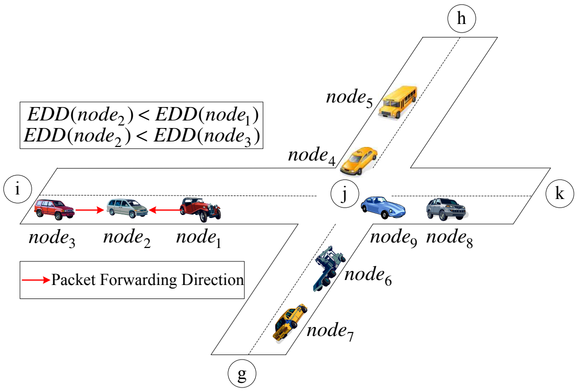
So far, we have explained how to compute the EDD based on the vehicular traffic statistics and individual vehicle trajectory. In the next section, we will explain how vehicles can use their EDDs in the packet forwarding process.

4.2 Forwarding Protocol Design

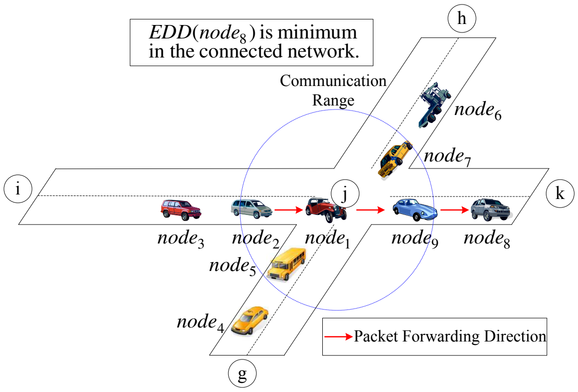
In this section, we describe our design of *the TBD forwarding protocol* to perform data forwarding among vehicles in order to deliver data packets to the destination in the given road network. Our *TBD forwarding rule* is as simple as the following:

Within a connected component, packets are forward to the vehicle with a minimum EDD.

Each individual vehicle updates its *EDD* with (9), based on its trajectory from the current position to the destination position every update period (e.g., one second). This vehicle's EDD is broadcasted within the connected component. In this way, each vehicle can recognize the EDDs of other vehicles. Figure 10 illustrates our *TBD forwarding protocol*. Figure 10(a) shows the data forwarding on road segment e_{ij}. Suppose that $node_1$ and $node_3$ are within the communication range of $node_2$ and they carry their packets. Therefore $node_1$, $node_2$ and $node_3$ form a connected component. Since $node_2$'s EDD is minimum in this connected network, $node_1$ and $node_3$ forward their packets to $node_2$. Figure 10(b) shows the data forwarding around intersection j. When $node_1$ arrives at intersection j, nine vehicles from $node_1$ to $node_9$ construct a connected component. Since $node_8$'s EDD is minimum in the connected network, the packets of $node_2$ are forwarded to $node_8$ via $node_1$ and $node_9$. Beside using this simple broadcast method, we can apply more advanced group management protocols for ad-hoc networks such



(a) Data Forwarding on Road Segment e_{ij}. Vehicles $node_1$, $node_2$ and $node_3$ construct a connected network. Since $node_2$'s EDD is less than $node_1$'s and $node_3$'s, the packets of $node_1$ and $node_3$ are forwarded to $node_2$.



(b) Data Forwarding around Intersection j. Nine vehicles from $node_1$ to $node_9$ construct a connected network. Since $node_8$'s EDD is minimum in the connected network, $node_2$ forwards its packets to $node_8$ via $node_1$ and $node_9$.

Figure 10. TBD Forwarding Protocol in VANET

as in [9], which handles group update, mergence and partition in a more efficient manner. We leave this type of optimization as future work, because in vehicular networks, communication energy is not a key resource constraint.

5 Performance Evaluation

In this section, we evaluate the performance of *TBD* by comparing it with a state-of-the-art scheme.

- **Performance Metrics:** We use (i) *average delivery delay* and (ii) *packet delivery ratio* as the performance metrics.
- **Baseline:** For the performance comparison, we use *VADD* [24] which is a state-of-the-art *carry-and-forward* approach for the *lowest delivery delay*.
- **Parameters:** In the performance evaluation, we investigate the effect of (i) *vehicular traffic density*, (ii) *vehicle speed*, (iii) *vehicle speed deviation* and (iv) *packet time-to-live (TTL)*.

