Trajectory-Based Data Forwarding for Light-Traffic Vehicular Ad Hoc Networks

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Abstract—This paper proposes a Trajectory-Based Data (TBD) Forwarding scheme, tailored for the data forwarding for roadside reports in light-traffic vehicular ad hoc networks. 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). 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 effectively utilize vehicles' trajectory information in a privacy-preserving manner. In our design, such trajectory information is combined with the vehicular traffic statistics for a better performance. In a distributed way, each individual vehicle computes its end-to-end expected delivery delay to the Internet access points based on its position on its vehicle trajectory and exchanges this delay with neighboring vehicles to determine the best next-hop vehicle. For the accurate end-to-end delay computation, this paper also proposes a link delay model to estimate the packet forwarding delay on a road segment. Through theoretical analysis and extensive simulation, it is shown that our link delay model provides the accurate link delay estimation and our forwarding design outperforms the existing scheme in terms of both the data delivery delay and packet delivery ratio.

Index Terms—Vehicular network, road network, data forwarding, trajectory, link delay, delivery delay.

1 Introduction

With the standardization of Dedicated Short Range Communication (DSRC) by the IEEE [1], 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: 1) vehicle-to-vehicle (v2v) communications [2], [3] and 2) vehicle-to-infrastructure (v2i) communications [4], [5], [6], [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 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 1) the roadside reports, such as the time-critical reports (e.g., driving accident and driving hazard), the road traffic statistics (e.g., vehicle density and vehicle speed) and 2) the drivers' video/audio data (e.g., video clip, photo, and voice/music recording). 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* techniques are proposed for use by several opportunistic forwarding schemes [4], [9], [10]. 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, the previous forwarding schemes [4], [9], [10] 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 toward the wrong direction, introducing excessive long delays. In our study, we let a packet carrier vehicle select a best next packet carrier with its neighboring vehicles' trajectories. Also, in our study, we try to reduce the amount of data packets using the unicasting based on the vehicles' trajectories. Note that in light-traffic road networks, the volume of data traffic is not necessarily light. For example, in the delivery of the video/audio data for drivers or road networks, the data volume can be high. If these high-volume data are delivered using broadcasting or Epidemic routing [9], the packet traffic will be high. Thus, our goal is to reduce the volume of packet traffic through the vehicle-trajectory-based forwarding.

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,

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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 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-the-art solution. Besides serving as a critical building block of our TBD design, this link delay model is useful for other VANET designs, such as the E2E delay estimation in VANET routing protocols [11] and the data dissemination through networkwide 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. Our trajectory-based delivery scheme opens a new door of a potential research direction based on vehicle trajectory in vehicular networks.
- A data forwarding with multiple Internet Access Points (APs). Our earlier work TBD [12] utilizes vehicle trajectory information along with vehicular traffic statistics to further improve communication delay and delivery probability for vehicle-to-static destination communications. In TBD [12], the data forwarding is designed only for single AP scenarios, not for multiple AP scenarios. In this paper, we take a step further and provide an efficient solution based on vehicle trajectory for the data forwarding with multiple APs.

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. In Section 6, we summarize the related work for vehicular networking. We conclude this paper along with future work 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 [13]. We leave two-way delivery as future work.

In this paper, we refer

1. *Vehicle trajectory* as the moving path from the vehicle's starting position to its destination position in a road network;
2. *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;
3. *Carry delay* as a part of the delivery delay introduced while a packet is carried by a moving vehicle;
4. *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, is available to vehicles. A couple of studies have been done to utilize the Internet access points available on the roadsides [6], [7].
- Vehicles participating in VANET have a wireless communication device, such as the DSRC device [1]. Nowadays, many vehicle vendors, such as GM and Toyota, are planning to install DSRC devices at vehicles [14], [15].
- 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 Traffic [16].
- 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. Thus, 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 Fig. 1. The first scenario, as shown in Fig. 1a, 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 toward the access point. The first challenging problem is how to make such a decision when privacy-sensitive trajectories are not shared directly.

The second scenario, as shown in Fig. 1b, 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*

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

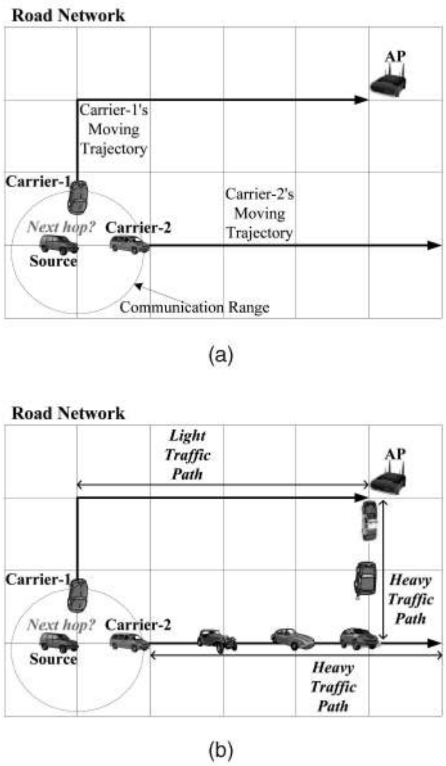

Fig. 1. Packet delivery scenarios. (a) A light-traffic road network. (b) A road network with unbalanced traffic density.

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 next sections, we will deal with the two challenges raised in this section through the Link delay modeling (in Section 3) and the Trajectory-based forwarding (in Section 4).

3 The Link Delay Model

This section analyzes the link delay for one road segment with one-way vehicular traffic given the vehicle arrival rate λ, the vehicle speed v, and the communication range R; note that a constant vehicle speed v is used for the link delay analysis and that the impact of the variable vehicle speed on the link delay will be shown in comparison of simulation results at the end of this section; the results indicate that our link delay model is a good approximation to the simulation result. 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 (Network Component). *Let* Network Component *be a group of vehicles that can communicate with each other via either one-hop or multihop communication, that is, a connected ad hoc network. Fig. 2 shows a network component consisting of vehicles $n_1, \ldots, n_k$.*

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. Fig. 2 shows the forwarding distance l_f for the network component.*

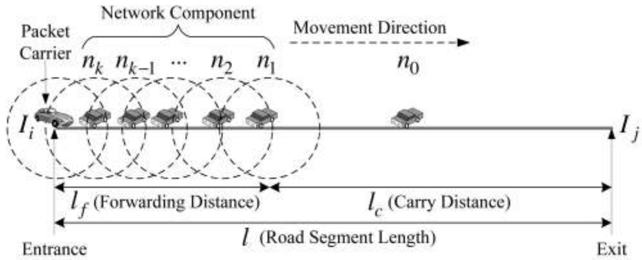

Fig. 2. Forwarding distance l_f and Carry distance l_c.

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. Fig. 2 shows the carry distance l_c of vehicle n_1.*

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 (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 network component that is near the entrance as shown in Fig. 2. To illustrate our modeling approach, we use Fig. 3a to explain how the forwarding distance l_f change over time under different traffic arrival patterns.

