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Utilizing Shared Vehicle Trajectories for Data Forwarding in Vehicular Networks

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Abstract—**Vehicular ad hoc networks (VANETs) represent promising technologies for improving driving safety and efficiency. Due to the highly dynamic driving patterns of vehicles, it has been a challenging research problem to achieve effective and time-sensitive data forwarding in vehicular networks. In this paper, a Shared-Trajectory-based Data Forwarding Scheme (STDFS) is proposed, which utilizes shared vehicle trajectory information to address this problem. With access points sparsely deployed to disseminate vehicles' trajectory information, the encounters between vehicles can be predicted by the vehicle that has data to send, and an encounter graph is then constructed to aid packet forwarding. This paper focuses on the specific issues of STDFS such as encounter prediction, encounter graph construction, forwarding sequence optimization and the data forwarding process. Simulation results demonstrate the effectiveness of the proposed scheme.**

I. INTRODUCTION

Vehicular Ad Hoc Networks (VANETs) have recently emerged as one of the most promising research areas to improve transportation safety and efficiency [1]–[4]. As an important component of Intelligent Transportation Systems (ITS) [5], [6], it promises a wide range of valuable applications including real-time traffic estimation for trip planning, mobile access to Internet, and in-time dissemination of emergency information such as accidents and weather hazards.

As one of key research topics in vehicular networks, data forwarding schemes for VANETs have been focused. In dynamic and mobile vehicular networks, most of the 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) [6], [7]. Among the existing protocols, many ones take advantage of the road network layout and traffic statistics, such as VADD [2] and SADV [8]. As these protocols are based on the road traffic statistics, the data forwarding process can be modeled and studied from a macro point of view. With the popular usage of GPS-based navigation systems, the trajectory information becomes available to data forwarding schemes. A few protocols such as TBD [9] and TSF [10], are designed to adopt available vehicle trajectories along with such road traffic statistics. It is proved that with the trajectory information, the pure stochastic forwarding models (i.e., VADD) can be improved further because more detailed information about vehicle mobility is provided. However, existing protocols (e.g., TBD) use the trajectory in a privacy-preserving way, which means the individual vehicle only acquire its own trajectory and does not share with other vehicles.

In this paper, we propose Shared Trajectory based Data Forwarding Scheme (STDFS), which aims at providing effective vehicle-to-vehicle (V2V) communications over multi-hops in VANETs. STDFS 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. STDFS uses shared trajectory information to predict the encounters between vehicles, and a predicted encounter graph is then constructed. Based on the encounter graph, STDFS optimizes the forwarding sequence to achieve the minimal delivery delay given a specific delivery ratio threshold. The optimal forwarding metrics allow the vehicle forwards packets to the vehicle in its communication range that provides the best forwarding performance.

The rest of the paper is organized as follows: Sec. II formulates the problem. Sec. III explains the encounter prediction and the construction of a encounter graph. Sec. IV presents the design of STDFS. Sec. V shows the effectiveness of STDFS via simulation. Sec. VI concludes the paper.

II. PROBLEM FORMULATION

Due to the high network dynamics, it's a challenging problem to achieve multi-hop data forwarding effectively. Our work is to design an effective data forwarding scheme in 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 [11]. 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.

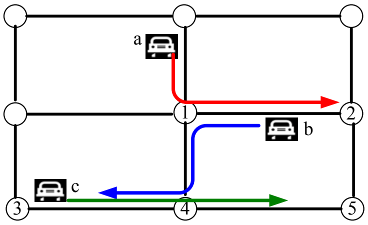


Fig. 1. Data forwarding through predicted encountered vehicles

- Access points (APs) are deployed at the entrances and roadside of a road network sparsely. They are interconnected and disseminate vehicles' real time trajectory information. 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 [6], [12]. We propose that such RSUs can be used as APs, which collect trajectory from vehicles and also allow vehicles to download the latest trajectory information of others.

