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TPD: Travel Prediction-based Data Forwarding for light-traffic vehicular networks

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ABSTRACT

This paper proposes *T*ravel *P*rediction-based *D*ata forwarding (TPD), tailored and optimized for multihop vehicle-to-vehicle communications. The previous schemes forward data packets mostly utilizing statistical information about road network traffic, which becomes much less accurate when vehicles travel in a light-traffic vehicular network. In this light-traffic vehicular network, highly dynamic vehicle mobility can introduce a large variance for the traffic statistics used in the data forwarding process. However, with the popularity of GPS navigation systems, vehicle trajectories become available and can be utilized to significantly reduce this uncertainty in the road traffic statistics. Our TPD takes advantage of these vehicle trajectories for a better data forwarding in light-traffic vehicular networks. Our idea is that with the trajectory information of vehicles in a target road network, a vehicle encounter graph is constructed to predict vehicle encounter events (i.e., timing for two vehicles to exchange data packets in communication range). With this encounter graph, TPD optimizes data forwarding process for minimal data delivery delay under a specific delivery ratio threshold. Through extensive simulations, we demonstrate that our TPD significantly outperforms existing legacy schemes in a variety of road network settings.

1. Introduction

Vehicular Ad Hoc Networks (VANETs) have emerged as one of key components in Cyber-Physical Systems for Intelligent Transportation Systems (ITS) [1–5]. This VANET can support the prompt delivery of warning messages for vehicle collision avoidance, in-time dissemination of emergency information (e.g., accidents and driving hazards), real-time traffic estimation for trip planning, and mobile Internet access. Especially, for the driving safety (e.g., warning message delivery), the VANET is more prompt and reliable than the cellular networks (e.g., 3G and 4G-LTE) needing the data relay via base stations. When the base stations in the cellular networks are congested or malfunctioning, the data delivery among mobile nodes might not be prompt enough to prevent the vehicles from colliding with each other. In VANET, this additional delay due to the base station in the cellular networks does not exist because the vehicles can communicate directly with each other without any intervention of

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base stations. Also, to cover the road networks with cellular networks while servicing the data and voice traffic generated by cellular phones and smartphones, the cost required by service providers in the cellular networks will be significantly expensive. For the special purposes (e.g., driving safety and efficiency) in road networks, the vehicular networks can be managed cost-effectively as separate networks considering the characteristics of road networks.

In this paper, we focus on the multihop data forwarding problem in VANET. In dynamic and mobile vehicular networks, many data forwarding schemes [2,6–8] adopt the carry-and-forward approach, based on Dedicated Short-Range Communications (DSRC) [9,10]. The existing protocols [2,6] utilize macroscopic information about road network traffic (e.g., traffic density and average speed per road segment) 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 multihop data forwarding in a light-traffic vehicular network. A few recent protocols, such as Trajectory-Based Data Forwarding (TBD) [7] and Trajectory-Based Statistical Forwarding (TSF) [8], have demonstrated promising performance results by combining the physical trajectory information (i.e., future moving path) of a vehicle and the vehicular traffic statistics (i.e., vehicle arrival rate and average speed) in the rest of a network. TBD [7] supports the multihop Vehicle-to-Infrastructure (V2I) data delivery to a fixed packet destination node, such as Access Point (AP), and TSF [8] supports the multihop Infrastructure-to-Vehicle (I2V) data delivery to a moving packet destination node, such as vehicle. Although this literature including TBD and TSF is encouraging till now, we found that there is still room to improve significantly with less infrastructure cost (i.e., without relay nodes required by TSF). The major issue about the previous work such as TBD and TSF is that the trajectory information available in the network is not fully utilized for data forwarding. In other words, individual vehicles only know their own trajectory and do not share it with other vehicles for data forwarding through a trustable entity, such as Traffic Control Center (TCC) [8,11], which is a constraining factor leading to low performance. Therefore, the challenging question addressed in this work is how we can push up the performance limits of legacy schemes (e.g., TBD and TSF) by fully 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) communications over multihop in light-traffic vehicular networks. Of course, TPD can support multihop I2V communications like our earlier work of TSF [8]. TPD is built upon the concept of participatory services in which users of a service (e.g., data forwarding service) share their travel path (i.e., trajectory) through TCC in order to establish the service. The privacy-sensitive users can opt out, while participatory users can exchange their trajectories for convenience and performance.