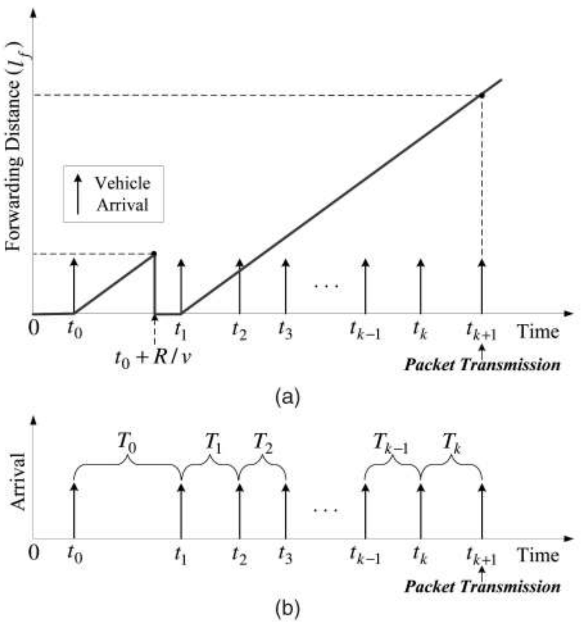

Fig. 3. Forwarding distance (l_f) for vehicle arrivals. (a) Forwarding distance (l_f) over time. (b) Vehicle arrival sequence on one-way road segment.

- 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 $n_2, \ldots, n_k$ arrive at I_i with the interarrival time less than R/v, forming a network component of k vehicles.

To formally derive $E[l_f]$, we model the forwarding distance l_f as the sum of the intervehicle distance of vehicles within the component at any time. Fig. 3b shows the corresponding vehicle arrival times as in Fig. 3a. Let t_h be the arrival time of the hth vehicle. Let T_h be the interarrival interval of the hth 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 [17], because the *Kolmogorov-Smirnov test* can accurately approximate the statistics of vehicle interarrival time based on the empirical data for a real roadway into an *exponential distribution*.

As shown in Fig. 3b, 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 network 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 interdistances (i.e., vT_h) within a network component is the ratio between $P[vT_h \leq R]$ and $P[vT_h > R]$, according to detailed derivation in Appendix. Therefore, we obtain $E[l_f]$ for the road segment (I_i, I_j) as follows:

$$E[l_f] = E[vT_h | vT_h \leq R] \times \frac{P[vT_h \leq R]}{P[vT_h > R]}. \quad (3)$$

From (3), we can see that $E[l_f]$ is the multiplication of 1) the *average interdistance* of two adjacent vehicles within the same component and 2) the *ratio* of the probability that the interdistance is not greater than the communication range *to* the probability that the interdistance is greater than the communication range. As the interarrival time decreases, this ratio increases, leading to the longer average forwarding distance; note that as the interarrival time decreases, the average interdistance decreases, but the increasing rate of the ratio is much faster. Therefore, this fits well our intuition that the shorter interarrival time, the shorter interdistance for communication, leading to the longer average forwarding distance.

Fig. 4 shows the average forwarding distance l_f comparison among simulation model and two analytical models for one-way roadway: 1) Our *TBD* link model for finite road length in the Appendix and 2) *VADD* link model proposed by Zhao and Cao [4]. As shown in Fig. 4, our link model gives very accurate average forwarding distance l_f estimates under different interarrival 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 network component starting from the entrance can actually be used for data forwarding.

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

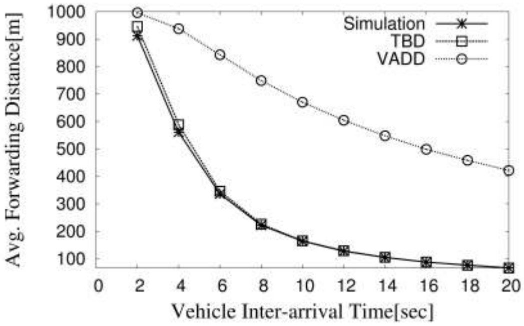

Fig. 4. Validation and comparison of analytical models.

deviation is 6.2 MPH (i.e., 9.98 km/h), according to field study conducted by Muchuruza and Mussa [18]. To investigate how robust our link delay model is, we test the accuracy of our model under three different settings: 1) a constant vehicle speed of 40 MPH, 2) a normal speed distribution of $N(40, 3.5)$, and 3) a normal speed distribution of $N(40, 7)$. Our model is compared with simulation, which approximates the ground truth, and VADD [4]. Fig. 5 illustrates that as the vehicle speed deviation is within the realistic bound, the link delay of *TBD* 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 three steps: First, we will explain how to compute the EDD considering both *vehicular traffic statistics* and *individual vehicle trajectory* in Section 4.1. Second, we will describe how vehicles perform the data forwarding based on EDD in Section 4.2. Last, we will explain how to extend the *TBD* in the road networks with multiple Internet access points.

4.1 End-to-End Delay Model

In this section, we model the EDD with a *stochastic model* [4] for a given road network. We define the road network graph for the EDD computation as follows:

Definition 4 (Road Network Graph). *Let* Road Network Graph *be the directed graph of $G = (V, E)$, where $V = \{v_1, v_2, \ldots, v_n\}$ 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 $e_{ij} \neq e_{ji}$. Fig. 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 toward the most preferred direction. In this case, the packet carrier needs to determine whether it can forward its packet to another vehicle moving toward 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*.

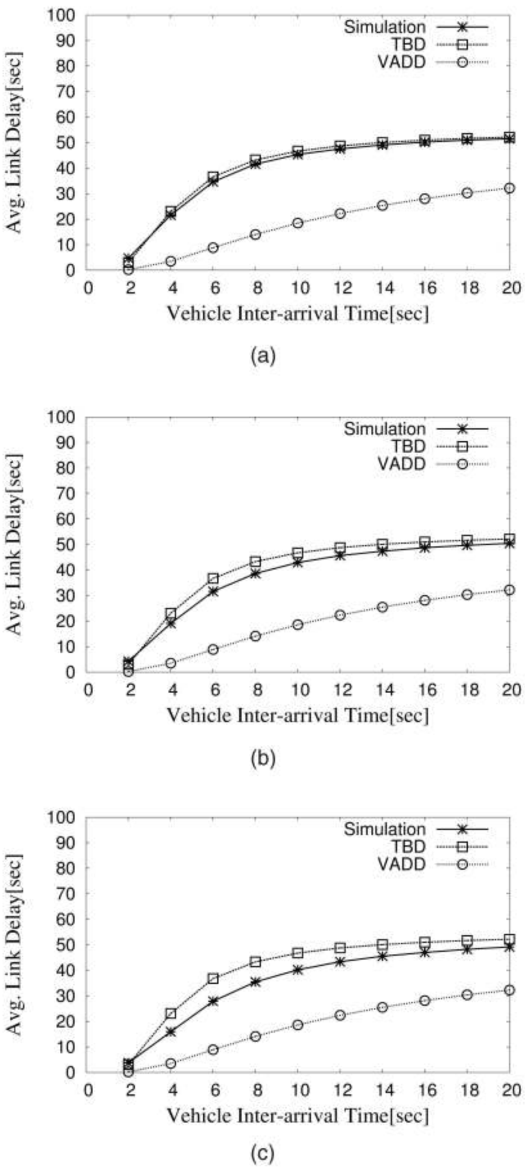

Fig. 5. Link delay comparison for model validation. (a) Constant vehicle speed with $\mu_v = 40$ MPH. (b) Vehicle speed with $N(40, 3.5)$ MPH. (c) Vehicle speed with $N(40, 7)$ MPH.

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 toward intersection j. Let d_{ij} be the expected link delay for edge e_{ij} in (2). We note the expected delay EDD at an intersection depends on the forwarding direction (i.e., edge). Therefore, we use D_{ij} to 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:

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

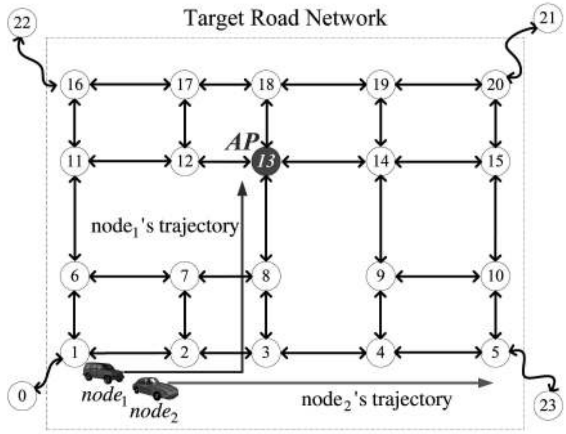

Fig. 6. Road network graph for data forwarding.