Our basic idea is based on vehicular encounter prediction. Given the trajectory information with certain precision, although it is difficult to credibly predict the encounter of two vehicles traveling in the same direction, it is typically easier to decide the encountering probability of two vehicles traveling in opposite directions. After we have 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 the encounter prediction, i.e., in Figure 1, 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 following "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.

III. ENCOUNTER PREDICTION AND CONSTRUCTING A PREDICTED ENCOUNTER GRAPH

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.

A. Travel Time Prediction

Researchers on transportation have demonstrated that the travel time of one vehicle over a fixed distance follows the Gamma distribution [13]. Therefore, given a specific traveling path from one position to another position in a road network, the travel time through it is modeled as: $d \sim \Gamma(\kappa, \theta)$. To calculate κ and θ, according to the feature of the Gamma distribution, we should only acquire the mean and the variance of d, both of which are the traffic statistical information provided by commercial service provider.

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 will travel through road section L_{12} (that joins intersections n_1 and n_2) 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 link is:

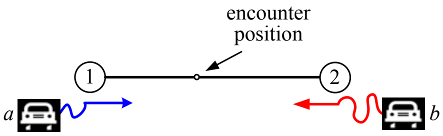


Fig. 2. Vehicle a and b will encounter at road section L_{12}

$$\mathrm{P}(V_a \otimes_{12} V_b) = \mathrm{P}(T_{a1} \leq T_{b1} \cap T_{a2} \geq T_{b2}) \tag{1}$$

where the "$\otimes_{12}$" means "encountering at road section L_{12}". Because $T_{a2} = T_{a1} + t_{12}$ and $T_{b2} = T_{b1} - t_{21}$ (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 from n_2 to n_1), we have:

$$P(V_a \otimes_{12} V_b) = P(T_{a1} \leq T_{b1} \leq T_{a1} + t_{12} + t_{21}) \tag{2}$$

As T_{a1} and T_{b1} are independent stochastic variables, $P(V_a \otimes_{12} V_b)$ can be calculated.

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, when vehicle V_a wants to send data to V_c (through V_b), the success probability is:

$$\begin{aligned} &P(V_a \otimes_{12} V_b \cap V_b \otimes_{34} V_c) \\ &\qquad = P(V_a \otimes_{12} V_b) P(V_b \otimes_{34} V_c | V_a \otimes_{12} V_b) \end{aligned} \tag{3}$$

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:

$$P(V_b \otimes_{34} V_c | V_a \otimes_{12} V_b) \neq P(V_b \otimes_{34} V_c) \tag{4}$$

It's difficult to calculate $P(V_b \otimes_{34} V_c | V_a \otimes_{12} V_b)$. However, we can first calculate $E(T_{b1} | V_a \otimes_{12} V_b)$. It is the conditional expectation of V_b's passing time through intersection n_1, under the condition that V_a encounters V_b at the road section L_{12}. After that, the approximate value of $P(V_b \otimes_{34} V_c | Va \otimes_{12} V_b)$ 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 $E(T_{b1} | V_a \otimes_{12} V_b)$.

C. Constructing a Predicted Encounter Graph

To forward packets through encounter vehicles, we should construct a predicted encounter graph based on these probabilistic encounters.

1) the Expectation of Encounter Time: We first calculate the expectation of the encounter time (also called expected encounter time) between two vehicles, which is used in the process of constructing the encounter graph. Let's see Figure 2 again, in fact, the encounter time T between V_a and V_b is also a stochastic variable. It is a function of T_{a1} and T_{b1}, so the expectation of the encounter time can be calculated.

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 (i.e., 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. For a node e, its child nodes are the vehicles it might encounter later after its parent vehicle, and they are sorted in the sequence of their expected encounter time with node e.

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, aided by an assistant ordered queue Q. 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) Predict node e's 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. 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 2); otherwise the construction process finishes.

IV. SHARED TRAJECTORIES BASED DATA FORWARDING

In this section we first give the definitions of the expected delivery ratio and the expected delivery delay, then discuss how to optimize these two metrics based on the predicted encounter graph. After that, we introduce our data forwarding process.