A road network with 36 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 random waypoint model where the vehicle moves along the shortest path from a randomly selected source position to a randomly selected destination position. During the simulation, following an exponential distribution with a mean of 5 seconds, packets are dynamically generated from 10 vehicles in the road network. The total number of generated packets is 50,000 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 [4]. Unless otherwise specified, the default values in Table 1 are used.

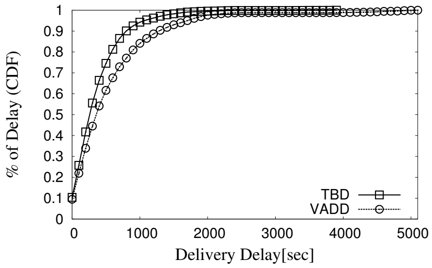


Figure 11. Cumulative Distribution Comparison for Delivery Delay

Table 1. Simulation Configuration

Parameter	Description
Road network	The number of intersections is 36. The area of the road map is 6.75km×6km (i.e., 4.2miles×3.7miles).
Communication range	$R = 200$ meters (i.e., 656 feet).
Number of vehicles	The number N of vehicles moving within the road network. The default N is 100.
Time-To-Live	The expiration time of a packet. The default TTL is ∞; that is, there exists no packet drop due to TTL expiration.
Vehicle speed	$v \sim N(\mu_v, \sigma_v)$ where $\mu_v = \{20, 25, ..., 60\}$ MPH and $\sigma_v = \{0, 1, ..., 10\}$ MPH. The maximum speed is 60 and the minimum speed is 20. The default (μ_v, σ_v) is $(40, 5)$.

5.1 Performance Comparison

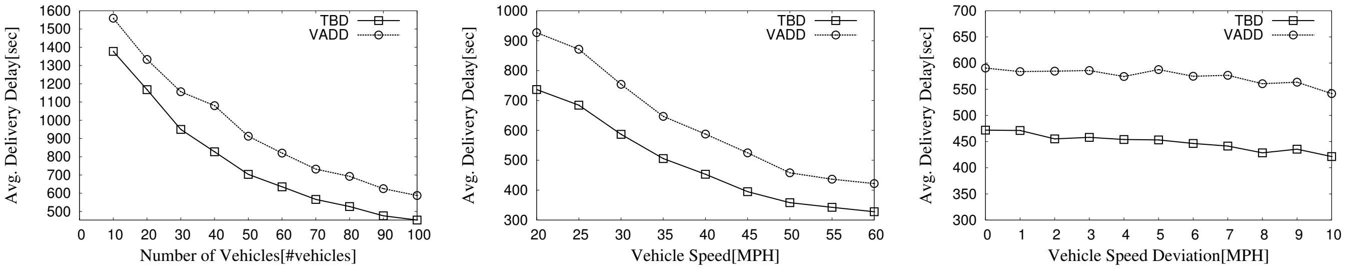
In this section, we compare the performance of the two approaches: (i) *TBD* (using our link delay model and our forwarding protocol) and (ii) *VADD* (using the link delay model and the Direction-First-Probe forwarding protocol proposed in [24]).

5.1.1 Forwarding Behavior Comparison between TBD and VADD

We compare the forwarding behaviors of *TBD* and *VADD* with the cumulative distribution function (CDF) of the actual packet delivery delays. From Figure 11, it is very clear that *TBD* has smaller packet delivery delay than that of *VADD*. For any given packet deliver delay, *TBD* always has a larger CDF value than that of *VADD* before they both reach 100% CDF. For example, *TBD* reaches 90% CDF with a delivery delay of 1000 seconds while the value for *VADD* is 2000 seconds. In other words, on average, the packet delivery delay for *TBD* is smaller than that of *VADD* and we will show this quantitatively in the following subsections.