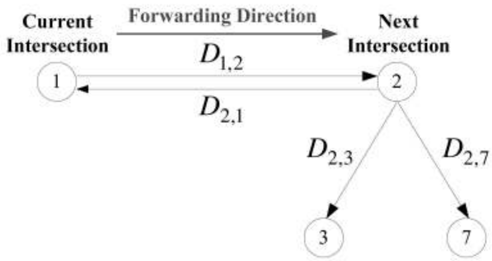

Fig. 7. EDD computation for edge $e_{1,2}$.

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 toward 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 Fig. 7, a packet carried by a vehicle arrives at intersection 1 and is sent toward 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., intersections 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:

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

Let n be the number of directed edges in the road network graph $G = (V, E)$, as shown in Fig. 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 toward the neighboring intersection j.

Contact probability. *Contact Probability* is defined as the chance that a vehicle can encounter another vehicle at an intersection. Let R be the communication range. Let v_i be the vehicle speed in the intersection area of intersection i which is a circle of radius R; that is, vehicles are considered passing through intersection i with the same constant speed v_i. This vehicle speed can be measured from vehicular traffic by dividing the communication diameter $2R$ by the average travel time per intersection. This indicates that vehicles may pass through another intersection with a different constant speed, depending on the model specification (e.g., traffic condition) for each intersection. For simplicity, we regard the vehicle speed v_i as constant. Note that this constant vehicle speed v_i is also used for the computation of the E2E delivery delay as forwarding guidance and that the impact of the variable vehicle speed on the performance will be shown in Section 5.5; the results show that our E2E delivery delay model is a good indicator for the decision making on the data forwarding.

Let T_i be the intersection passing duration during which a vehicle is able to communicate with the vehicles around the intersection i. Clearly, T_i is affected by the vehicle speed, the communication range, the traffic signal pattern, stop signs, and the queuing delay. In practice, average T_i can be obtained through empirical measurements based on GPS navigation systems [16]. In this study, we use a simplified model to calculate T_i by assuming the nominal communication range is R and a constant speed is v_i. Therefore, $T_i = 2R/v_i$. We note our design can use empirical T_i 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 toward j for during T_i. 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:

$$CP_{ij} = 1 - e^{-\lambda_{ij} T_i}. \tag{5}$$

Note that in order to compute an approximation of real contact probability, all of the vehicles passing through the intersection i are assumed to have the same constant speed v_i. Thus, they have the same contact probability CP_{ij} for edge e_{ij}; in Section 5, the simulation results indicate that our E2E delay model based on this contact probability is a good approximation for data forwarding.

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 toward 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} ($k = 1 \ldots m$), we can sort them in nondecreasing 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 *VADD* [4] 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 nongrid topology. Therefore, the forwarding probability P'_{ij_k} for each edge e_{ij_k} is computed as follows:

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

Now we can define the *forwarding success probability* P_i for intersection i as the probability that the packet carrier at intersection i can meet any other vehicle and forward its packet to the other vehicle during its passing duration T_i; this forwarding success probability is computed as $P_i = \sum_{k=1}^{m} P'_{ij_k}$. On the other hand, the case of forwarding failure happens when the packet carrier at intersection i cannot meet any other vehicle during its passing duration T_i and the *forwarding failure probability* Q_i is defined as the probability that this forwarding failure happens; this forwarding failure probability is computed as $Q_i = \prod_{s=1}^{m} (1 - CP_{ij_s}) = 1 - \sum_{k=1}^{m} P'_{ij_k} = 1 - P_i$. Thus, it is clear that the sum of the forwarding success probability P_i and the forwarding failure probability Q_i is 1.

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, $P_{ij_k|ij_h} = P[\text{packet is forwarded to } e_{ij_k} | \text{ carrier moves on } e_{ij_h}]$. The conditional forwarding probability $P_{ij_k|ij_h}$ is computed as follows:

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

Supposing that the packet carrier goes to edge e_{ij_h}, our forwarding rule is that only when the packet carrier meets another vehicle moving on the better edge e_{ij_k} in terms of expected E2E delay (i.e., EDD), it forwards its packet to the vehicle; this is case 1 ($k < h$) in (7). Otherwise, it tries to forward its packet to another vehicle moving on the same edge e_{ij_h} or carries its packet with itself in the case where there exists no heading vehicle on the edge e_{ij_h}; this is case 2 ($k = h$) in (7). Also, for case 3 ($k > h$) in (7) where the carrier's edge e_{ij_h} has shorter EDD than other edges e_{ij_k} for $k > h$, the packet carrier will not forward its packet to another vehicle moving on the longer-EDD edges, so the conditional forwarding probability for case 3 is zero. Note that the probability of case 1 ($k < h$) and the probability of case 2 ($k = h$) sums up to 1 because the probability to forward to edges e_{ij_k} for $k = 1..h-1$ other than the carrier's edge e_{ij_h} is $\sum_{s=1}^{h-1} P'_{ij_s}$ and the probability to forward or carry to the carrier's edge is $1 - \sum_{s=1}^{h-1} P'_{ij_s}$.

Average forwarding probability. Finally, we can compute the average forwarding probability P_{ij_k} that a packet

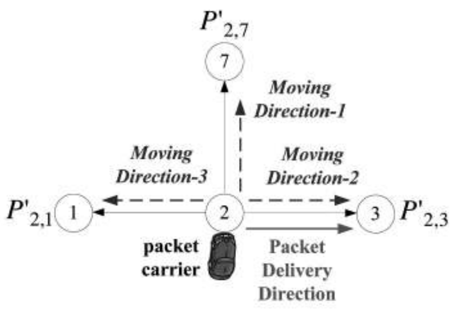

Fig. 8. Average forwarding probability $P_{2,3}$ at intersection 2.

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 B_{ij_h} can be obtained from the vehicular traffic statistics on the edge e_{ij_h}; that is, B_{ij_h} is the *ratio* of the number of vehicles branching from intersection i to intersection j_h *to* the number of vehicles arriving at intersection i during the traffic measurement time (e.g., 1 hour). Therefore, P_{ij_k} is calculated by *Law of total probability* [19] as follows:

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

From (8), P_{ij_k} is the average of the conditional forwarding probability $P_{ij_k|ij_h}$ with respect to the packet carrier's branch probability B_{ij_h} to edge e_{ij_h} incident to intersection i that is the current location of the packet carrier.

For example, as shown in Fig. 8, suppose that a packet carrier is placed at intersection 2 in Fig. 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 toward 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 1) $P_{2,3|2,1} = P'_{2,3}$ 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 $e_{2,3}$; 2) $P_{2,3|2,3} = 1 - P'_{2,7}$ since the shortest path length for the edge $e_{2,7}$ has the shortest among the three edges; 3) $P_{2,3|2,7} = 0$ 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. For example, if two vehicles $node_1$ and $node_2$ are placed at the same intersection 1 in Fig. 6, their EDDs toward 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 to 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 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: 1) The packet carry process at the current vehicle and 2) 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.

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 intersection i to 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 toward the neighboring intersection n. As a reminder, P^c_{mn} is 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:

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

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 intersection j. $E[\text{delivery delay at intersection } j] = \sum_{k \in N(j)} P'_{jk} D_{jk}$ is the expected delivery delay after the packet leaves the current vehicle.