The main idea of TPD is to utilize shared trajectory information to predict pairwise encounters and then construct an encounter graph to support End-to-End (E2E) data forwarding. Based on this encounter graph, TPD computes an optimal forwarding sequence to achieve the minimal delivery delay given a specific delivery ratio threshold. TPD performs source-routing-based data forwarding with the optimal forwarding sequence. 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 legacy scheme [14]. Specifically, our intellectual contributions are as follows:

- A vehicular network design of unicast data forwarding based on shared trajectory information without infrastructure nodes, such as relay nodes [8],
- A predicted encounter graph construction algorithm to compute the encounters for packet forwarding through optimal forwarding sequences, and
- A source-routing-based data forwarding protocol with a predicted encounter graph for V2V, V2I or I2V data forwarding.

The rest of the paper is organized as follows: First of all, we summarize related work in Section 2. Section 3 describes problem formulation in our TPD data forwarding. Section 4 explains both encounter prediction probability and predicted encounter graph to compute the forwarding metrics used for the decision-making in data forwarding process. Section 5 explains our TPD design and protocol. Section 6 evaluates our TPD design. Section 7 discusses practical issues in our TPD. We finally conclude this paper along with future work in Section 8.

2. Related work

In Vehicular Ad Hoc Networks (VANET), the data forwarding is a key function for the communications between vehicles (i.e., V2V) or between vehicle and infrastructure (i.e., V2I or I2V) [2–5,12,13]. It can take advantage of the following two types of information: (i) *Macroscopic information* about road network traffic statistics (e.g., traffic density and average speed per road segment) and (ii) *Microscopic information* about individual vehicle (e.g., vehicle trajectory). This information makes it possible to design new data forwarding schemes.

In this paper, we classify data delivery over VANET into (i) *micro-scoped data delivery* and (ii) *macro-scoped data delivery*. *First*, *micro-scoped data delivery* is defined as the data delivery over VANET consisting of vehicles interconnected by DSRC communication range in a road segment. The micro-scoped data delivery aims at the efficient data forwarding in either a single road segment or adjacent road segments rather than a target road network. In this micro-scoped data delivery, a source vehicles sets up a route toward its destination vehicle in a connection-oriented way through either route discovery as a reactive approach or routing information exchange as a proactive approach.

Second, *macro-scoped data delivery* is defined as the data delivery over vehicular networks on a target road network from a source vehicle (or AP) to a destination vehicle over the multihop carry-and-forward in terms of multiple intersections. The macro-scoped data delivery aims at the data forwarding in a target road network, that is, from a source vehicle (or AP) in an intersection to a destination vehicle at another intersection that is multihop away from the source vehicle in terms of intersections. In this macro-scoped data delivery, vehicles carry data packets until they encounter an appropriate next packet carrier vehicle. Whenever the current packet carrier vehicle encounters an appropriate next packet carrier vehicle, it keeps the packet copy or discards the packet copy according to the policy of data delivery schemes. Many macro-scoped data delivery schemes [2,3,6–8,14,15] are proposed for VANET as intermittently connected networks. Our TPD is the V2V or I2V data forwarding scheme for the macro-scoped data delivery in a unicast fashion rather than in a controlled-broadcast fashion, such as Epidemic Routing [16].