5.1.2 The 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 the *TBD* can forward packets towards the access point using individual vehicles' trajectory information. Through our extensive simulations, we observe that



(a) Impact of the Number of Vehicles (b) Impact of Vehicle Speed (c) Impact of Vehicle Speed Deviation

Figure 12. Performance Comparison between TBD and VADD under Low Vehicular Traffic Density

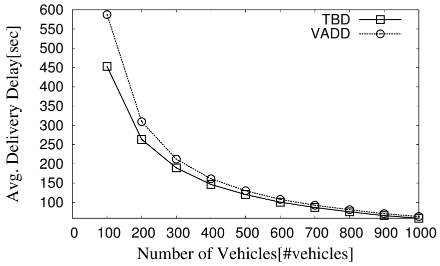


Figure 13. Delivery Delay Comparison under High Vehicular Traffic Density

under *low vehicular traffic density*, the *TBD* significantly outperforms *VADD* in terms of packet delivery delay. Figure 12(a) shows the packet delivery delay comparison between *TBD* and *VADD* with varying number of vehicles under low vehicular traffic density. As shown in Figure 12(a), *TBD* has smaller packet delivery delay than that of *VADD* at all vehicular densities. The smallest delay reduction is 11.6% for $N = 10$ while the largest delay reduction is 23.9% at $N = 80$. This shows that in the extremely sparse road networks, such as $N = 10$, the trajectory in *TBD* has less contribution than in the cases of not-so sparse road networks, such as $N \geq 30$. This is because when the number of vehicles is so small, the probability that vehicles can meet each other is also low. However, in the sparse road networks, by using both the trajectory and the vehicular traffic statistics, *TBD* has an average of 20.4% delivery delay reduction (from $N = 10$ to $N = 100$) over *VADD*, which only considers the vehiclular traffic statistics.

For high vehicular traffic density, Figure 13 shows the delivery delay comparison between *TBD* and *VADD* with varying number of vehicles from 100 to 1000. From Figure 13, it is shown that as the number of vehicles increases, the performance gap between *TBD* and *VADD* is decreasing accordingly. This is because the higher vehicular traffic density provides the higher probability that the packets can be forwarded to vehicles with small expected delivery delay (EDD) at every intersection. Consequently, we can conclude that the data forwarding decision made by considering *individual trajectory information* has *less benefits* in *high vehicular traffic density*. However, at all vehicular traffic densities, *TBD* still outperforms *VADD* in terms of packet delivery delay. As a result, we can see *TBD* not only provides significant better data forwarding quality than *VADD* in light-traffic road networks which is targeted in this paper, but also has smaller packet delivery delay even at high-traffic conditions.

5.1.3 *The Impact of Vehicle Speed* μ_v

In this subsection, we are interested to investigate how the change of mean vehicle speed affects the delivery delay. Figure 12(b) shows the delivery delay under different mean vehicle speeds. As shown in the Figure 12(b), for both *TBD* and *VADD*, the higher vehicle speed leads to the shorter delivery delay for both *TBD* and *VADD*. 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 *TBD* still outperforms *VADD*.

5.1.4 *The Impact of Vehicle Speed Deviation* σ_v

The vehicles moving with a high speed deviation can construct a longer ad-hoc network component for communications, so the delivery delay in a high speed deviation can be shorter than the delivery delay in a low speed deviation. This is because in such a high speed deviation, fast moving vehicles can connect two isolated network components with the communication range when they pass the middle of the two isolated components. On the other hand, in a low speed deviation, such as zero deviation, if two isolated components are isolated from the communication, they cannot be merged into a longer component.

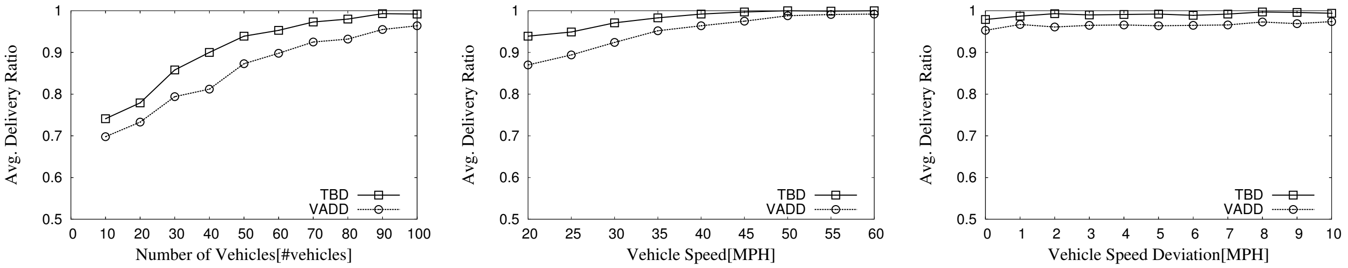
Figure 12(c) illustrates our observation for the delivery delay in the vehicle speed deviation. The higher vehicle speed deviation leads to the slightly shorter delivery delay in both *TBD* and *VADD*. Also, we can see that the performance difference between *TBD* and *VADD* according to the vehicle speed deviation from 0 to 10 MPH is almost constantly maintained. Therefore, we can conclude that even under variable vehicle speed deviation, *TBD* has better performance than *VADD*.