For example, as shown in Fig. 9, let the trajectory be $1 \rightarrow 2 \rightarrow 3$ in the road network in Fig. 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:

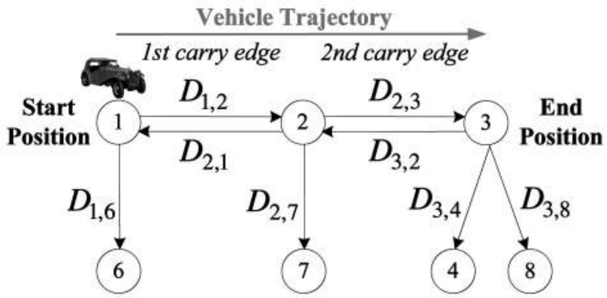

Fig. 9. EDD computation for vehicle trajectory.

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

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 ad hoc network, packets are forwarded to the vehicle with a minimum EDD.

In order to efficiently share the vehicles' EDD values within a connected ad hoc network, we can use the state-of-the-art vehicle information diffusion schemes in [20], [21]; that is, these vehicles' EDD values can be efficiently spread to neighboring vehicles through one of these diffusion schemes, and also along with the EDD value, each vehicle can piggyback its vehicle identifier (ID), location, moving direction, and vehicle speed onto its beacon message. Our TBD work is focused on the data forwarding based on the vehicle trajectory in light-traffic road networks, so the TBD uses the following simple diffusion operation for the data forwarding, used by many mobile ad hoc routing protocols, such as AODV and DSR [22]:

- **Step 1**: Each vehicle periodically updates its EDD, based on its current position on its trajectory, as discussed in Section 4.1.2. Vehicles exchange their beacon messages (containing the minimum EDD value and the next-hop vehicle's ID) with neighboring vehicles within one-hop communication range. Note that, initially, the minimum EDD value and the next-hop vehicle's ID are set to the vehicle's own EDD and the vehicle's ID, respectively.
- **Step 2**: When each vehicle receives the routing information (i.e., the minimum EDD value and the next-hop vehicle's ID) from its neighboring vehicles within one-hop communication range, it compares its EDD with the announced minimum EDD. If the minimum EDD is less than its own EDD, it updates and announces its routing information with the next-hop vehicle toward the minimum EDD vehicle in the ad hoc network. Otherwise, the vehicle announces the minimum EDD and the next-hop vehicle's ID with its own EDD and vehicle ID, respectively.
- **Step 3**: When these vehicles construct a connected ad hoc network, the routing information (i.e., the minimum EDD value and the next-hop vehicle's ID) can be spread to the ad hoc network.

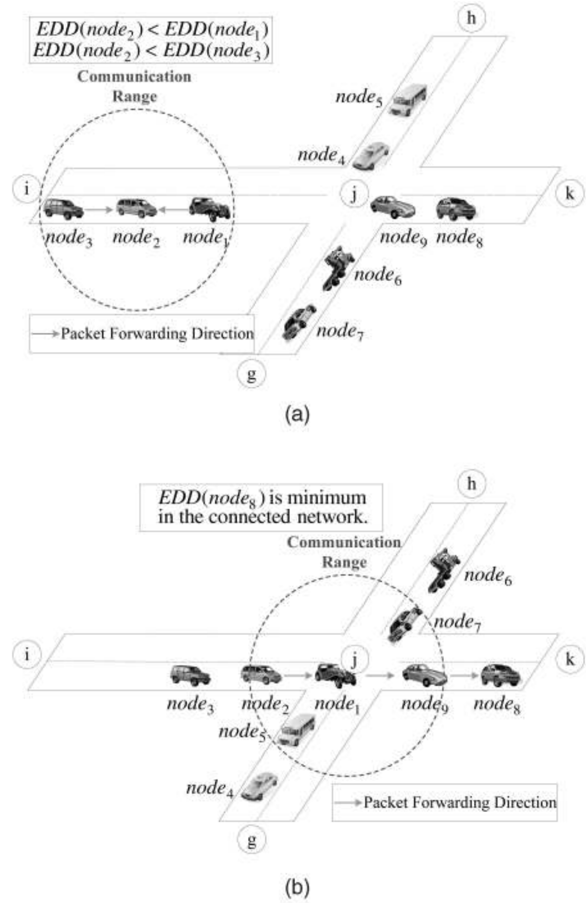

Fig. 10. TBD forwarding protocol in VANET. (a) Data forwarding on road segment e_{ij}. Vehicles $node_1$, $node_2$, and $node_3$ construct a connected network. Since $node_2$'s EDD is less than $node_1$'s and $node_3$'s, the packets of $node_1$ and $node_3$ are forwarded to $node_2$. (b) Data forwarding 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 $node_9$.

Thus, with this diffusion operation, vehicles with packets forward their packets to the next-hop toward the minimum EDD vehicle.

Fig. 10 illustrates our *TBD forwarding protocol*. Fig. 10a 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 network. Since $node_2$'s EDD is minimum in this connected network, $node_1$ and $node_3$ forward their packets to $node_2$. Fig. 10b 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 network. 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 $node_9$. Thus, through the diffusion operation for the data forwarding, vehicles can forward

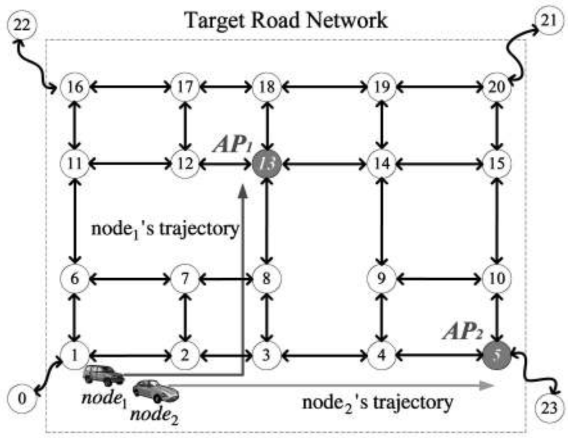

Fig. 11. Road network graph with two APs.

their packets to the best next-hop vehicle in terms of the minimum EDD in the current connected ad hoc network.

4.3 Forwarding for Multiple Access Points

In a large-scale road network, multiple Internet Access Points are usually required to accommodate the Internet access for vehicles. In this case, vehicles need to send their packets toward one of the APs; this is a kind of *anycast* toward the APs. We can easily extend our data forwarding framework for this anycast. The intersection EDD D_{ij} for a directed edge e_{ij} toward one of APs is the minimum among the EDDs toward the APs as follows:

$$D_{ij} = \min_{k \in AP} D_{ij}^{k}, \tag{10}$$

where AP is the set of APs and D_{ij}^{k} is the EDD for access point AP_k. For example, Fig. 11 shows the road network graph with two access points AP_1 and AP_2. The EDD $D_{1,2}$ for edge $e_{1,2}$ is $\min\{D_{1,2}^1, D_{1,2}^2\}$ where $D_{1,2}^1$ and $D_{1,2}^2$ are computed using (4), respectively.

Through (10), we can compute the EDD for each directed edge. Finally, we can compute the EDD based on the vehicle trajectory using (9) along with this intersection EDD considering the anycast. Note that we need to update the forwarding probability P'_{jk} and the carry probability $P^c_{h,h+1}$ in (9). Since we have the minimum EDD for each directed edge, we can compute the forwarding probability by sorting edges in nondecreasing order, based on the EDDs for the edges. After computing the forwarding probability at each intersection, we can compute the carry probability.