For the micro-scoped data delivery, many data forwarding schemes [17–21] are proposed for the efficient data forwarding in either a single road segment or adjacent road segments. They take advantage of the mobility information of destination vehicles via GPS-based navigation systems. TTBR (Two level Trajectory Based Routing) [17] uses two-level trajectories, such as (i) a high-level cell-based trajectory and (ii) a local trajectory. TTBR divides the target road network into grid cells as data forwarding units. For the network scalability, TTBR at first forms a high-level cell-based trajectory consisting of contiguous cells toward the destination cell where the packet will encounter the destination node in the road network. After this, TTBR constructs a local trajectory consisting of road segments and intersections that construct a forwarding path toward the destination node. To construct a high-level cell-based trajectory, TTBR performs trajectory discovery whenever either source node or destination node goes out of its current cell. Along with this expensive trajectory discovery, TTBR is not feasible in light-traffic vehicular networks that is the target setting in this paper because it is hard to let the packet be forwarded by intermediate vehicles over the intended forwarding path consisting of the high-level cell-based trajectory and local trajectory.

eSIFT (enhanced Simple Forwarding over Trajectory) [18] is an efficient, opportunistic trajectory-based routing protocol that has no discovery step. eSIFT constructs a geographical forwarding trajectory defined by road segments from source node to destination node. A packet sent the by source node is forwarded to a next-hop vehicle near the forwarding trajectory toward the destination node in the way of source routing. The selection of the next-hop vehicle is performed opportunistically by letting the neighboring vehicles for the current packet carrier vehicle run a random-length timer for the next-hop carrier. A neighboring vehicle with the shortest timer is selected as the next-hop carrier and other neighboring vehicles can know the newly selected vehicle by overhearing the packet forwarding activity by the newly selected vehicle. However, this packet forwarding based on the forwarding trajectory will be ineffective in light-traffic vehicular networks that are the target in this paper. This is because the continuous forwarding along the geographical forwarding trajectory is infeasible in the light-traffic vehicular networks.

Wisitpongphan et al. [19] show routing issues in sparse vehicular ad hoc networks. Through empirical vehicle traffic measurement, they develop a comprehensive analytical framework for disconnected vehicular ad hoc networks by investigating the disconnected network phenomenon and network characteristics in VANET. With such network characteristics, they estimate the *average forwarding time* (called *re-healing time*) taken to propagate a packet to disconnected vehicles. Thus, their developed analytical framework provides a prediction method for the estimation of VANET routing performance rather than a new VANET routing protocol.

ROMSGP (Receive On Most Stable Group-Path) [20] is a VANET routing protocol that is robust to frequent path disruptions caused by high vehicles' mobility. To construct a robust packet forwarding path, ROMSGP utilizes vehicles' movement information, such as the position, direction, and speed of each vehicle along with digital road maps. Vehicles are grouped according to their velocity vectors to form a stable multihop path in VANET. Since ROMSGP works in the connection-oriented way along with route discovery, it is not suitable for the packet forwarding in light-traffic vehicular networks.

GSR (Geographic Source Routing) [21] is a position-based routing in city environments through GPS-based navigation systems. A source vehicle obtains the current position of its destination vehicle through a Reactive Location Service (RLS), which is a kind of route discovery. It then forwards its packet toward the destination vehicle by the greedy position-based routing such that the packet is forwarded to a direct neighboring vehicle closest to the destination vehicle's position. However, GSR is not suitable for the packet forwarding in light-traffic vehicular networks. This is because the RLS's route discovery for the destination vehicle does not work well due to the low vehicular density.

For the macro-scoped data delivery, many data forwarding schemes [2,3,6] have been recently developed. They are designed for multihop V2I communications. VADD (Vehicle-Assisted Data Delivery) [2] investigates the data forwarding using a stochastic model based on vehicle traffic statistics. The objective is to achieve the *lowest delivery delay* from a mobile vehicle to a stationary destination. Delay-Bounded Routing [3] has the objective to satisfy the *user-defined delay bound*. Also, this scheme pursues the minimization of the channel utilization. SADV (Static-node-assisted Adaptive data Dissemination protocol for Vehicular networks) [6] 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, TBD (Trajectory-Based Data forwarding) [7] proposes a more efficient data forwarding for V2I communications than VADD. TBD can compute forwarding metric (i.e., E2E Expected Delivery Delay) with both vehicular traffic statistics and vehicle trajectory information to further improve communication delay and delivery probability. For the data delivery from fixed nodes to moving vehicles (i.e., I2V), TSF (Trajectory-based Statistical Forwarding) [8] is proposed.

