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Abstract—**Vehicular Ad Hoc Networks (VANETs) represent promising technologies of cyber-physical systems for improving driving safety and communication mobility. Due to the highly dynamic driving patterns of vehicles, effective packet forwarding, especially for time sensitive data, has been a challenging research problem. Previous works forward data packets mostly utilizing statistical information about road network traffic, which becomes much less accurate when vehicles travel in sparse network as highly dynamic traffic introduces large variance for these statistics. With the popularity of on-board GPS navigation systems, individual vehicle trajectories become available and can be utilized for removing the uncertainty in road traffic statistics and improve the performance of the data forwarding in VANETs. . In this paper, we propose Travel Prediction based Data-forwarding (TPD), in which vehicles share their trajectory information to achieve the low delay and high reliability of data delivery in multi-hop carry-and-forward environments. The driven idea is to construct a vehicle encounter graph based on pair-wise encounter probabilities, derived from shared trajectory information. With the encounter graph available, TPD optimizes delivery delay under a specific delivery ratio threshold, and the data forwarding rule is that a vehicle carrying packets always selects the next packet-carrier that can provide the best forwarding performance within the communication range. Through extensive simulations we demonstrate that TPD significantly outperforms existing schemes of TBD and VADD with more than 5% more packets delivery while reducing more than 40% delivery delay.**

I. INTRODUCTION

Vehicular Ad Hoc Networks (VANETs) have emerged as one of the most promising cyber-physical system applications to improve transportation safety and efficiency [1]–[5]. As an important component of Intelligent Transportation Systems (ITS) [6], [7], it promises a wide range of valuable applications including real-time traffic estimation for trip planning, mobile Internet access, and in-time dissemination of emergency information such as accidents and weather hazards. In this paper, we focus on the multi-hop data forwarding problem in VANET. In dynamic and mobile vehicular networks, most of the data forwarding schemes adopt the carry-and-forward approach, where a vehicle carries messages temporarily until it can relay its messages to a better next-hop vehicle using Dedicated Short Range Communications (DSRC) [7], [8]. The existing protocols, such as VADD [2] and SADV [9], utilize macroscopic information about road network traffic (e.g., traffic density and road section average speed) to guide forwarding operation among vehicles. This type of forwarding protocols is very effective in dense vehicular networks where statistics are relatively stable and insensitive to individual vehicle's behavior. However, it becomes less robust when a vehicular network becomes sparse and unpredictable.

Fortunately, with a wide adoption of the GPS for navigation, we can now easily obtain vehicular trajectories in the physical world, which significantly reduces the uncertainty of multi-hop data forwarding in a sparse vehicular network. A few recent protocols, such as TBD [10] and TSF [11], have demonstrated promising performance results by combining the physical trajectory information of a source vehicle and traffic statistics in the rest of a network. Although literature is encouraging till now, we found there are still rooms to improve significantly. The major issue about previous work such as TBD and TSF is that vehicles did not fully share and utilize trajectory information available in the network. In other words, individual vehicle only knows its own trajectory and does not share with other vehicles, a constraining factor leading to low performance. Therefore, the challenging question addressed in this work is how we can push performance limits by utilizing all trajectories available.

In this paper, we propose Travel Prediction based Data forwarding (TPD) scheme, which aims at providing effective vehicle-to-vehicle (V2V) communication over multi-hops in sparse vehicular networks. TPD is built upon the concept of participatory services in which users of a service (e.g., data forwarding service) share their information (e.g., trajectory) to establish the service. The privacy-sensitive users can opt out, while participatory users can exchange privacy for convenience and performance.

The main idea of TPD is to utilize shared trajectory information to predict pair-wise encounters and then construct an encounter graph to support end-to-end data forwarding. Based on the encounter graph, TPD optimizes the forwarding sequence to achieve the minimal delivery delay given a specific delivery ratio threshold. The optimal forwarding metrics allow the vehicle to always forward packets to the vehicle in its communication range that is expected to provide the best forwarding performance. With microscopic information about individual trajectories available, TPD can achieve much more effective data forwarding performance in terms of delay and delivery ratio than the ones that largely depend on road traffic statistics. Specifically, our intellectual contributions are as follows:

- To the best of our knowledge, TPD is the first attempt to design the data forwarding for VANETs with the shared trajectory information, tightly couples information from both physical and cyber world.
- We design a novel statistic method to construct a vehicle encounter graph, which effectively reduces uncertainty in a sparse vehicular network.
- We optimize the predicted encounter graph using dynamic programming to achieve a low delivery delay under the

required delivery ratio. With online forwarding, our design is robust to the trajectory change of individual vehicles.

II. Model and Assumptions

Our work is to design an effective data forwarding scheme in sparse vehicular networks based on the following assumptions:

- Vehicles are installed with a GPS-based navigation system and digital road maps. Traffic statistics, such as the mean and variance of the travel time for each road section, are available via a commercial navigation service [12].
- A vehicle's trajectory, defined as the moving path from the vehicle's starting position to its destination position in a road network, is also available for sharing when this vehicle decides to participate data forwarding service. Popular crowdsource traffic and navigation applications such as Waze [13], TomTom Crowdsourcing [14] and iCartel [15] have attracted millions of voluntary users and support the feature of trajectory sharing among application users. Further, we assume such shared trajectory information can be inaccurate and a small percentage of trajectories (e.g. less 20%) are subject to change after sharing.
- Access points (APs) are deployed at the entrances and roadside of a road network sparsely. They are inter-connected and disseminate rajectory information of moving vehicles. With the recent developments in ITS, it has been practical to install Roadside Units (RSUs) at intersections, which communicate with On-Board Units (OBUs) carried on vehicles for various purposes such as driving safety and electronic fee collection [7], [16]. We propose that such RSUs can be used as APs, which may collect trajectory and current location information from vehicles, and also allow vehicles to download the latest trajectory information of others.
- The overhead and delay for downloading vehicle trajectories are very limited. Assume one vehicle's trajectory size is 200 bytes (it contains the vehicle's starting time, starting location and a series of intersections it will pass), and the data transmission rate from an AP to a vehicle is 10 Mbps, so the downloading of the shared trajectory information from an AP is very fast (i.e., the time to download 100 trajectories is less than 20 ms).
- The Vehicle-to-Vehicle communication supported by TPD operates in a participatory manner. A vehicle is allowed to obtain the V2V communication service, only when this vehicle shares its trajectory information with other participated vehicles. Packets are forwarded only among participated vehicles. For now, we assume the participated vehicles are willing to sacrifice a certain level of privacy in exchange of the service. Advanced designs with enhanced privacy and security are left as future work.