5 Performance Evaluation

In this section, we evaluate the performance of *TBD* by comparing it with a state-of-the-art scheme, *VADD* (using the Direction-First-Probe forwarding protocol proposed in [4]) while for the fairness, our link delay model is used for both *TBD* and *VADD*. The evaluation is based on the following:

- **Performance Metrics:** We use 1) *average delivery delay* and 2) *packet delivery ratio* as the performance metrics.
- **Parameters:** In the performance evaluation, we investigate the impacts of
  - *Vehicular traffic density* (N),
  - *Vehicle speed* (μ_v),
  - *Vehicle speed deviation* (σ_v),
  - *Packet Time-To-Live* (TTL), and
  - *Internet access point density* (M).

TABLE 1
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 100.
Time-To-Live (TTL)	The expiration time of a packet. The default TTL is ∞; that is, there exists no packet drop due to TTL expiration.
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).

Note that the link delay model and E2E delay models in both *TBD* and *VADD* are based on constant vehicle speed(s) given to road networks. These two E2E delay models are used to make a forwarding decision-making metric called *EDD*. We investigate the effectiveness of these two forwarding schemes in terms of performance metrics.

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 [23] and Manhattan Mobility model [24]. 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 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 1, 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 their 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.

The vehicle speed is generated from a normal distribution of $N(\mu_v, \sigma_v)$ [18], [25], as shown in Table 1. In the simulation, the forwarding probability used in the EDD computation is computed using (5) to (8) in Section 4.1.1, based on the *average vehicle speeds* to generate vehicle speeds

TABLE 2
Probabilities and Estimates for E2E Delay over Time

Variable	2hour	3hour	4hour	5hour	6hour	7hour
λ_{ij}	0.008	0.008	0.008	0.008	0.009	0.009
B_{ij}	0.260	0.273	0.291	0.284	0.300	0.299
CP_{ij}	0.159	0.159	0.168	0.169	0.177	0.180
P'_{ij}	0.159	0.159	0.168	0.169	0.177	0.180
P_{ij}	0.427	0.465	0.456	0.464	0.464	0.425
D_{ij}	1303	1367	1500	1555	1577	1581

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 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 [1]. Unless otherwise specified, the default values in Table 1 are used.

5.1 Verification of Probability Model

In this section, first of all, we verify the E2E delay model discussed in Section 4.1. In our simulation, for each directed edge e_{ij}, the vehicle arrival rate (λ_{ij}), and the branch probability (B_{ij}) are measured every one hour, based on accumulated vehicular traffic statistics. With these λ_{ij} and B_{ij}, we compute the contact probability CP_{ij}, forwarding probability P'_{ij}, average forwarding probability P_{ij}, and the E2E delivery delay D_{ij}. Table 2 shows the update of these values in one edge (i.e., $e_{10,11}$) over the simulation time, that is, from the second hour to the seventh hour. From this table, it can be observed that these probabilities and the E2E delay estimate are converged over the time. This observation indicates that the *forwarding-related probabilities* and the *E2E delay estimate* based on the past statistics can be used for the forwarding-related computation in the near future. Thus, with these verified probabilities and estimates, we compute the trajectory-based E2E delay D in (9) as forwarding metric.

5.2 Forwarding Behavior Comparison

We compare the forwarding behaviors of *TBD* and *VADD* with the cumulative distribution function (CDF) of the actual packet delivery delays. From Fig. 12, it is very clear that *TBD* has smaller packet delivery delay than *VADD*. For any given packet deliver delay, *TBD* always has a larger CDF value than *VADD* before they both reach 100 percent CDF. For example, *TBD* reaches 90 percent CDF with a delivery delay of about 1,500 seconds while the value for *VADD* is about 1,800 seconds. In other words, on average, the packet

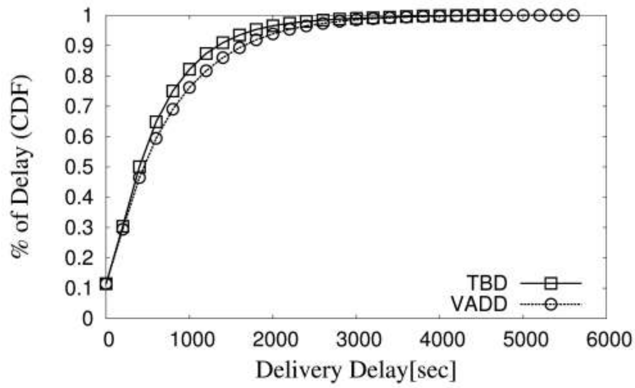

Fig. 12. CDF comparison for delivery delay.

delivery delay for *TBD* is smaller than that for *VADD* and we will show this quantitatively in the following sections.

5.3 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 section, we intend to study how effectively *TBD* can forward packets toward the access point using individual vehicles' trajectory information. Through our extensive simulations, we observe that under *low vehicular traffic density*, *TBD* significantly outperforms *VADD* in terms of packet delivery delay. Fig. 13a shows the packet delivery delay comparison between *TBD* and *VADD* with varying the number of vehicles under low vehicular traffic density. As shown in Fig. 13a, *TBD* has smaller packet delivery delay than *VADD* at all vehicular densities. As expected, one trend is that the delivery delays in both *TBD* and *VADD* decrease as the number of vehicles increases. This is because the more vehicles increase the contact probability among vehicles and have a higher probability that they will pass the Internet access point. The smallest delay reduction is 7.8 percent at $N = 200$ while the largest delay reduction is 16.7 percent at $N = 40$. From this figure, it can be seen that in the extremely light-traffic road networks, such as $N = 20$, the trajectory in *TBD* has less contribution (i.e., 15 percent reduction) than in the cases of not-so-light-traffic road networks, such as $N = 40$ (i.e., 16.7 percent reduction). This is because when the number of vehicles is so small, the probability that vehicles can meet each other is relatively low and also the probability that the carriers will pass the Internet access point is low.

Another important trend is that as the number of vehicles is increasing (e.g., $N \geq 160$), the performance gap between *TBD* and *VADD* is decreasing. For example, for $N = 180$, *TBD* reduces the delivery delay of *VADD* by 8.9 percent, but reduces the delivery delay by about 8.5 and 7.8 percent for $N = 180$ and $N = 200$, respectively. This is because the higher vehicular traffic density provides the higher probability that the packets can be forwarded to the vehicle with a smaller EDD on the road segment or at every intersection; that is, since *TBD* lets a packet carrier forward its packets to its preceding vehicle on the road segment with a high probability, it works in the similar way with *VADD*. Thus, both will have almost the same performance in an extremely high-traffic density. As a result, we found that *TBD* not only provides significant better data forwarding quality than

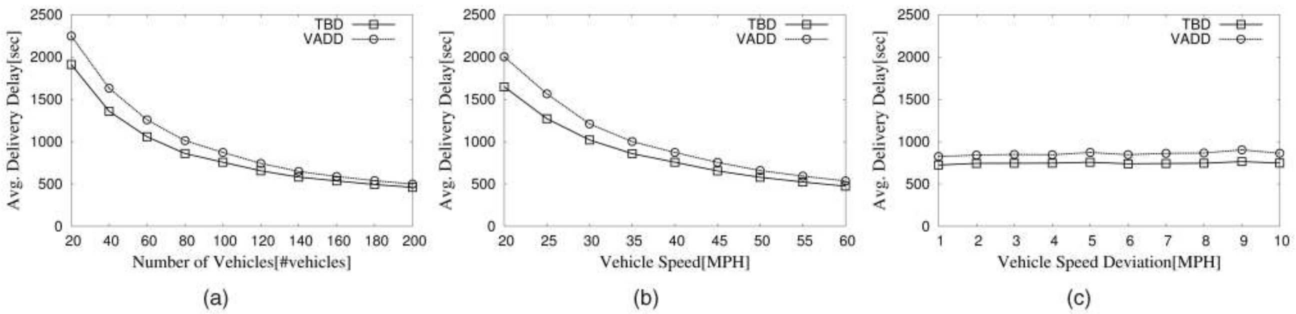

Fig. 13. Performance comparison between TBD and VADD for infinite TTL. (a) Impact of the number of vehicles. (b) Impact of vehicle speed. (c) Impact of vehicle speed deviation.