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 additionally infrastructure nodes (called relay nodes) at intersections in road networks that temporarily hold packets in the forwarding path toward the packet destination.

TBR [14] supports multihop I2V data delivery based vehicle trajectories without infrastructure nodes, such as relay nodes [8]. TBR uses vehicle trajectories to compute vehicle encounters in the road network and select next packet carriers in the data forwarding process. The major difference between TPD and TBR is that TBR does not consider encounter probability between two encountering vehicles in the next data forwarding. Also, TBR does not consider E2E Expected Delivery Ratio (EDR) to construct forwarding paths from a packet source to a packet destination. On the other hand, TPD considers both encounter probability and EDR. Thus, TPD can support more reliable data forwarding than TBR.

TaDB [15] investigates multihop I2V data delivery without infrastructure nodes, such as relay nodes unlike TSF [8]. A service request node sends its request message including the future trajectory of the request node to an AP that will process the request message. The AP will send back the reply message to the request node by predicting the rendezvous points of the reply message and the request node with the trajectory encoded in the request message. For the packet delivery, a delay-constrained minimum transmission-cost multicast tree is constructed with these rendezvous points. However, in light-traffic vehicular networks, it is hard to forward the packet and its packet copies over the multicast tree due to the frequent wireless link breakage among vehicles by low vehicular density and high-speed vehicle mobility. Also, the objective of TaDB is to minimize the transmission cost rather than the E2E delivery delay. This is different from the objective of TPD that is to minimize the E2E delivery delay, while guaranteeing the required delivery ratio.

Epidemic Routing [16] is proposed to deliver messages to a moving destination node in partially-connected ad hoc networks, such as Mobile Ad Hoc Networks (MANET). This Epidemic Routing does not assume the position or trajectory of the destination node as well as the network topology. A message source node delivers its message to an encountered node. As a packet carrier, this encountered node will carry the message in order to deliver it to the destination node in a probabilistic fashion. That is, the packet carrier will deliver the copy of the packet to another encountered node. In this way, the copies of the packet will be disseminated toward the destination node with a high probability. To prevent the flooding of the message packet, Epidemic Routing specifies the *packet hop count* and *carry buffer size* to limit the number of the packet copies for the controlled broadcast. This Epidemic Routing can be used for the E2E data delivery in VANET, but the data delivery cost will increase according to the allowed *packet hop count* and *carry buffer size*. Also, the redundant packet copies will be in transit even though one of the packet copies has already been received by the packet destination.

Unlike the data forwarding scheme mentioned so far, our TPD can efficiently support the multihop I2V or V2V data forwarding in light-traffic vehicular networks in a unicast fashion. TPD investigates the in-depth usage of shared trajectory information for the efficient data delivery. Note that TPD is totally different from TBD in the forwarding design such that in TPD, TCC utilizes the trajectories of other vehicles in a road network in the charge of it in order to compute an optimal forwarding sequence for a packet from a packet source to a packet destination. On the other hand, in TBD, each vehicle uses only its own trajectory with vehicular traffic statistics to compute its forwarding metric. That is, each vehicle individually limits its own trajectory information to itself without sharing its detailed trajectory information with other vehicles. TPD is also different from TSF because TPD does not require relay nodes that are infrastructure nodes needed by TSF for the reliable data forwarding. Therefore, TPD can efficiently support the I2V and V2V data delivery at a low cost.