III. Encountering Prediction and Constructing a Predicted Encounter Graph

Our basic idea is based on vehicular encounter prediction. From the trajectory information with certain precision, although it is difficult to accurately predict the encounter of two vehicles traveling in the same direction, it is typically easier to decide the encountering probability of the two vehicles traveling in opposite directions. After we derive sufficient knowledge on vehicle encounters, we schedule message transmissions so that a message goes from the source to the destination hop by hop based on our encounter prediction. Figure 1 shows an example of this idea, in which, V_a is predicted to encounter V_b at road section L_{12} (between the intersection n_1 and n_2) and V_b is predicted to encounter V_c at road section L_{34}. Then, packets generated by V_a and destined to V_c can be forwarded through the "encountered vehicles path": $V_a \rightarrow V_b \rightarrow V_c$. In the following sections, based on this idea, we will explain this design in more detail.

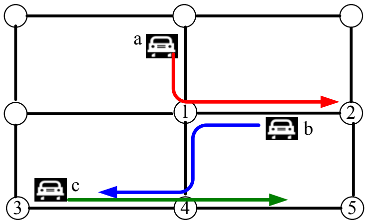


Fig. 1. Data forwarding through predicted encountered vehicles

As the foundation of our protocol, this section introduces how to calculate the encounter probability between vehicles, and further how to construct a predicted encounter graph based on probabilistic encounter events.

A. Travel Time Prediction

1) Travel Time through a Road Section: Researchers on transportation have demonstrated that the travel time of one vehicle over a fixed distance follows the Gamma distribution [11] [17]. Therefore, the travel time through a road section i in the road network is modeled as: $d_i \sim \Gamma(\kappa_i, \theta_i)$. d_i is also called link delay for road section i. To calculate the parameters κ_i and θ_i, we use the mean and the variance of the link delay, which are the traffic statistical information (provided by commercial service provider). Let the mean of d_i be $E[d_i] = \mu_i$, the variance of d_i be $Var[d_i] = \sigma_i^2$, the formulas for κ_i and θ_i are as follows:

$$\theta_i = \frac{Var[d_i]}{E[d_i]} = \frac{\sigma_i^2}{\mu_i} \tag{1}$$

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

2) Travel Time on an End-to-End Path: Here we model the end-to-end travel delay from one position to another position in a given road network. As discussed above, the link delay is modeled as the Gamma distribution of $d_i \sim \Gamma(\kappa_i, \theta_i)$ for road section i. Given a specific traveling path, we assume the link delays of different road sections for the path are independent. Under this assumption, the mean and variance of the end-to-end travel delay are computed as the sum of the means and the variances of the link delays that the end-to-end path consists of. Assuming that the traveling path consists of N road sections, the mean and variance of the end-to-end packet delay distribution can be computed as follows:

$$E[P] = \sum_{i=1}^{N} E[d_i] = \sum_{i=1}^{N} \mu_i \tag{3}$$

$$Var[P] = \sum_{i=1}^{N} Var[d_i] = \sum_{i=1}^{N} \sigma_i^2 \tag{4}$$

With (3) and (4), the end-to-end packet delay distribution can be modeled as $P \sim \Gamma(\kappa_p, \theta_p)$ and the κ_p , and θ_p can be calculated using $E[P]$ and $Var[P]$.

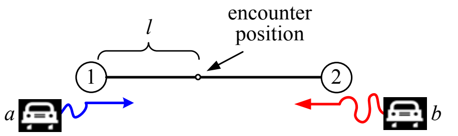


Fig. 2. Vehicle a and b will encounter at road section L_{12}

B. *Encounter Event Prediction*

1) Encounter Probability between Vehicles: Based on the travel time prediction, the encounter event between two vehicles can be predicted. In Figure 2, suppose vehicle V_a and V_b's trajectories overlap at road section L_{12} that joins intersections n_1 and n_2. V_a will travel through L_{12} from n_1 to n_2, while V_b will travel through L_{21} from n_2 to n_1. Assuming the initial time as 0, let T_{a1} and T_{a2} be the time when V_a moves past n_1 and n_2, respectively. Let T_{b1} and T_{b2} be the time when V_b moves past n_1 and n_2, respectively. The probability that they will encounter each other on this road section:

$$\mathrm{P}(V_a \otimes_{12} V_b) = \mathrm{P}(T_{a1} \leq T_{b1} \cap T_{a2} \geq T_{b2}) \tag{5}$$

where the "$\otimes_{12}$" means "encountering at road section L_{12}".

As discussed above, T_{a1}, T_{b1}, T_{a2}, T_{b2} are stochastic variables following the Gamma distribution. It's clear that T_{a1} and T_{a2} are not independent, and T_{b1} and T_{b2} are not independent, either. To calculate (5), they have the following relationship:

$$T_{a2} = T_{a1} + t_{12} \tag{6}$$

$$T_{b2} = T_{b1} - t_{21} \tag{7}$$

where t_{12} is the statistic mean travel time through L_{12} from n_1 to n_2; t_{21} is the statistic mean travel time through L_{21} from n_2 to n_1. Replace T_{a2} and T_{b2} in (5) by (6) and (7), we get:

$$P(V_a \otimes_{12} V_b) = P(T_{a1} \leq T_{b1} \leq T_{a1} + t_{12} + t_{21}) \tag{8}$$

Let $f(x)$ and $g(y)$ represent the probability density function of stochastic variables T_{a1} and T_{b1} respectively. Because T_{a1} and T_{b1} are independent, we have:

$$P(V_a \otimes_{12} V_b) = \int_0^{\infty} \int_x^{x+t_{12}+t_{21}} f(x)g(y)dydx. \tag{9}$$

So far we have discussed how to calculate the encounter probability in one road section. If the trajectories of two vehicles overlap by more than one road section, we can still calculate the overall probability by treating these adjacent overlapping roads as a long one.

2) Conditional Encounter Probability Calculation in Multi-hop Encounter Prediction: Data forwarding through multi-hops of encountered vehicles should use the conditional probability calculation. Let's get back to Figure 1. As discussed earlier, if vehicle V_a wants to send data to V_c, it should transmit packets to V_b when they encounter, so that when V_b meets V_c, packets could be transmitted to V_c. The success probability of this forwarding process is as follows:

$$\begin{aligned} &P(V_a \otimes_{12} V_b \cap V_b \otimes_{34} V_c) \\ &\quad = P(V_a \otimes_{12} V_b) P(V_b \otimes_{34} V_c | V_a \otimes_{12} V_b) \end{aligned} \tag{10}$$

Because the encounter between V_a and V_b affects the encounter probability between V_b and V_c, the two events "$V_a \otimes_{12} V_b$" and "$V_b \otimes_{34} V_c$"are not independent, therefore:

$$P(V_b \otimes_{34} V_c | V_a \otimes_{12} V_b) \neq P(V_b \otimes_{34} V_c) \tag{11}$$

It's difficult to calculate $P(V_b \otimes_{34} V_c | V_a \otimes_{12} V_b)$. However, an approximate value can be obtained as follows: we first calculate the conditional expectation of V_b's passing time through intersection n_1 (it's the outlet intersection that V_b would pass after the encountering with V_a in road L_{12}), under the condition that V_a encounters V_b at the road section L_{12}. It's indicated by $E(T_{b1} | V_a \otimes_{12} V_b)$. Then the approximate value of $P(V_b \otimes_{34} V_c | V a \otimes_{12} V_b)$ can be obtained by calculating $P(V_b \otimes_{34} V_c)$ using the method in the previous subsection with the precondition that V_b starts its traveling from n_1 at time $E(T_{b1} | V_a \otimes_{12} V_b)$. The formula to calculate $E(T_{b1} | V_a \otimes_{12} V_b)$ is:

$$E(T_{b1} | V_a \otimes_{12} V_b) = \int h(y | V_a \otimes_{12} V_b) y dy \tag{12}$$

where $h(y | V_a \otimes_{12} V_b)$ is the conditional probability density function of T_{b1} under the condition that $(V_a \otimes_{12} V_b)$. It can be easily deduced.