VADD in light-traffic road networks that are targeted by this paper, but also has smaller packet delivery delay even at high-traffic conditions.

5.4 The Impact of Vehicle Speed μ_v

In this section, we investigate how the change of mean vehicle speed affects the delivery delay. Fig. 13b shows the delivery delay under different mean vehicle speeds. As shown in the Fig. 13b, for both *TBD* and *VADD*, 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 *TBD* still outperforms *VADD*.

5.5 The Impact of Vehicle Speed Deviation σ_v

In this section, we investigate the impact of vehicle speed deviation on the performance. We found that under light-traffic road networks, the probability that vehicles meet each other is low, so the speed deviation has little impact on the delivery delay. Fig. 13c illustrates our observation for the delivery delay according to the vehicle speed deviation when the number of vehicles is $N = 100$. The delivery delays in both *TBD* and *VADD* are almost constant at all of the vehicle speed deviations from 1 to 10 MPH.

5.6 The Impact of Packet Time-To-Live (TTL)

In this section, we investigate the impact of the packet's *Time-To-Live* on the *packet delivery ratio*, defined as the ratio of the number of delivered packets to the number of generated packets. We set TTL to 30 minutes (i.e., 1,800 seconds) in our simulation; that is, if a packet is not delivered within 30 minutes hour after its generation, it will be discarded by a packet carrier.

Fig. 14a shows the delivery ratio comparison between *TBD* and *VADD* with varying the number of vehicles in the road network. As expected, the larger number of vehicles yields the higher average delivery ratio. The delivery ratio for *TBD* is increasing roughly linearly with respect to the number of vehicles. On the other hand, in *VADD*, the increase of the number of vehicles under the light-traffic does not contribute much to the increase of delivery ratio. Clearly, we can see even at light-traffic condition, *TBD* has better delivery ratio than *VADD*. Especially, at $N = 40$, the delivery ratio for *TBD* is 7.8 percent higher than that for *VADD*.

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

We also investigate the impact of vehicle speed deviation on the delivery ratio. Fig. 14c shows the delivery ratio comparison between *TBD* and *VADD* according to the vehicle speed deviation from 1 to 10 MPH. In the simulation, the other parameters use the default values specified in Table 1; that is, the number of vehicles is 100 and the average vehicle speed is 40 MPH. *TBD* is overall better than *VADD* with 4.1 percent more delivery ratio. Also, as discussed in Section 5.5, the vehicle speed deviation does not affect the delivery ratios of both *TBD* and *VADD*.

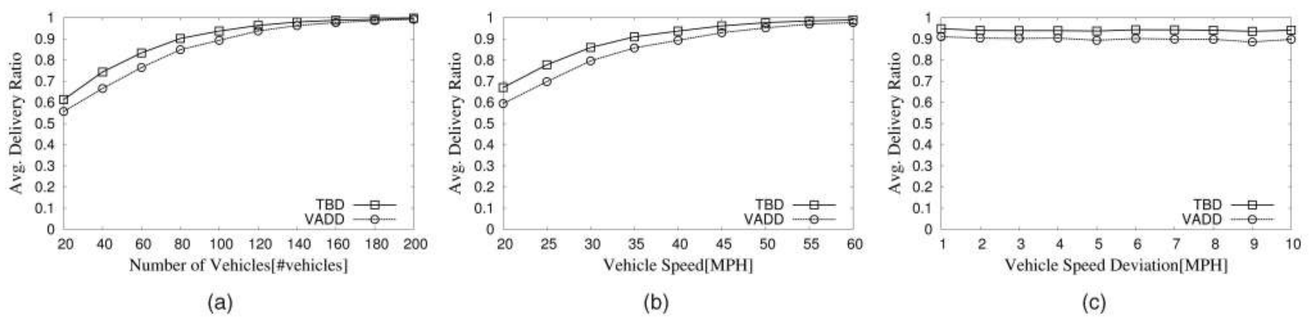

Fig. 14. Performance comparison between TBD and VADD for finite TTL ($TTL = 1,800$ seconds). (a) Impact of the number of vehicles. (b) Impact of vehicle speed. (c) Impact of vehicle speed deviation.

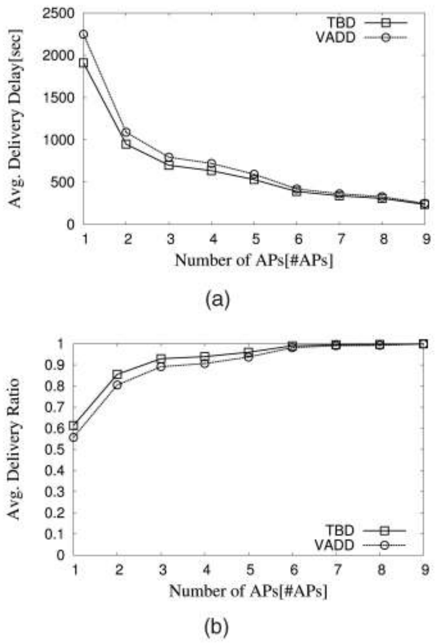

Fig. 15. Performance comparison between TBD and VADD according to the number of APs. (a) #APs versus delivery delay. (b) #APs versus delivery ratio.

5.7 The Impact of Internet Access Point Number M

In this section, we explain how multiple Internet Access Points 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 1; that is, the number of vehicles is $N = 20$; note that this is an extremely light-traffic density.

Fig. 15 shows the performance comparison between *TBD* and *VADD* according to the number of APs in terms of delivery delay and delivery ratio. As observed in Fig. 15a, the delivery delays for both *TBD* and *VADD* are dramatically decreasing and the delivery ratio are quickly increasing as the number of APs increases. *TBD* outperforms *VADD* by reducing the *VADD*'s delivery delay by more than 10 percent up to five APs. On the other hand, as shown in Fig. 15b, for the delivery ratio, *TBD* has at least 5 percent better ratio than *VADD* under a low AP density (e.g., up to two APs). However, both have the similar ratio (i.e., more than 98 percent) under a high AP density (e.g., from 6 to 10 APs).

Through the performance evaluation, we can conclude that by using the vehicle trajectory information, *TBD* can provide better data delivery than *VADD* in light-traffic vehicular networks at a variety of settings in terms of the vehicular traffic density, vehicle speed distribution, and AP density.

6 Related Work

Data forwarding and data access issues in VANET have gained a lot of attention recently [2], [4], [5], [26], [27], [28], [29]. The data forwarding in VANET is different from that in the traditional mobile ad hoc networks (MANETs) [22] for the reason of 1) vehicles are moving on the physically constrained areas (i.e., roadways), 2) the moving speed is also limited by the speed limit on the roadways, and 3) 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 door of research opportunities for the data forwarding in the VANET. Also, the frequent network partition and mergence due to the high mobility makes the MANET routing protocols [22] ineffective in the VANET settings [17]. Thus, in order to deal with this frequent network partition and mergence, the *carry-and-forward* approaches are necessary in the Disruption Tolerant Networks (DTN), such as VANET.