A. Expected Delivery Ratio and Expected Delivery Delay

To forward data, the first step is to construct a predicted encounter graph. For a node e in the graph, all of its child nodes which have a path to the destination node are potential forwarding nodes. Formally, we define the sequence of forwarding vehicles at a node e as $V_n^e = (v_1^e, v_2^e, \cdots, v_n^e)$, which includes n vehicles that can forward packets from vehicle e to the destination. This sequence is sorted by the expected encounter time.

STDFS employs the unicast strategy. To send a packet, the vehicle e looks up the predicted encounter time and road section associated with the first vehicle v_1^e in its forwarding sequence V_n^e, and expects to encounter it. If it encounters v_1^e successfully at the right road section, the packet is transmitted, and the sender e no longer needs to carry the packet. Otherwise, vehicle e prepares for encountering with the next vehicle v_2^e in V_n^e and tries to send the packet again. This transmission process over a single hop continues until the sender e has successfully sent the packet to one of forwarding vehicles or the sender misses all and the forwarding fails. Let p_{ei} be the encounter probability between vehicle e and its i^{th} forwarder v_i^e in V_n^e. The overall probability $P_e(i)$ that a packet is transmitted by vehicle e to v_i^e when they encounter is:

$$P_e(i) = [\prod_{j=1}^{i-1} (1 - p_{ej})]p_{ei}. \tag{5}$$

1) Expected Delivery Ratio (EDR): The expected delivery ratio 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 forwarders in its forwarding sequence and the i^{th} forwarder's EDR value is EDR_i, we have the following recursive equation for EDR_e:

$$EDR_e = \sum_{i=1}^{n} P_e(i) EDR_i \tag{6}$$

2) Expected Delivery Delay (EDD): The expected delivery delay of a given vehicle e, denoted by EDD_e, is the expected data delivery delay for the packets sent by vehicle e and received by the destination.

EDD is defined under the condition that packets are successfully received by the destination. To calculate EDD_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 by the destination. 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 V_n^e and d_i be the delay (carrying time) for vehicle e to carry the packet until it encounters v_i^e, then EDD_e is:

$$EDD_e = \sum_{i=1}^{n} Q_e(i)(d_i + EDD_i). \tag{7}$$

The calculation of EDR and EDD for the whole encounter graph is a recursive process. At the destination node s, obviously, $EDR_s = 1$ (i.e., no packet loss), while $EDD_s = 0$ (i.e., no delay). Consequently, start from the node s and recursively apply Equation (6) and (7), the process of calculating EDR and EDD propagates outward to the rest of the graph, and finally to the root node.

B. Optimizing Expected Delivery Ratio and Delivery Delay

Here we discuss how to obtain a forwarding subsequence that is optimal in terms of maximizing the EDR and minimizing the EDD respectively.

1) Optimizing Expected Delivery Ratio (EDR): Let V_n^e be vehicle e's full forwarding sequence. As defined earlier, each forwarder in V_n^e can forward packets from vehicle e to the destination with certain success ratio. However, as STDFS adopts unicast strategy, only one copy of the packet can be forwarded to a certain forwarder in V_n^e. To maximize the expected delivery ratio at vehicle e, not all the forwarders in V_n^e should be selected to forward packets. Therefore, we shall select a optimal subsequence from the full sequence V_n^e.

A dynamic approach is described here to get an optimal subsequence V_o^e from the full sequence V_n^e. The basic idea to decide whether v_i^e in V_n^e should be included into V_o^e can be described as a judgement. That is, when vehicle e carries the packet and encounters the forwarder v_i^e, if it does not forward the packet to v_i^e, how many chances are left to successfully forward the packet using the latter forwarders in V_n^e?