C. *Constructing a Predicted Encounter Graph*

To forward packets through predicted encounter vehicles, we construct a predicted encounter graph based on these probabilistic encounters. We first discuss how to calculate the expectation of two vehicles' encounter time.

1) Expectation of Encounter Time: We can also calculate the expectation of the encounter time between two vehicles. The expectation of encounter time is used in the process of constructing the predicted encounter graph.

Let's get back to see Figure 2, which still illustrates the possible encounter between V_a and V_b at road L_{12}. Suppose the encounter position is l meters away from n_1, the mean travel speed from n_1 to n_2 is v_{12}, the mean travel speed from n_2 to n_1 is v_{21}, and the encounter time is T, we have:

$$l = (T - T_{a1}) v_{12} = (T_{b1} - T) v_{21} \tag{13}$$

therefore:

$$T = \frac{T_{a1} v_{12} + T_{b1} v_{21}}{v_{12} + v_{21}}. \tag{14}$$

Formula 14 shows T is a function of T_{a1} and T_{b1}. As T_{a1} and T_{b1} are independent stochastic variables, the expectation of the encounter location is:

$$E(T | V_a \otimes_{12} V_b) = \iint T(x,y) h'(x,y | V_a \otimes_{12} V_b) dxdy \tag{15}$$

Where $h'(x,y | V_a \otimes_{12} V_b)$ is the joint conditional density function of T_{a1} and T_{b1} under the condition that $(V_a \otimes_{12} V_b)$.

2) Constructing the Predicted Encounter Graph: The predicted encounter graph is a directed graph that originates from the source vehicle that intends to forward packets, and ends at the forwarding destination, which could be a moving vehicle or a fixed point at roadside. Each node in this graph denotes a vehicle. For convenience, both "node" and "vehicle" are used to refer to a node in the graph. For a node e, its child nodes are the vehicles it might encounter later after its parent vehicle. These child nodes are sorted in the sequence of their expected encounter time with node e. That is, if the expectations of the encounter time between node e and its n child nodes satisfy $t_1 \leq t_2 \leq \cdots \leq t_n$, these child nodes are sorted in the sequence $C_{t1}, C_{t2}, \cdots, C_{tn}$, where C_{ti} $(i \in [1,n])$ is the child whose expected encounter time with node e is t_i.

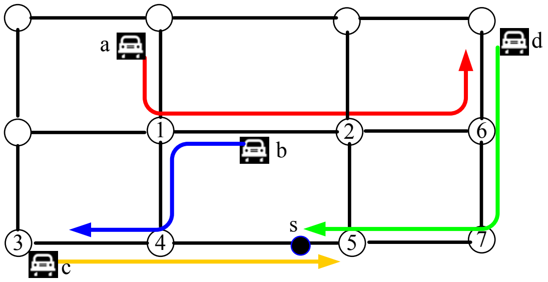


Fig. 3. Vehicles travel in the road network

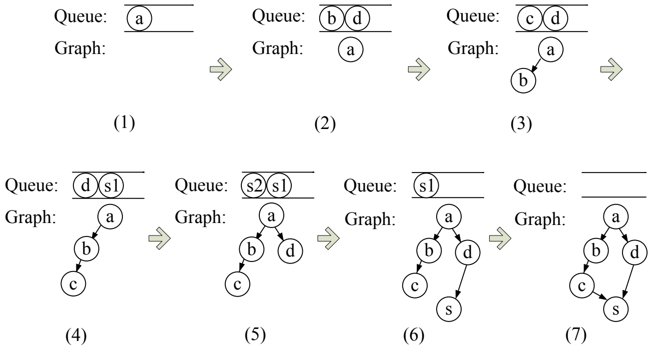


Fig. 4. construction of the predicted encounter graph

The construction of a predicted encounter graph is a process of expanding the graph by adding new nodes into it one by one. The expansion is performed according to the sequence of the expected encounter time. That is, when adding a node into the graph, each node denoting a possible encounter event that would have happened earlier than the current node should have been already handled and inserted into the graph. We use an assistant ordered queue Q to implement it. The algorithm is represented as follows:

1) Generate the root node and insert it into Q. The root node is the source vehicle that has packets to forward;
2) Take out the first node (denoted by node e here) in Q;
3) Calculate node e's child nodes using the trajectory information. That is, predict the possible encounters during its following travel and get its child nodes. Insert the child nodes into Q, if the expected encounter time is earlier than TTL (Time-To-Live). Note that all the nodes in Q are sorted in the order of the expected time of encountering with their own parents.
4) If node e is the root node, it's the first node in the graph; otherwise, add node e into the graph by inserting it into its parent's child-list. The nodes in the child-list are also ordered by the expected encounter time, as stated above.
5) If Q is not empty, go to step 2; otherwise the construction process finishes.

We illustrate the construction process through an example. In Figure 3, a,b,c and d are four vehicles in the network and nodes from 1 to 7 are road network intersections. For demonstration purpose, in Figure 3, the fixed point s at roadside is selected as the packet destination. In fact, the destination could be simply replaced by a moving vehicle. Assuming vehicle V_a intends to forward packets to the fixed node s. Firstly the root node is inserted into Q, as shown in Figure 4(1). When we move the node a out of Q, the possible encounter vehicles V_b and V_d are predicted. Therefore node b and node d are inserted into Q according to the expected encounter sequence, as shown in Figure 4(2). Figure 4(3) shows that when the first node b in Q is taken out, it's predicted that node b could encounter vehicle V_c(under the condition that V_a encounters V_b first). So node c is inserted into Q and then node b is added into the graph. Suppose the expected encounter time between V_b and V_c is earlier than the encounter between V_a and V_d, node c is ahead of d in Q. Figure 4(4) shows the result when node c is out of Q. Note that the node s_1 in Q indicates that the destination node s would be encountered by node c. We differentiate the destination nodes in Q because it can differentiate the transmission delay of different paths. When node d is taken out of Q, its child node s_2 is inserted into Q. Node s_2 is inserted ahead of s_1 because it's predicted that V_d encounters destination s earlier than V_c, as shown in Figure 4(5). Figure 4(6) and 4(7) show that in the graph, two links emitting from node d and node c are pointed to the destination node sequentially.