Epidemic Routing in [9] is an early work to support the data forwarding in the DTN consisting of mobile nodes, designed for two-dimensional open fields, not for the vehicular networks with the confined routes for vehicles. It allows the random pairwise exchange of data packets among mobile nodes in order to maximize the possibility that data packets can be delivered to their destination node. Thus, multiple copies of data packets exist during the delivery. This scheme is effective to deliver the data packets for critical messages (e.g., accidents) to the destination (e.g., AP) as soon as possible. On the other hand, our TBD investigates how effectively to deliver data packets with both vehicles' trajectories and vehicular traffic statistics; our TBD is based on the unicasting, that is, with one copy of a data packet on-the-fly rather than multiple copies.

Data forwarding schemes investigating the layout of road network and vehicular traffic statistics are proposed in *VADD* [4] and Delay-Bounded Routing [5]. *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 [26] 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 an edge in the packet trajectory can be high in the light-traffic road networks.

For dense road networks, such as urban roadways, *CAR*, *MMR*, and *VVR* are proposed [2], [27], [28]. *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 toward 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.

In [7], Bychkovsk et al. show the possibility that vehicles can access open WiFi access points for the Internet access in vehicular networks. *Cabernet* [6] proposes one-hop Internet access schemes using open WiFi access points in vehicular networks, whose target is different from *TBD*'s, that is, the multihop ad hoc networking in VANET.

OPERA [30] investigates an opportunistic packet replaying using two-way vehicular traffic on road segments. The data packets forwarded in one direction on a road segment can advance toward the end point of the road segment using other vehicles moving in the opposite direction. On the other hand, our *TBD* uses only vehicles moving in the same direction on the road segment for the clarity of the link delay modeling. The link delay model based on two-way vehicular traffic is left as future work.

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 interarrival 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 the first door for exploiting the potential benefit of the vehicle trajectory for the performance of VANET networking. As a future work, we will develop a data forwarding scheme from stationary nodes (i.e., Internet access points) to moving vehicles for supporting the Infrastructure-to-Vehicle data delivery in vehicular networks. This reverse forwarding to moving vehicles is needed to deliver the road condition information such as the bumps and holes for the driving safety. However, this reverse data forwarding is a more challenging problem because we need to consider both the destination vehicle's mobility and the packet delivery delay. Also, we will investigate the impact of data traffic volume on the trajectory-based data forwarding in light-traffic vehicular networks and develop a data forwarding scheme considering the data traffic volume, the vehicle trajectory, and the vehicle contact time for communications along the road segment.

Appendix

Link Delay Modeling

A.1 Average Forwarding Distance for Infinite Road Segment

The $E[l_f]$ can be computed as the expected sum of the interdistances within the network component. Suppose that the interarrival 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 interarrivals such that $C(k)$: $T_0 > a$ and $T_h \leq a$ for $h = 1..k$. Let $L(k)$ be the length of the network component of k vehicle interarrivals. Then, $E[l_f]$ can be derived using the law of total expectation as follows:

$$\begin{aligned} E[l_f] = E[L] &= \sum_{k=1}^{\infty} E[L(k)|C(k)] \times P[C(k)] \\ &= v \times \sum_{k=1}^{\infty} E\left[\sum_{h=1}^{k} T_h | T_0 > a, T_h \leq a \text{ for } h = 1..k\right] \\ &\quad \times P[T_0 > a, T_h \leq a \text{ for } h = 1..k]. \end{aligned} \tag{11}$$

Since, in (11), T_h for $h = 0..k$ are *i.i.d.* for the exponential distribution with parameter λ, we can rewrite (11) as follows:

$$E[l_f] = v \times \sum_{k=1}^{\infty} k \times E[T_h|T_h \leq a] \times P[T_h \leq a]^k \times P[T_0 > a]. \tag{12}$$

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 (12):

$$\begin{aligned} E[T_h|T_h \leq a] &= \int_0^a t \times P[T_h = t|T_h \leq a]dt \\ &= \int_0^a t \times \frac{P[T_h = t, T_h \leq a]}{P[T_h \leq a]}dt \\ &= \int_0^a t \times \frac{P[T_h = t]}{P[T_h \leq a]}dt \\ &= \int_0^a t \times \frac{\lambda e^{-\lambda t}}{1 - e^{-\lambda a}}dt \\ &= \frac{1/\lambda - (a + 1/\lambda)e^{-\lambda a}}{1 - e^{-\lambda a}}. \end{aligned} \tag{13}$$

Therefore, (12) can be rewritten as follows:

$$E[l_f] = \alpha \times \sum_{k=1}^{\infty} k\beta^{k-1}, \tag{14}$$

where $\alpha = ve^{-\lambda a}(\frac{1}{\lambda} - (a + \frac{1}{\lambda})e^{-\lambda a})$ and $\beta = 1 - e^{-\lambda a}$.

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:

$$E[l_f] = \frac{\alpha}{(1-\beta)^2} = v\frac{1/\lambda - (a + 1/\lambda)e^{-\lambda a}}{1 - e^{-\lambda a}} \times \frac{1 - e^{-\lambda a}}{e^{-\lambda a}}. \tag{15}$$

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

$$\begin{aligned} E[l_f] &= vE[T_h|T_h \leq a] \times \frac{P[T_h \leq a]}{P[T_h > a]} \\ &= E[vT_h|vT_h \leq R] \times \frac{P[vT_h \leq R]}{P[vT_h > R]}. \end{aligned} \tag{16}$$

A.2 Average Forwarding Distance 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:

$$L'(k) = \min\{l, L(k)\}, \quad \text{where } L(k) = v \sum_{h=1}^{k} T_h. \tag{17}$$

Equation (11) can be rewritten using (17) as follows:

$$\begin{aligned} E[l_f] &= \sum_{k=1}^{\infty} E[L'(k)|C(k)] \times P[C(k)] \\ &= \sum_{k=1}^{\infty} E[L'(k)|T_0 > a, T_h \leq a \text{ for } h = 1..k] \\ &\quad \times P[T_0 > a, T_h \leq a \text{ for } h = 1..k] \\ &= \sum_{k=1}^{N-1} E[L(k)|T_0 > a, T_h \leq a \text{ for } h = 1..k] \\ &\quad \times P[T_0 > a, T_h \leq a \text{ for } h = 1..k] \\ &\quad + \sum_{k=N}^{\infty} l \times P[T_0 > a, T_h \leq a \text{ for } h = 1..k]. \end{aligned} \tag{18}$$

In (18), 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:

$$\begin{aligned} g(k) &= vk \times E[T_h|T_h \leq a] \\ &= vk \times \frac{1/\lambda - (a + 1/\lambda)e^{-\lambda a}}{1 - e^{-\lambda a}} \\ &= \frac{\alpha}{\beta(1-\beta)} \times k, \\ &\quad \text{where } \alpha = ve^{-\lambda a}\left(\frac{1}{\lambda} - \left(a + \frac{1}{\lambda}\right)e^{-\lambda a}\right) \text{ and } \beta = 1 - e^{-\lambda a}. \end{aligned} \tag{19}$$

We can search the smallest positive integer N to satisfy $g(N) \geq l$ with (19) as follows:

$$\frac{\alpha}{\beta(1-\beta)} \times N \geq l \Rightarrow N = \left\lceil \frac{\beta(1-\beta)}{\alpha} l \right\rceil. \tag{20}$$

In the similar way with (14), we can compute the summations of (18) using the differential of $f(\beta) = \sum_{k=1}^{N-1} \beta^k = \frac{\beta - \beta^N}{1-\beta}$. Therefore, $E[l_f]$ is as follows:

$$E[l_f] = \frac{\alpha((N-1)\beta^N - N\beta^{N-1} + 1)}{(1-\beta)^2} + l\beta^N, \tag{21}$$

where $\alpha = ve^{-\lambda a}(\frac{1}{\lambda} - (a + \frac{1}{\lambda})e^{-\lambda a})$ and $\beta = 1 - e^{-\lambda a}$, and $N = \lceil \frac{\beta(1-\beta)}{\alpha} l \rceil$.