3. Problem formulation

In this section, we formulate our data forwarding based on vehicle travel path (called *vehicle trajectory*) in light-traffic vehicular networks. Given a target road network with the vehicle trajectories, our goal is to select intermediate vehicles as packet forwarders to satisfy the user-required Expected Delivery Ratio (EDR) threshold from a packet source to a packet destination. First, we describe a system architecture for vehicular networks. Second, we articulate assumptions for TPD data forwarding. Finally, we suggest a viable service model for TPD.

3.1. Vehicular network architecture

In this section, we describe a vehicular network architecture to support our TPD data forwarding in road networks. Our vehicular network architecture consists of (i) Traffic Control Center (TCC), (ii) Access Points (APs), and (iii) Vehicles:

- *Traffic Control Center (TCC)*: TCC [11] is a road traffic management node that maintains the trajectories and locations of vehicles for the location management as used in Mobile IPv6 [22]. TCC has up-to-date vehicular traffic statistics, such as vehicle arrival rate and average speed per road segment in the road network under its management. As shown in Fig. 1, Access Points (APs) are connected to TCC so that they can collect the vehicle trajectories of the vehicles participating in TPD data forwarding service.
- *Access Point (AP)*: AP is a gateway to connect wireless vehicular ad hoc network to the wired network (e.g., the Internet). AP has DSRC communication device to communicate with vehicles with DSRC communication device [9,10]. APs are sparsely deployed at the entrances and roadsides in a target road network, as shown in Fig. 1. They are connected to each other through wired networks (e.g., the Internet). They play a role of a backbone network for the target road network to perform multihop data forwarding. With the recent development in ITS, it has been practical to install Road-Side Units (RSUs) at intersections, which communicate with On-Board Units (OBUs) carried on vehicles for the safety and efficiency in the driving [10,23]. We propose that such RSUs can be used as APs, which can collect the trajectory and current

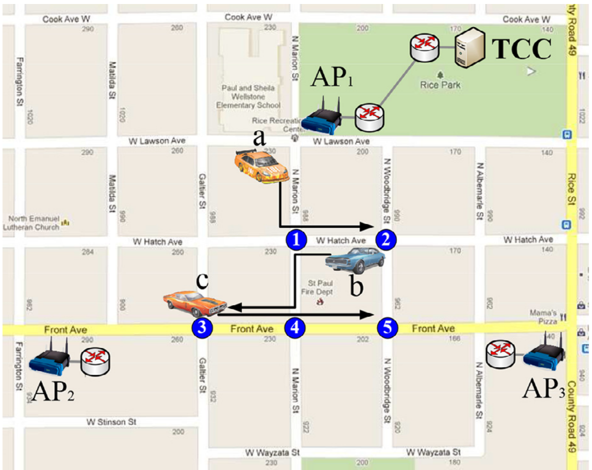


Fig. 1. TPD data forwarding in target road network.

location information from vehicles. These APs can also be used for the data forwarding as backbone network nodes, as discussed in Section 7.1. With the trajectories shared by the vehicles through the TCC, TPD lets a vehicle be able to send (or receive) packets to an AP (from an AP) over multihop. Thus, TPD can reduce this data delivery (or retrieval) delay by using intermediate vehicles as mobile relay nodes along with APs.

- *Vehicle*: Vehicle is equipped with DSRC communication device [9,10] to communicate with other vehicles or APs. Vehicle is also equipped with GPS-based navigation systems and digital road maps. Traffic statistics, such as the mean and variance of the travel time for each road segment, are available via a commercial navigation service [24].

3.2. Assumptions

In this section, we list up the following assumptions for designing an effective data forwarding scheme in light-traffic vehicular networks:

- 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 in data forwarding service. Popular crowd-source traffic and navigation applications such as Waze [25], TomTom Crowdsourcing [26] and iCartel [27] have attracted millions of voluntary users and support the feature of trajectory sharing among application users through TCC as a trustable entity. Further, we assume such shared trajectory information can be inaccurate and a small percentage of trajectories (e.g., less than 20%) are subject to change after sharing. We show the impact of trajectory change on the performance in Section 6.5.
- The V2V communication supported by TPD operates in a participatory manner. A vehicle is allowed to use the V2V communication service, only when this vehicle shares its trajectory information through a trustable TCC. Packets are forwarded only among participating vehicles as intermediate packet carriers. Thus, we assume that the participating vehicles are willing to forward the other vehicle's packet toward the packet destination.