Let $V_o^e(k)$ denote the optimal forwarding sequence in terms of maximizing EDR metric from $(v_{n-k+1}^e, v_{n-k+2}^e, \cdots, v_n^e)$, which is a subsequence of V_n^e with its last k forwarders, and $EDR_e(V_o^e(k))$ denotes the optimal EDR value of vehicle e based on $V_o^e(k)$. Clearly, $EDR_e(V_o^e(k))$ is the maximal EDR value the vehicle e can achieve using the last k forwarders. Therefore, after the forwarder v_i^e, the chances left for packet forwarding using the later $n-i$ forwarders of V_n^e is $EDR_e(V_o^e(n-i))$. If $EDR_i \geq EDR_e(V_o^e(n-i))$, meaning that vehicle v_i^e can offer higher expected delivery ratio than $EDR_e(V_o^e(n-i))$, so v_i^e should be included into the optimal sequence and then forms the $V_o^e(n-i+1)$. Otherwise if $EDR_i \leq EDR_e(V_o^e(n-i))$, v_i^e should not be included into V_o^e. Based on the judgement, the last vehicle v_n^e in V_n^e must be included in V_o^e because it is the last chance for e to transmit the packet. The optimizing process starts backwardly from the last forwarder, judges every forwarder one by one to obtain V_o^e.

2) Optimizing Expected Delivery Delay (EDD): In vehicular network, while a low delivery delay is preferable, it is meaningless if the corresponding delivery ratio is low. Our goal is to optimize the EDD metric for the root node under the constraint that the EDR metric is no less than a certain threshold R.

The method to optimize EDD is based on the approach for maximizing EDR. As discussed above, constructing the encounter graph is an expanding process by adding new nodes into the graph according to the sequence of the expected encounter time. Therefore, in the expansion process, when the target node is taken out from Q and added into the graph for the first time, the first connected path from the source vehicle to the target is found. Obviously, 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 graph construction stops and the optimal forwarding sequence is acquired; otherwise the expanding continues until the EDR of the source node satisfies the bound R (because more paths to the target are found) or the construction is stopped by the TTL constraint. When the graph expanding is over, the EDD value of the root vehicle can be calculated using Equation (7).

C. Data Forwarding Process in STDFS

Data forwarding in STDFS is a dynamic process. When a vehicle needs to forward packets, it constructs a predicted encounter graph with the desired TTL and the EDR bound R, and then obtains the optimal forwarding sequence. Basically, the forwarding can be guided by this forwarding sequence and packets are transmitted through the encounter graph.

However, the packet carrier may meet some other vehicles not in its forwarding sequence when traveling, because: 1) the encounter prediction only considers vehicles encountering face-to-face. It doesn't include the case that vehicles traveling in the same direction, and 2) there may be missing trajectory information maintained by APs. Therefore, once the packet carrier meets vehicles not in its forwarding sequence, it first notifies these neighbors the packet destination and the time left for the forwarding (because of the TTL constraint). Each neighbor calculates the EDR and EDD it could achieve, and replies to the packet carrier. During the travel, as the EDR and EDD of the carrier vary with time, the packet carrier should first re-estimate its current EDR and EDD value, and then compare with all its neighbors using the following rule to select the best forwarder:

- If the EDRs of all the connected vehicles can not meet the EDR 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, within these vehicles we select the one which has the minimal EDD value as the next-hop forwarder.

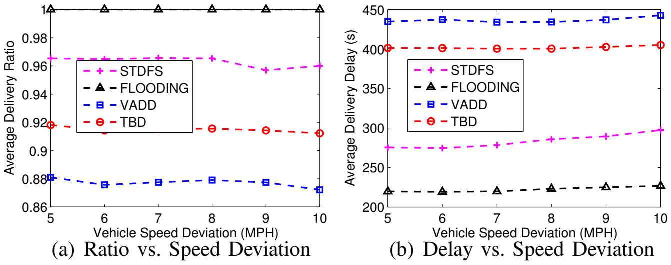
V. PERFORMANCE EVALUATION

This section evaluates the performance of STDFS. In the simulation, we use a road network with 36 intersections (6.75km×6km), and one fixed target point is located in the center. By default, 100 vehicles move in the network, and their movement pattern is determined by a Manhattan Mobility model [14]. The vehicle speed follows the normal distribution of $N(\mu_v, \sigma_v)$ where $\mu_v = 40$ MPH and the default $\sigma_v = 7$ MPH, and a vehicle can change its speed at each road section. The communication range is 200 m. During the simulation, packets are dynamically generated from randomly selected vehicles. We set the TTL to 1000 s and the EDR bound R to 0.9.