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REFERENCES

[1] A. Carter, "The Status of Vehicle-to-Vehicle Communication as a Means of Improving Crash Prevention Performance," Technical Report 05-0264, http://www-nrd.nhtsa.dot.gov/pdf/nrd-01/esv/esv19/05-0264-W.pdf, 2005.

[2] V. Naumov and T.R. Gross, "Connectivity-Aware Routing (CAR) in Vehicular Ad Hoc Networks," *Proc. IEEE INFOCOM,* May 2007.

[3] Q. Xu, R. Sengupta, and D. Jiang, "Design and Analysis of Highway Safety Communication Protocol in 5.9 GHz Dedicated Short Range Communication Spectrum," *Proc. IEEE Vehicular Technology Conf. (VTC),* Apr. 2003.

[4] J. Zhao and G. Cao, "VADD: Vehicle-Assisted Data Delivery in Vehicular Ad Hoc Networks," *IEEE Trans. Vehicular Technology,* vol. 57, no. 3, pp. 1910-1922, May 2008.

[5] A. Skordylis and N. Trigoni, "Delay-Bounded Routing in Vehicular Ad-Hoc Networks," *Proc. ACM MobiHoc,* May 2008.

[6] J. Eriksson, H. Balakrishnan, and S. Madden, "Cabernet: Vehicular Content Delivery Using WiFi," *Proc. ACM MobiCom,* Sept. 2008.

[7] V. Bychkovsky, B. Hull, A. Miu, H. Balakrishnan, and S. Madden, "A Measurement Study of Vehicular Internet Access Using In Situ Wi-Fi Networks," *Proc. ACM MobiCom,* Sept. 2006.

[8] H. Yomogita, "Mobile GPS Accelerates Chip Development," http://techon.nikkeibp.co.jp/article/HONSHI/20070424/131605/, 2010.

[9] A. Vahdat and D. Becker, "Epidemic Routing for Partially-Connected Ad Hoc Networks," technical report, http://www.cs.duke.edu/vahdat/ps/epidemic.pdf, 2000.

[10] L. Pelusi, A. Passarella, and M. Conti, "Opportunistic Networking: Data Forwarding in Disconnected Mobile Ad Hoc Networks," *IEEE Comm. Magazine,* vol. 44, no. 11, pp. 134-141, Nov. 2006.

[11] Y. Ding, C. Wang, and L. Xiao, "A Static-Node Assisted Adaptive Routing Protocol in Vehicular Networks," *Proc. Fourth ACM Int'l Workshop Vehicular Ad Hoc Networks (VANET),* Sept. 2007.

[12] J. Jeong, S. Guo, Y. Gu, T. He, and D. Du, "TBD: Trajectory-Based Data Forwarding for Light-Traffic Vehicular Networks," *Proc. 29th IEEE Int'l Conf. Distributed Computing Systems (ICDCS),* June 2009.

[13] B. Hull, V. Bychkovsky, Y. Zhang, K. Chen, M. Goraczko, A. Miu, E. Shih, H. Balakrishnan, and S. Madden, "Cartel: A Distributed Mobile Sensor Computing System," *Proc. Fourth Int'l Conf. Embedded Networked Sensor Systems (SenSys),* Nov. 2006.

[14] General Motors (GM), "Vehicle-to-Vehicle (V2V) Communications," http://www.gm.com/experience/technology/research/overview/isl/vcim.jsp, 2010.

[15] Toyota Motor Corporation (TMC), "TMC Develops Onboard DSRC Unit to Improve Traffic Safety," http://www2.toyota.co.jp/en/news/09/09/0903.html, 2010.

[16] Garmin Ltd., "Garmin Traffic," http://www8.garmin.com/traffic/, 2010.

[17] N. Wisitpongphan, F. Bai, P. Mudalige, and O.K. Tonguz, "On the Routing Problem in Disconnected Vehicular Ad Hoc Networks," *Proc. IEEE INFOCOM,* May 2007.

[18] V. Muchuruza and R. Mussa, "Traffic Operation and Safety Analyses of Minimum Speed Limits on Florida Rural Interstate Highways," *Proc. Mid-Continent Transportation Research Symp.,* Aug. 2005.

[19] M. DeGroot and M. Schervish, *Probability and Statistics,* third ed., Addison-Wesley, 2001.

[20] T. Nadeem, S. Dashtinezhad, C. Liao, and L. Iftode, "TrafficView: Traffic Data Dissemination Using Car-to-Car Communication," *ACM Mobile Computing and Communications Rev.,* Special Issue on Mobile Data Management, vol. 8, no. 3, pp. 6-19, July 2004.

[21] L. Wischhof, A. Ebner, and H. Rohling, "Information Dissemination in Self-Organizing Intervehicle Networks," *IEEE Trans. Intelligent Transportation Systems,* vol. 6, no. 1, pp. 90-101, Mar. 2005.

[22] E.M. Royer and C.K. Toh, "A Review of Current Routing Protocols for Ad-Hoc Mobile Wireless Networks," *IEEE Personal Comm.,* vol. 6, no. 2, pp. 46-55, Apr. 1999.

[23] T. Camp, J. Boleng, and V. Davies, "A Survey of Mobility Models for Ad Hoc Network Research," *Wireless Comm. and Mobility Computing,* Special Issue on Mobile Ad Hoc Networking: Research, Trends and Applications, vol. 2, pp. 483-502, 2002.

[24] F. Bai, N. Sadagopan, and A. Helmy, "IMPORTANT: A Framework to Systematically Analyze the Impact of Mobility on Performance of Routing Protocols for Adhoc Networks," *Proc. IEEE INFOCOM,* Mar. 2003.

[25] D.S. Berry and D.M. Belmont, "Distribution of Vehicle Speeds and Travel Times," *Proc. Second Berkeley Symp. Math. Statistics and Probability,* 1951.
[26] H. Wu, R. Fujimoto, R. Guensler, and M. Hunter, "MDDV: A Mobility-Centric Data Dissemination Algorithm for Vehicular Networks," *Proc. First ACM Int'l Workshop Vehicular Ad Hoc Networks (VANET),* Oct. 2004.
[27] Y. Lee, H. Lee, N. Choi, Y. Choi, and T. Kwon, "Macro-level and Micro-level Routing (MMR) for Urban Vehicular Ad Hoc Networks," *Proc. IEEE Global Telecomm. Conf. (GLOBECOM),* Nov. 2007.
[28] H. Lee, Y. Lee, T. Kwon, and Y. Choi, "Virtual Vertex Routing (VVR) for Course-Based Vehicular Ad Hoc Networks," *Proc. IEEE Wireless Comm. and Networking Conf. (WCNC),* Mar. 2007.
[29] P. Rodriguez, R. Chakravorty, J. Chesterfield, I. Pratt, and S. Banerjee, "MAR: A Commuter Router Infrastructure for the Mobile Internet," *Proc. ACM MobiSys,* June 2004.
[30] M. Abuelela, S. Olariu, and I. Stojmenović, "OPERA: Opportunistic Packet Relaying in Disconnected Vehicular Ad Hoc Networks," *Proc. Fifth Int'l Conf. Mobile Ad Hoc and Sensor Systems (MASS),* Sept. 2008.

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