When forwarding packets in a high traffic density road network, the graph construction might take some time. Some useful methods can be used to reduce the time, i.e., we can limit the search zone, and only the encounters within the geographical zone are predicted and adopted; we can also delete the nodes in the graph, if the product of the encounter probabilities from it up to root is smaller than a threshold. More importantly, in the next section we will see that, the expansion process of the graph will finish earlier when it achieves the requested delivery ratio bound.

IV. TRAVEL PREDICTION BASED DATA FORWARDING SCHEME

Like other schemes such as VADD and TBD, our TPD employs the unicast strategy. That is we only keep one copy of the message in the network. After constructing the predicted encounter graph, as shown in Figure 4, each vehicle normally would encounter multiple other vehicles with different probabilities and different delays during the data forwarding process. To guarantee the system requirements such as data delivery probability and minimize end-to-end (E2E) packet delivery delay in the network, we discuss how to optimize E2E message delivery delay under a specific delivery ratio threshold by only selecting a subset of encountered vehicles for data delivery.

A. Calculating Expected Delivery Ratio (EDR)

For each node in the encounter graph, all of its children that have a path to the destination node are potential next-hop forwarders. To send a packet, the vehicle looks up the predicted encounter time and road section associated with the first vehicle in its forwarding paths, and expects to encounter it. If this vehicle encounters the first forwarding vehicle successfully at the right road section, the packet is transmitted, and the sender no longer needs to carry this packet. Otherwise, the sender prepares for the encountering with the next vehicle in its forwarding paths and tries to send the packet again. This transmission process over a single hop continues until the sender has successfully sent the packet to one of the forwarding vehicles or the sender reaches the end of all its forwarding vehicles, meaning that the packet fails to be delivered.

In this section, we discuss how to calculate the expected delivery ratio based on the predicted encounter graph. Let p_{ei} be the encounter probability between vehicle e and its i^{th} forwarder in the predicted encounter graph. The overall probability $P_e(i)$ that a packet is transmitted by vehicle e to the i^{th} forwarder when they encounter (which means e fails to encounter with the former $i-1$ forwarders) can be represented as:

$$P_e(i) = [\prod_{j=1}^{i-1}(1-p_{ej})]p_{ei}. \tag{16}$$

The expected delivery ratio (EDR) of a given vehicle e, denoted by EDR_e, is the expected packet delivery ratio from vehicle e to its destination. Assuming vehicle e has n children in its predicted encounter graph and the i^{th} forwarder's EDR value is EDR_i, we have the following recursive equation for EDR_e:

$$EDR_e = \sum_{i=1}^{n} P_e(i)EDR_i \tag{17}$$

To calculate the E2E expected delivery ratio at the root node in the predicted encounter graph, a recursive process starts from the target node S. At the target node S, obviously, $EDR_S = 1$ (i.e., no packet loss), while $EDD_S = 0$. To calculate EDR for the whole encounter graph, we start from known initial conditions and recursively apply Equation 17. The whole process of calculating EDR values propagates upwardly from the destination nodes to the rest of the graph until finally reaches the root node.

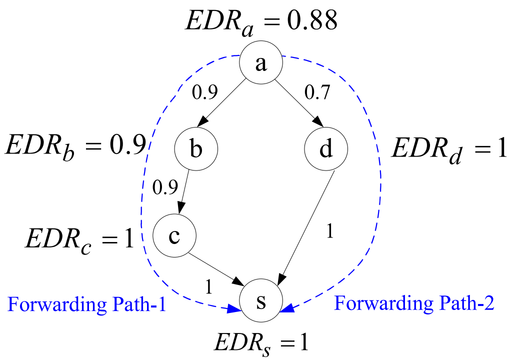


Fig. 5. EDR Calculation of Vehicle V_a

To illustrate the whole EDR calculation process for a predicted encounter graph, we show a walkthrough example in Figure 5. From Figure 5, vehicle a forwards data packets toward the destination S through *Forwarding Path-1* (i.e., $a \rightarrow b \rightarrow c \rightarrow S$) and *Forwarding Path-2* (i.e., $a \rightarrow d \rightarrow S$). The weights on the edges in Figure 5 denote the encounter probability between two connected vehicles. At the initial state, the $EDR_S = 1$ at the target node S. Then based on the Equation 17, we can recursively calculate the EDR value for vehicles c, d and b, respectively. Finally for source vehicle a, we can calculate its EDR value as: $EDR_a = p_{ab}EDR_b + (1-p_{ab})p_{ad}EDR_d = 0.9*0.9 + (1-0.9)*0.7*1 = 0.88$.

B. Optimizing Expected Delivery Delay (EDD)

Similar to calculate EDR, we can also recursively calculate E2E expected delivery delay from the target vehicle based on the predicted encounter graph,. Formally, we define the expected delivery delay of a given vehicle e, denoted by EDD_e, as the expected data delivery delay for the packets sent by vehicle e and received by the destination.

EDD is defined based on the condition that the packets are successfully transmitted to the destination. To calculate the EDR value of vehicle e, let $Q_e(i)$ be the probability that the packet transmission is successful at the i^{th} forwarder under the constraint that the packet is received successfully by the destination node. Clearly, $Q_e(i) = \frac{P_e(i)EDR_i}{EDR_e}$. Let EDD_i be the EDD value for the i^{th} forwarder in vehicle e's children nodes, and d_i be the delay (carrying time) for vehicle e to carry the packet until it encounters forwarder v_i^e in V_n^e, then EDD_e can be represented as:

$$EDD_e = \sum_{i=1}^{n} Q_e(i)(d_i + EDD_i). \tag{18}$$

In order to optimize the expected delivery delay, we observe that in vehicular network, while a low delivery delay is preferable, this typically requires that a threshold on delivery ratio is maintained at the same time. In fact, if there is no bound on the expected delivery ratio (EDR), the optimal delay can be easily achieved by including only a single vehicle v_j that has the minimum $(d_j + EDD_j)$ value among all next-hop potential encountered vehicles. Because the corresponding delivery ratio may be very low, such an optimal solution is not suitable for practical applications. We will next discuss how to optimize the EDD metric for the node e under the constraint that the EDR metric is no less than a certain threshold R.

As discussed above, in the process of constructing the encounter graph, when a new node is added into the graph, all the encounter events which are predicted to have happened earlier than the new node must have already been included. Therefore, in the process of constructing the graph, when the target node is taken out from the ordered queue Q and added into the predicted encounter graph for the first time, the first connected path from the source vehicle to the target is found. Because of the way that this graph is constructed, this path has the minimal delay for packet forwarding. We then calculate the EDR of the root node at the current graph extension. If the EDR value is greater than the required bound R, the construction of the graph stops and the optimal path is acquired; otherwise the process of expanding the graph continues until the EDR of the source node satisfies the bound R or the construction is stopped by the TTL constraint. This approach of optimizing the delivery delay is integrated into the process of constructing the encounter graph. It can be represented as follows:

1) In the process of constructing the graph, when taking out the first node in Q and adding it into the graph, judge whether this new node is a target node;
2) If the newly added node is a target node, we use a dynamic programming approach (detail in Appendix) to calculate the maximum EDR that the source node of the graph could achieve with the current graph expansion;
3) If the calculated EDR is smaller than the requested EDR bound R, go to 1) and continues; otherwise the process stops, because at the current graph extension, the optimal forwarding paths have already met the requirement of EDR bound R and at the same time optimal delivery delay.