Since there are no other protocols based on unicasting for V2V communications over multi-hops, we focus on the data forwarding from vehicles to a fixed point, evaluating STDFS by comparing it with VADD, TBD and flooding. Note that for flooding, we assume there is no transmission conflict and vehicles have infinite buffer to store packets. Due to space limit, here we only investigate the effectiveness of STDFS under different speed deviations and vehicular densities.

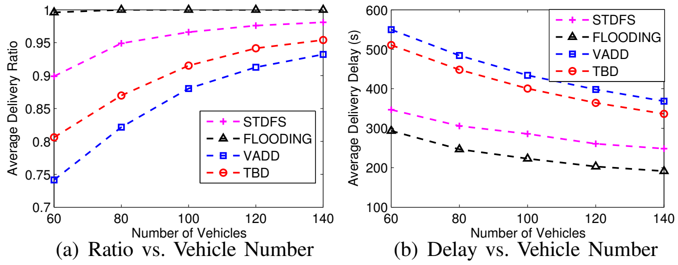
A. Impact of Vehicle Speed Deviation σ_v

As STDFS is based on the encounter prediction, the accuracy of prediction will affect its performance. Intuitively, traffic mainly affects the traveling time, making the encounters probabilistic. For simplicity, we use vehicle speed deviation to reflect the traffic condition. As shown in Figure 3, for STDFS, with greater speed deviation, the packet delivery ratio has a slight decrease, but the average delay obviously increases. This is because when the vehicle speed deviation becomes larger, the predicted encounter probabilities between vehicles generally decrease. Therefore, to meet the requested EDR bound R, packets may have to be forwarded through paths having longer delays. Comparatively, other protocols are slightly affected by speed deviation. However, even when the speed deviation is as large as 10 MPH, STDFS still outperforms VADD and TBD



(a) Ratio vs. Speed Deviation (b) Delay vs. Speed Deviation

Fig. 3. Impact of Vehicle Speed Deviation



(a) Ratio vs. Vehicle Number (b) Delay vs. Vehicle Number

Fig. 4. Impact of Vehicle Number

significantly in terms of both delivery ratio and delay, and is closer to the performance of flooding. As expected, flooding achieves the maximal delivery ratio and minimal delay in the network with the assumptions of infinite buffer and collision-free transmission, but it is hard to work in real life because these assumptions are not reasonable due to hardware and cost issues. The simulation 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.

B. *Impact of Vehicular Density*

We investigate the effectiveness of STDFS under different vehicular densities by increasing the vehicle number from 60 to 140. As shown in Figure 4, with different densities STDFS always performs better than VADD and TBD. Especially when the vehicle density is low, STDFS 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 trajectory information provides more detailed knowledge than macroscopic statistics, STDFS could forward packets through better paths, and it is more suitable for data forwarding when vehicular networks become sparse. We also find that, 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.

VI. CONCLUSION

It is widely believed that vehicular networks can bring great benefit on driving safety and many practical applications. As a key function for the communications between vehicles, data forwarding in vehicular networks is still a challenging problem. In this paper, we adopt microscopic information about vehicular trajectories and propose a Shared-Trajectory-based Data Forwarding Scheme (STDFS) for multi-hop communications between vehicles in VANETs. Different from TBD and TSF which use only vehicles' own trajectories, STDFS utilizes the shared trajectory information in a participatory manner, which can overcome the uncertainty of statistics and make the forwarding more accurate. STDFS predicts the encountering events between vehicles and constructs a predicted encounter graph. With the dynamic expansion of encounter graph, STDFS optimizes the forwarding sequences in terms of delivery ratio and delivery delay, and gets the corresponding forwarding metrics, which guides data forwarding by allowing vehicles to always forward packets to the best forwarder in communication range. Simulation results demonstrate the effectiveness of STDFS.

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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