5.1.5 *The Impact of Packet Time-To-Live* TTL

In this subsection, we investigate the impact of the packet's *Time-To-Live (TTL)* on the *packet delivery ratio*, defined as the ratio between the number of delivered packets to the number of packets generated. We set TTL to 30 minutes in our simulation; that is, if a packet is not delivered within 30 minutes after its generation, it will be discarded by a packet carrier.

Figure 14(a) shows the delivery ratio comparison between *TBD* and *VADD* with varying number of vehicles in the road network. As expected, the larger number of vehicles yields higher average delivery ratio. The delivery ratios for both *TBD* and *VADD* are increasing roughly linearly with respect to the number of vehicles. In average, the delivery ratio for *TBD* is 5% higher than that of *VADD*. Clearly, we can see even at light-traffic condition, *TBD* has better delivery ratio than *VADD*.

We investigate the impact of vehicle speed on the delivery



(a) Impact of the Number of Vehicles (b) Impact of Vehicle Speed (c) Impact of Vehicle Speed Deviation

Figure 14. Performance Comparison between TBD and VADD for Finite TTL ($TTL = 30$ minutes)

ratio in Figure 14(b). We can see at all vehicle speeds, *TBD* has larger delivery ratio than the *VADD*. However, the performance difference between two schemes is getting smaller as the vehicle speed increases. This is because with higher vehicle speed, the vehicle arrival rate also increases at each road segment and this gives the *VADD* a higher forwarding probability.

We also investigate the impact of vehicle speed deviation on the delivery ratio. Figure 14(c) shows the delivery ratio comparison between *TBD* and *VADD* according to the vehicle speed deviation from 0 MPH to 10 MPH. The performance difference is almost constant. Thus, we can conclude that the vehicle speed deviation does not affect the delivery ratio.

6 Related Work

Data forwarding and data access issues in VANET have gained a lot of attentions recently [14, 24, 18, 21, 12, 8, 7, 2, 13, 16]. The data forwarding in VANET is different from that in the traditional mobile ad-hoc networks (MANETs) [17] for the reason of (i) vehicles are moving on the physically constrained areas (i.e., roadways), (ii) the moving speed is also limited by the speed limit on the roadways and (iii) the communication shortest path does not always match the physical shortest path due to heterogeneous vehicular traffic conditions on road segments. These unique characteristics of the road networks open the doors of research opportunities for the data forwarding in the VANET. Also, the frequent network partition and mergence due to the high mobility make the MANET routing protocols [17] ineffective in the VANET settings [20]. Thus, in order to deal with this frequent network partition and mergence, the *carry-and-forward* approaches are necessary. Epidemic Routing in [19] 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 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* [24] and Delay-Bounded Routing [18]. *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. On the other hand, 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. Our *TBD*, in contrast, improves forwarding performance by utilizing the *vehicle trajectory information* along with vehicular traffic statistics in order to compute the accurate expected delivery delay for better forwarding decision making.

MDDV [21] proposes a forwarding scheme in VANET to allow the predefined packet trajectory. The packet trajectory in this scheme is the path where this packet traverses through, and so is different from the vehicle trajectory. Since this scheme forces the packet to traverse through the predefined path, it can be inefficient in the light-traffic road networks. This is because the probability that no vehicle moves along a road segment that is on the edge of packet trajectory is high in the light-traffic road networks.

For dense road networks, such as urban roadways, *CAR*, *MMR* and *VVR* are proposed [12, 8, 7]. *CAR* forwards data packets through the connected path from the packet source to the packet destination. In rural roadways which is our focus in this paper, this connectivity-based data forwarding may not work well due to the sparse vehicular traffic. *MMR* and *VVR* use *greedy forwarding* choosing the next packet carrier based on the geographical proximity towards the packet destination. However, in road networks, since the vehicular traffic distribution is not uniform, this geographical greedy forwarding does not always provide the communication shortest path. On the other hand, our *TBD* allows a packet carrier to choose the best next packet carrier on the communication shortest path since it is aware of the road-network-wide vehicular traffic density along with individual vehicle trajectory.