When the graph extension is over, the EDD value of the root vehicle can be calculated using Equation 18. Note that because the optimal forwarding paths are acquired in terms of maximizing the EDR metric, in some cases the EDD value we get is not the lowest delay that meets the EDR bound R (it's hard to get). However, based on the chronological graph expansion, the EDD value we get is close to the lowest delay.

C. Data Forwarding Process in TPD

Data forwarding in TPD is a dynamic process. When the vehicle needs to forward packets, it constructs a predicted encounter graph with the desired TTL and delivery ratio bound R, and then obtains the optimal forwarding paths. Basically, the forwarding can be guided by this optimal forwarding paths and then packets are transmitted through the predicted encounter graph. As discussed above, packets can be forwarded to the destination with the performance of the root vehicle's EDR and EDD value.

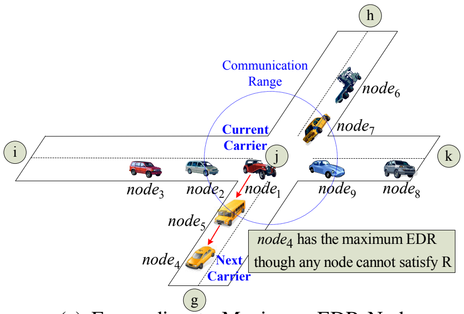
Besides the predicted vehicles in it's forwarding paths, it can meet some other vehicles not in its predicted forwarding paths when the packet carrier is moving along its trajectory. The reasons are: 1) the encountering prediction only considers the case that vehicles encounter face-to-face. It doesn't include the case that two vehicles travel a road in the same moving direction (because it's hard to accurately predict), and 2) there may be missing trajectory information maintained by the access points, and some vehicles encountered by the packet carrier are perhaps not in the packet carrier's trajectory database. Therefore, during the travel time, once the packet carrier meets other vehicles which are not in its forwarding paths, it first notifies these neighbors the destination it wants to forward packets to and the time left for the forwarding (because of the TTL constraint). Each neighbor receives the notification, calculates the EDR and EDD it could achieve using the method of optimizing delay with the requested EDR bound R, and replies the result to the packet carrier. During the travel, as the EDR and EDD of the carrier vary with time (i.e., some expected vehicles in its optimal forwarding paths are not actually encountered, then the EDR and EDD change), packet carrier should first re-estimate its current EDR and EDD value, and then compare these values with all its neighbors using the following rules to select the best forwarder for packet transmission:

- If the EDRs of all the connected vehicles can not meet the requested bound R, select the vehicle having the highest EDR as the next-hop forwarder;
- If there exists the vehicles whose EDRs are greater than the bound R ($EDR \geq R$), within these vehicles we select the one which has the minimal EDD value as the next-hop forwarder.

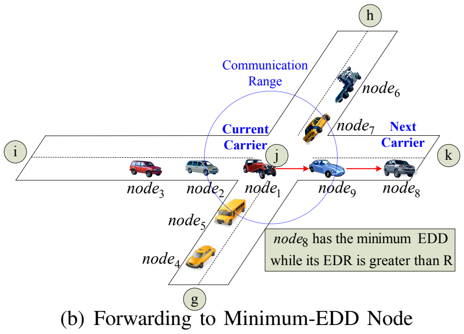
For example, Figure 6 shows the TPD forwarding protocol. Each vehicle calculates its own forwarding metric pair of (EDR, EDD). Using the TPD forwarding rule, whenever the packet carrier encounters a better forwarder, the packet forwarding could be improved by (i) increasing the EDR (when the current carrier cannot meet the requested EDR bound R, as shown in Figure 6(a)) or (ii) reducing the EDD (when the requested EDR bound R can be achieved, as shown in Figure 6(b)).

V. PERFORMANCE EVALUATION

This section evaluates the performance of TPD. To our best knowledge, existing well-known protocols do not support multi-hop unicast between two moving vehicles. Therefore in evaluation, we mainly focus on the data forwarding from moving vehicles to fixed points, enabling us to compare TPD with VADD, TBD and flooding under common settings. It can be easily achieved for TPD by selecting stationary vehicles as packet destinations. We also compare the performance of TPD and flooding on the vehicle-to-vehicle data forwarding. Note that for flooding, we assume there is no transmission conflict and vehicles have infinite buffer to store packets, based on which a vehicle simply forwards packets to every other vehicle it meets. With these assumptions, the flooding protocol achieves the maximal delivery ratio and minimal delivery delay. The evaluation is based on the following settings:



(a) Forwarding to Maximum-EDR Node



(b) Forwarding to Minimum-EDD Node

Fig. 6. TPD Forwarding Protocol

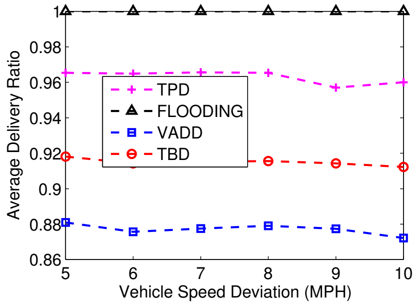
TABLE I
DEFAULT PARAMETERS

Parameter	Description
Road network	The number of intersections is 36. The area of the road map is 6.75km×6km
Communication range	$R = 200$ meters.
Number of vehicles (N)	The number N of vehicles moving within the road network. The default of N is 100.
Time-To-Live	The expiration time of a packet. The default TTL is 1000 seconds.
Vehicle speed (v)	$v \sim N(\mu_v, \sigma_v)$ where $\mu_v = 40$ MPH and $\sigma_v = \{5, 6, ..., 10\}$ MPH. The default of (μ_v, σ_v) is $(40, 7)$ 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.
Min available encounter probability	The minimal encounter probability we adopt when constructing the encounter graph. The default value is 0.3.
Requested EDR bound R	The requested EDR bound the forwarding should achieve. The default is R=0.9.

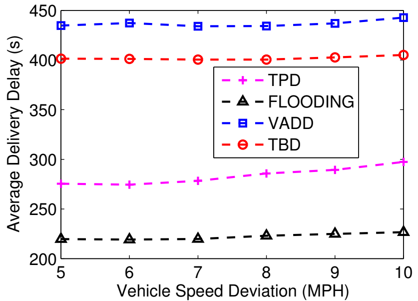
Performance Metrics: We use (i) packet delivery ratio and (ii) average delivery delay as the performance metrics.

Parameters: We investigate the impact of (i) vehicle speed deviation, (ii) communication range, and (iii) vehicular density.

In the simulation a road network with 36 intersections is used, and one fixed target point (stationary vehicle) is located in the center of the network. Each vehicle moves from a randomly selected source position to a randomly selected destination position. The movement pattern is determined by a Manhattan Mobility model [18]. Based on the characteristics of Manhattan

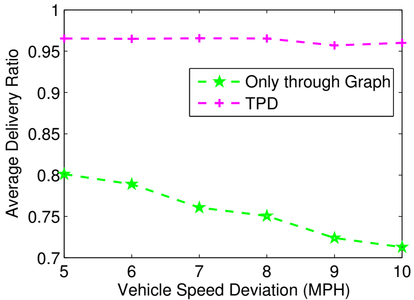


(a) Delivery Ratio vs. Speed Deviation

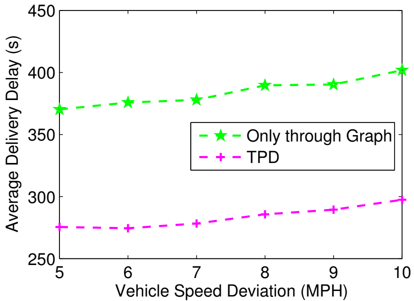


(b) Delivery Delay vs. Speed Deviation

Fig. 7. Impact of Speed Deviation

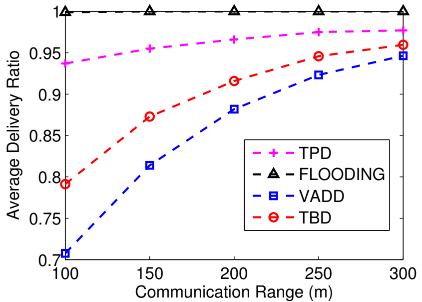


(a) Delivery Ratio vs. Speed Deviation

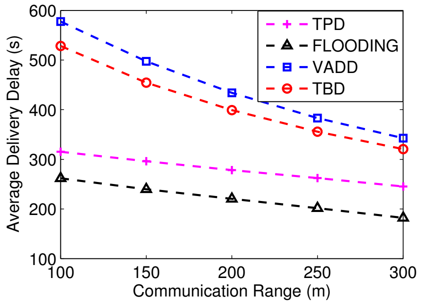


(b) Delivery Delay vs. Speed Deviation

Fig. 8. Packet Forwarding through Predicted Graph



(a) Delivery Ratio vs. Communication Range



(b) Delivery Delay vs. Communication Range

Fig. 9. Impact of Communication Range

Mobility, as shown in Table 1, the vehicle travel path length l from starting position u to ending 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 between their starting position and their ending position. After arriving at its driving destination, a vehicle will be deleted; and at the same time another fresh vehicle is generated into the road network, so the total number of vehicles in the road network is constant. The vehicle speed follows the normal distribution of $N(\mu_v, \sigma_v)$ [19], and a vehicle may change its speed at each road section. During the simulation, packets are dynamically generated from randomly selected vehicles in the road network. The simulation continues until all of these packets are either delivered or dropped due to TTL expiration. Unless otherwise specified, the default values in Table 1 are used.

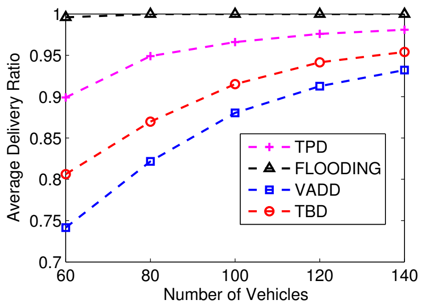
A. *Impact of Vehicle Speed Deviation σ_v*

As TPD is travel prediction-based, the accuracy of prediction will affect its performance. Intuitively, traffic mainly affects the traveling time, making the encounters probabilistic. In our simulation, for simplicity we use vehicle speed deviation to reflect the traffic condition, and intend to study to what extent the speed deviation could affect TPD. As shown in Figure 7, for TPD, with greater speed deviation, the packet delivery ratio has a slight decrease, but the average delay obviously increases. This is because in TPD, we set the default value of Requested EDR bound R to 0.9. TPD tries to satisfy this EDR bound, and at the same time to forward packets through paths with lower delay. In general, as the vehicle speed deviation becomes larger, the predicted encounter probabilities between vehicles decrease (our simulation result in Figure 10 verifies this). Therefore, to meet the requested EDR bound, packets may have to be forwarded through paths which have longer delays. Comparatively, other protocols are slightly affected by speed deviation. However, even when the speed deviation is as large as 10 MPH, TPD still outperforms VADD and TBD significantly in terms of both delivery ratio and delay, and is closer to the performance of flooding. As discussed earlier, flooding achieves the theoretical maximal delivery ratio and minimal delay in the network with the assumptions of infinite buffer and collision-free transmission. These assumptions, however, are not reasonable in reality due to hardware and cost issues, so flooding is hard to work in real life. Generally, for different protocols, if more information is used, better performance could be achieved. Since TBD utilizes more information than VADD by allowing a vehicle employing its own trajectory for data forwarding, it performs better than VADD. In TPD, we take a step further and adopt more trajectories than TBD, using the optimized encounter prediction as guidance so that packets can be forwarded through better paths to destinations. Our simulation results indicate that utilizing more information indeed achieves better performance.

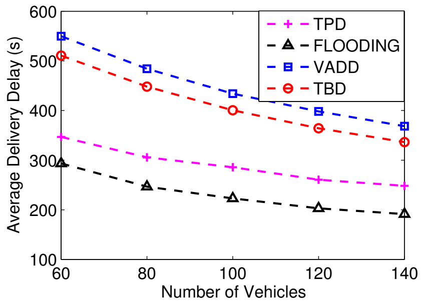
To further learn the impact of the speed deviation on TPD, another experiment is performed, in which a packet can only be forwarded to its destination through the source vehicle's predicted encounter graph. In Figure 8 we find that, for the data forwarding only through the encounter graph, both the delivery ratio and the delivery delay are obviously affected by the vehicle speed deviation. Because TPD can forward packets through more vehicles with better performance metrics, the impact of the speed deviation on the delivery ratio of TBD is relatively less.