7 Conclusion

In this paper, we propose a trajectory-based data forwarding scheme for light-traffic road networks, where the carry delay is the dominating factor for the end-to-end delivery delay. We compute the aggregated end-to-end carry delay using the *individual vehicle trajectory* along with the *vehicular traffic statistics*. Our design allows vehicles to share their trajectory information without exposing their actual trajectory to neighbor vehicles. This privacy-preserving trajectory sharing scheme is made possible by exchanging only the expected delay value using local vehicle trajectory information. We also propose a link delay model based on the common assumption of exponential vehicle inter-arrival time. It is shown to be more accurate than the state-of-the-art solution. With the increasing popularity of vehicular ad-hoc networking, we believe that our forwarding scheme opens a first door for exploiting the potential benefit of the vehicle trajectory for the performance of VANET networking. As future work, we will explore in-depth research on the reverse forwarding from a stationary Internet access point to a moving vehicle and also the extension of our forwarding scheme in the scenarios of multiple Internet access points.

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A Appendix: Link Delay Modeling

A.1 Link Delay Modeling for Infinite Road Segment

In this section, we derive $E[l_f]$ for infinite road length for one-way traffic road segment where vehicles arrive with arrival rate λ. We derive $E[l_f]$ for the modeling for the finite road length case in the next section.

The $E[l_f]$ can be computed as the expected sum of the inter-distances within the connected component. Suppose that the inter-arrival time T_h is exponentially distributed with arrival rate λ. So T_h for $h = 1..k$ are i.i.d. for the exponential distribution with parameter λ. Let $a = R/v$; that is, a is the time taken for a vehicle to move out of the communication range R with speed v. Let $C(k)$ be the condition for the component consisting of k vehicle inter-arrivals such that $C(k)$: $T_0 > a$ and $T_h \leq a$ for $h = 1..k$; Let $L(k)$ be the length of the connected component of k vehicle inter-arrivals. Then, $E[l_f]$ can be derived as follows:

$$\begin{aligned} E[l_f] = E[L] &= \sum_{k=1}^{\infty} E[L(k)|C(k)] \times P[C(k)] \\ &= v \times \sum_{k=1}^{\infty} E[\sum_{h=1}^{k} T_h | T_0 > a, T_h \leq a \text{ for} \\ &\quad h = 1..k] \times P[T_0 > a, T_h \leq a \text{ for } h = 1..k] \end{aligned} \tag{10}$$

Since, in (10), T_h for $h = 0..k$ are *i.i.d.* for the exponential distribution with parameter λ, we can rewrite (10) as follows:

$$E[l_f] = v \times \sum_{k=1}^{\infty} k \times E[T_h | T_h \leq a] \times P[T_h \leq a]^k \times P[T_0 > a] \tag{11}$$

Since $P[T_h \leq a] = 1 - e^{-\lambda a}$ and $P[T_0 > a] = e^{-\lambda a}$, respectively, we need to compute $E[T_h | T_h \leq a]$ to compute (11).

$$\begin{aligned} E[T_h | T_h \leq a] &= \int_0^a t \times P[T_h = t | T_h \leq a] dt \\ &= \int_0^a t \times \frac{P[T_h = t, T_h \leq a]}{P[T_h \leq a]} dt \\ &= \int_0^a t \times \frac{P[T_h = t]}{P[T_h \leq a]} dt \\ &= \int_0^a t \times \frac{\lambda e^{-\lambda t}}{1 - e^{-\lambda a}} dt \\ &= \frac{1/\lambda - (a + 1/\lambda) e^{-\lambda a}}{1 - e^{-\lambda a}}. \end{aligned} \tag{12}$$

Therefore, (11) can be rewritten as follows:

$$\begin{aligned} &E[l_f] = \alpha \times \textstyle\sum_{k=1}^{\infty} k \beta^{k-1} \\ &\quad \text{where } \alpha = v e^{-\lambda a} (\tfrac{1}{\lambda} - (a + \tfrac{1}{\lambda}) e^{-\lambda a}) \text{ and } \beta = 1 - e^{-\lambda a}. \end{aligned} \tag{13}$$