B. *Impact of Communication Range*

The Figure 9 shows the impact of communication range on the performance. As expected, when the communication range is larger, the packet delivery ratio of all the protocols increases, and the average delivery delay decreases. This is because with a larger communication range, a vehicle has more opportunities to meet other vehicles in the road network, therefore packets have more

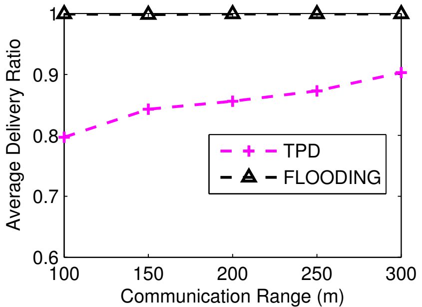


(a) Delivery Ratio vs. Vehicle Number

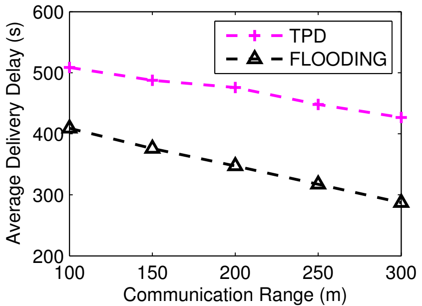


(b) Delivery Delay vs. Vehicle Number

Fig. 11. Impact of Vehicle Number

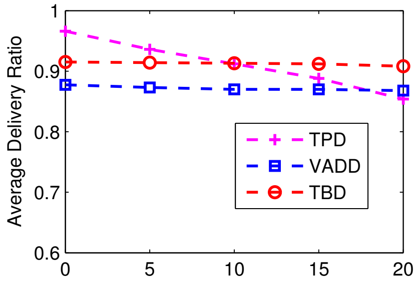


(a) Delivery Ratio vs. Communication Range

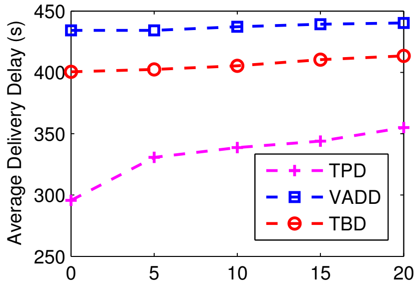


(b) Delivery Delay vs. Communication Range

Fig. 12. Packet Forwarding from Vehicle to Vehicle



(a) Delivery Ratio vs. Changing Percentage



(b) Delivery Delay vs. Changing Percentage

Fig. 13. Packet Forwarding with Trajectory change

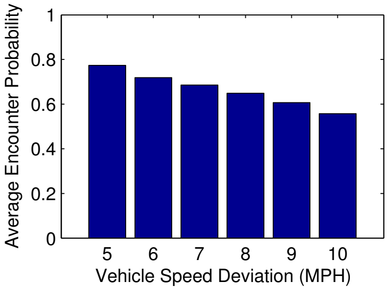


Fig. 10. Average Predicted Encounter Prob vs. Speed Deviation

opportunities to be forwarded to destinations. For the same reason, the carrying time of packets is also reduced. With the largest communication ranges (300 m), the performances of VADD and TBD are close to TPD. However, when the communication range reduces to 100 m, the performance of VADD and TBD decrease heavily, while TPD achieves a delivery ratio of 93.7% with a low average delay (315 s). The results show that besides statistical traffic information, if detailed traveling information of individual vehicles can be employed, packet forwarding could be more accurate and effective.

C. Impact of Vehicular Density

The vehicular density can be expressed by the number of vehicles in the network. We investigate the effectiveness of TPD under different vehicular densities by increasing the vehicle number from 60 to 140. As shown in Figure 11, all of the protocols have better performance in terms of both delivery ratio and delivery delay when the density becomes higher. This is because higher vehicular density could increase the connectivity among vehicles and then promote the data forwarding in the network. We also find that, with different densities TPD always performs better than VADD and TBD. Especially, when the vehicle density is low, TPD still achieves a good performance (e.g., when vehicle number is 60, its delivery ratio is 90% and delay is 346 s), which is much better than VADD and TBD. Since the microscopic trajectory information provides more accurate knowledge than statistics, TPD is more suitable for data forwarding than VADD and TBD in sparse vehicular networks.

D. Data Forwarding from Vehicle to Vehicle

Now we show the vehicle-to-vehicle data forwarding performance of TPD. Because the targets are moving, it's comparatively more challenging for both target location and next-hop selection. As no other protocol is found for vehicle-to-vehicle communication through multi-hops, we only compare TPD with flooding under different communication ranges. Note that in our simulation the vehicle that arrives at its destination will be deleted, so we only select the moving vehicles whose following travel time is longer than 1000 s as data destinations. As shown in Figure 12, larger communication range can improve the performance of both TPD and flooding. With the default communication range (200 m), the delivery ratio of TPD is 84.7%, and its average delivery delay is 475.7 s. When the communication range is 300 m, TPD achieves a higher delivery ratio of 90.3% with the average delay of 426.8 s.

VI. DISCUSSION

As trajectory information plays an important role that directly affects the feasibility and effectiveness of TPD, we discuss in this section a number of practical issues associated with the process of sharing trajectory information, including communication overhead, trajectory change, and the use of APs.

A. Robustness against Trajectory Change

In a real driving process, travel trajectory would be temporarily changed for many reasons. If a vehicle changes its trajectory without disseminating it in time, other vehicles that are calculated (based on the old trajectory information) to meet this vehicle will definitely miss it. To see how robust our TPD is against

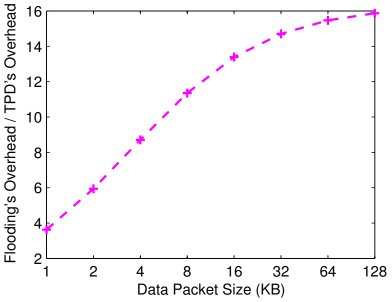


Fig. 14. Ratio of Flooding's Communication Overhead to TPD's Communication Overhead vs. Data Packet Size

trajectory change, an experiment is performed in which a certain percentage of vehicles change their travel route silently. As shown in Figure 13, the performance of TPD in terms of both delivery ratio and delivery delay decreases as more vehicles change their trajectories. However, even when 15% of total vehicles change routes, TPD still achieves a shorter delivery delay and a similar delivery ratio compared with TBD and VADD. In TPD, since a pre-calculated forwarding sequence contains many forwarders, if one forwarder is missed because of trajectory change, the forwarding would not be affected heavily because packets could be transmitted through the following forwarders. In addition, the data forwarding of TPD could utilize other vehicles not in the forwarding sequence during travel, which also weakens the impact of trajectory change. Figure 13 also shows that VADD and TBD are less sensitive to the trajectory changes.

B. Communication Overhead

We discuss the communication overhead of TPD caused by acquiring the trajectory information. Since the average frequency that a vehicle meets an AP can be obtained through statistics (it is actually decided by the density and the deployment of APs), this overhead can be easily calculated.

With default parameters, we simulate the data forwarding process and compare the communication overhead between TPD and flooding, which diffuses packets in an immoderate way. Since different applications require different data packet sizes, we first estimate the communication overheads of TPD and flooding with different data packet sizes. In this experiment, 2500 packets are forwarded within 60 minutes, and the result is shown in Figure 14. As we can see, when the data packet size is only 1 KB, the communication overhead of flooding is 3 times more than that of TPD. With a larger packet size, the increase of flooding's communication overhead is much greater than that of TPD's, so the ratio of flooding's overhead to TPD's overhead increases. It means that TPD has greater advantage than flooding in term of transmission overhead for applications requiring larger data packet (i.e., multimedia applications). Considering the different complexity of implementation and communication overheads between this two protocols, when the data packet size is bigger than 8 KB, TPD is better than flooding for data forwarding because of its competitive low communication overhead (less than 10% of flooding's overhead); otherwise if the packet size is smaller than 8 KB, flooding could also be selected because it is simple to implement, while its overhead is acceptable.

C. Using APs to Form a Wormhole Backbone

In our basic design, APs are used to provide only trajectory information to vehicles, and the data forwarding is done exclusively through vehicles. In practice, APs are interconnected with fast cables, creating shortcuts in a carry-and-forward vehicular network. We can consider the interconnections between APs as a wormhole backbone, which can be used to expedite vehicular-to-vehicular delivery process. If we remodel the topology of a road network with zero-delay road sections between APs and model each AP as a stationary vehicle, the TPD design can be used without modification. For evaluation purpose, we intentionally do not allow APs to involve in the data forwarding in order to show the effectiveness of the vehicle trajectory sharing at the micro-level. We expect improved performance can be achieved with APs' involvement in data forwarding.

VII. RELATED WORK

The research on vehicular networks has become popular in terms of driving safety, efficient traveling, and the data service through infrastructure [2]–[5], [20]–[22]. In vehicular networks, the data forwarding is a key function for the communications between vehicles or between vehicle and infrastructure. It can take advantage of the following two types of information: (i) Macroscopic information about road network traffic statistics (e.g., traffic density and road section average speed), and (ii) Microscopic information about individual vehicle (e.g., vehicular trajectory). This information make it possible to design new data forwarding schemes.

New data forwarding schemes have been recently developed for multi-hop vehicle-to-infrastructure communications. VADD investigates the data forwarding using a stochastic model based on vehicular traffic statistics. The objective is to achieve the *lowest delivery delay* from a mobile vehicle to a stationary destination. Delay-Bounded Routing has the objective to satisfy the *user-defined delay bound*. Also, this scheme pursues the minimization of the channel utilization. SADV [9] is a forwarding scheme based on stationary nodes, it can provide more stable, expected data delivery delay using the stationary nodes. VADD, Delay-Bounded Routing, and SADV are using the macroscopic information about the road network traffic.

With the microscopic information about vehicular trajectory, we developed TBD [10] for more efficient data forwarding. TBD can compute forwarding metric (i.e., expected End-to-End delay) with both vehicular traffic statistics and vehicle trajectory information, and further improve communication delay and delivery probability by selecting the best next-packet carrier with the smallest metric value among neighbor vehicles. TBD is also the data forwarding scheme for vehicle-to-static-destination communications.

For the reverse data forwarding, such as multi-hop infrastructure-to-vehicle communications, we took a step further with TSF [11]. TSF can provide an efficient solution for forwarding messages from a fixed point (i.e., AP) to a mobile node (i.e., vehicle) using the destination vehicle's trajectory. TSF selects a packet destination point on the road network along the destination vehicle's trajectory, considering the rendezvous probability of the packet and the destination vehicle. However, TSF needs additional stationary nodes at intersections in road networks as packet buffer to reduce the delivery delay variance.

Unlike the data forwarding scheme mentioned so far, in this paper we take a in-depth usage of shared trajectory information, which makes the effective packet forwarding for the multi-hop vehicle-to-vehicle communications in sparse VANETs. Note that

TPD is totally different from TBD and TSF in the forwarding design, although all of them take advantage of microscopic information about vehicular trajectory. As is known, TBD enhances the vehicle-to-infrastructure communications by employing vehicles' own trajectories, which is based on the VADD protocol; TSF supports infrastructure-to-vehicle communications using the destination vehicle's trajectory, and it is achieved with the help of stationary nodes deployed at each intersection. For our TPD, data forwarding is performed based on the prediction of encounters between vehicles, which works in an participatory manner to share trajectories between vehicles.

VIII. CONCLUSION

It is widely believed that vehicular networks can bring great benefit to driving safety and many practical applications. For the data forwarding in VANETs, existing protocols mainly take advantage of macroscopic information about road traffic statistics and achieve effective performances in dense networks. However, when the vehicular network becomes sparse, the traffic statistics become unreliable and are sensitive to individual vehicle's traveling, thus the performances of these protocols are affected. To address this problem, we adopt information about vehicular trajectories and propose a travel prediction-based data forwarding scheme (TPD) for multi-hop communications between vehicles in sparse VANETs. Different from TBD and TSF which use only vehicles' own trajectories, TPD utilizes the shared trajectory information in a participatory manner, which can overcome the uncertainty of statistics and make the forwarding more accurate. TPD predicts the encountering events between vehicles and constructs a predicted encounter graph. With the dynamic expansion of encounter graph, TPD optimizes the forwarding sequences in terms of delivery ratio and delivery delay, and guides data forwarding by allowing vehicles to always forward packets to the best forwarder in communication range. Simulation results demonstrate the effectiveness of TPD. Since our current work mainly concerns on the data forwarding problem, the privacy issue caused by sharing trajectories with public has not been addressed. As future work, we will consider this issue and design an advanced protocol which can provide better security and privacy-protection.

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APPENDIX

In this section, we briefly introduce a dynamic programming approach to find the optimal forwarding paths within the predicted encounter graph. The basic idea to decide whether a child node v_i should be included in the forwarding paths can be described as a judgement. That is, when vehicle e carries the packet and encounters the forwarder v_i, if it does not forward the packet to v_i, how many chances are left to successfully forward the packet using the latter forwarders in the predicted encounter graph?

Let $V_o(k)$ denote the optimal set of forwarding nodes in terms of maximizing EDR from child node set of node e, $(v_{n-k+1}, v_{n-k+2}, \cdots, v_n)$, which is a subset of all child nodes with its last k forwarders, and $EDR_e(V_o(k))$ denotes the optimal EDR value of vehicle e based on $V_o(k)$. Clearly, $EDR_e(V_o(k))$ is the maximal EDR value the vehicle e can achieve using its subsequence containing the last k forwarders. Therefore, after the forwarder v_i, the chances left for packet forwarding from vehicle e using the later $n-i$ forwarders of V_n is $EDR_e(V_o(n-i))$. If $EDR_i \geq EDR_e(V_o(n-i))$, meaning that vehicle v_i can offer higher expected delivery ratio than $EDR_e(V_o(n-i))$, so v_i should be included into the optimal paths and then forms the $V_o(n-i+1)$. Using Equation 17 it's clear that $EDR_e(V_o(n-i+1)) \geq EDR_e(V_o(n-i))$, indicating that the inclusion of v_i increases the EDR value of vehicle e. Otherwise if $EDR_i \leq EDR_e(V_o(n-i))$, v_i should not be included into V_o. Based on the judgement, as the last vehicle v_n in the child node set V_n is the last chance for vehicle e to transmit the packet, so v_n must be included in V_o. The optimizing process starts backwardly from the last forwarder, judges every forwarder one by one to obtain V_o. For each backward augmentation of the forwarding sequence, we guarantee the maximum data delivery ratio of the sequence between the newly augmented vehicle and the last vehicle. This forwarding sequence, then, serves as an optimal substructure for augmenting additional forwarders until the process reaches the first vehicle in the sequence.