Let $f(\beta) = \sum_{k=1}^{\infty} \beta^k$. Since $0 < \beta < 1$, $f(\beta) = \frac{\beta}{1-\beta}$. Accordingly, $f'(\beta) = \frac{d}{dk} (\sum_{k=1}^{\infty} \beta^k) = \sum_{k=1}^{\infty} k \beta^{k-1} = \frac{1}{(1-\beta)^2}$. Therefore, $E[l_f]$ is as follows:

$$E[l_f] = \frac{\alpha}{(1-\beta)^2} = v \frac{1/\lambda - (a + 1/\lambda) e^{-\lambda a}}{1 - e^{-\lambda a}} \times \frac{1 - e^{-\lambda a}}{e^{-\lambda a}} \tag{14}$$

Since $P[T_h \leq a] = 1 - e^{-\lambda a}$ and $P[T_0 > a] = e^{-\lambda a}$, we have

$$\begin{aligned} E[l_f] &= vE[T_h|T_h \leq a] \times \frac{P[T_h \leq a]}{P[T_h > a]} \\ &= E[vT_h|vT_h \leq R] \times \frac{P[vT_h \leq R]}{P[vT_h > R]}. \end{aligned} \tag{15}$$

A.2 Link Delay Modeling for Finite Road Segment

For the finite road length l, we need to guarantee that the component length must be less than or equal to the road segment length. The idea is to let the component length $L'(k) \leq l$ using function *min* along with $L(k)$ for the infinite road length as follows:

$$L'(k) = \min\{l, L(k)\} \quad \text{where } L(k) = v\sum_{h=1}^{k} T_h. \tag{16}$$

(10) can be rewritten using (16) as follows:

$$\begin{aligned} E[l_f] &= \sum_{k=1}^{\infty} E[L'(k)|C(k)] \times P[C(k)] \\ &= \sum_{k=1}^{\infty} E[L'(k)|T_0 > a, T_h \leq a \text{ for } h = 1..k] \\ &\quad \times P[T_0 > a, T_h \leq a \text{ for } h = 1..k] \\ &= \sum_{k=1}^{N-1} E[L(k)|T_0 > a, T_h \leq a \text{ for } h = 1..k] \\ &\quad \times P[T_0 > a, T_h \leq a \text{ for } h = 1..k] \\ &\quad + \sum_{k=N}^{\infty} l \times P[T_0 > a, T_h \leq a \text{ for } h = 1..k] \end{aligned} \tag{17}$$

In (17), we need to determine N which is the index to let the component length longer than the road length l. Let $g(k) = E[L(k)|C(k)]$. We can compute $g(k)$ as follows:

$$\begin{aligned} g(k) &= vk \times E[T_h|T_h \leq a] \\ &= vk \times \frac{1/\lambda - (a + 1/\lambda)e^{-\lambda a}}{1 - e^{-\lambda a}} \\ &= \frac{\alpha}{\beta(1-\beta)} \times k \\ &\quad \text{where } \alpha = ve^{-\lambda a}(\frac{1}{\lambda} - (a + \frac{1}{\lambda})e^{-\lambda a}) \text{ and } \beta = 1 - e^{-\lambda a}. \end{aligned} \tag{18}$$

We can search the smallest positive integer N to satisfy $g(N) \geq l$ with (18) as follows:

$$\frac{\alpha}{\beta(1-\beta)} \times N \geq l \Rightarrow N = \lceil \frac{\beta(1-\beta)}{\alpha} l \rceil. \tag{19}$$

In the similar way with (15), we can compute the summations of (17) using the differential of $f(\beta) = \sum_{k=1}^{N-1} \beta^k$. Therefore, $E[l_f]$ is as follows:

$$\begin{aligned} E[l_f] &= \frac{\alpha((N-1)\beta^N - N\beta^{N-1} + 1)}{(1-\beta)^2} + l\beta^N \\ &\quad \text{where } \alpha = ve^{-\lambda a}(\frac{1}{\lambda} - (a + \frac{1}{\lambda})e^{-\lambda a}) \text{ and } \beta = 1 - e^{-\lambda a} \\ &\quad \text{and } N = \lceil \frac{\beta(1-\beta)}{\alpha} l \rceil. \end{aligned} \tag{20}$$