3.3. Service model

Now, we propose a service model based on TPD data forwarding. One target service model is the customized notification delivery service for individual vehicles with their vehicle trajectory in the following two notification delivery services: (i) I2V notification delivery and (ii) V2V notification delivery.

First, for the I2V notification delivery, TCC can provide vehicles with relevant road conditions or accident information along their trajectory. That is, with individual vehicle trajectory, TCC can deliver each vehicle with customized driving information relevant to its trajectory.

Second, for the V2V notification delivery, a police car can report some accident to vehicles that will pass through this accident road spot (i) directly if it knows the vehicles approaching this spot or (ii) indirectly if it sends its report to TCC that is aware of the mobility of vehicles so that TCC can disseminate the report to the relevant vehicles by the I2V notification delivery. In the next section, for the data delivery based on vehicle trajectory, we will introduce the concept of encounter prediction and explain the predicted encounter graph construction to compute encounter probability between vehicles.

4. Encounter prediction and predicted encounter graph construction

Our data forwarding is based on vehicular encounter prediction with the trajectories of all of vehicles within a target road network. 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 from the vehicle trajectories, we schedule message transmissions so that a message can go from the source vehicle to the destination vehicle hop by hop, based on our encounter prediction for vehicles encountering in opposite directions. Fig. 1 shows an example of our idea. Vehicle V_a is predicted to encounter vehicle V_b on road segment $L_{1,2}$ (between intersections n_1 and n_2) and vehicle V_b is predicted to encounter vehicle V_c on road segment $L_{3,4}$. Packets from V_a can be forwarded to V_c through the following *encountered vehicle path*: $V_a \to V_b \to V_c$. Thus, through the encounter process of pairs of vehicles, the packet from the source vehicle V_a can be forwarded to the destination vehicle V_c.

We have two research challenges for the data forwarding above. *The first challenge* is how to predict the encounters for the given vehicle trajectories. *The second challenge* is how to perform the data forwarding with the predicted encounters for the minimum delivery delay under a given delivery ratio. In the following sections, we will propose our design to address these two challenges. For the first challenge, we will explain how to calculate the encounter probability between vehicles, and then, for the second challenge, we will describe how to construct a predicted encounter graph based on probabilistic encounter events.

4.1. Travel time prediction

4.1.1. Travel time through road segment

Researchers on transportation have demonstrated that the travel time of one vehicle over a fixed distance in light-traffic vehicular networks follows the Gamma distribution [8,28]. Therefore, the travel time through a road segment i in the road network (called *link travel delay*) is modeled as: $d_i \sim \Gamma(\kappa_i, \theta_i)$ where κ_i is a shape parameter and θ_i is a scale parameter; note that $d_i \sim \Gamma(\alpha_i, \beta_i)$ where $\alpha(=\kappa_i)$ is a shape parameter and $\beta(=1/\theta_i)$ is an inverse scale parameter [29]. d_i denotes the link travel delay for road segment i. To calculate the parameters κ_i and θ_i, we use the mean μ_i and the variance σ_i^2 of the link travel delay [29]. Note that the traffic statistics of μ_i and σ_i^2 can be provided by a commercial navigation service provider (e.g., Garmin [24]).

Let the mean of d_i be $E[d_i] = \mu_i$ and the variance of d_i be $Var[d_i] = \sigma_i^2$, the formulas for κ_i and θ_i are as follows:

$$\theta_i = \frac{Var[d_i]}{E[d_i]} = \frac{\sigma_i^2}{\mu_i}, \quad (1)$$

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

Note that if we have a more accurate link travel delay distribution from either mathematical model or empirical measurement, we can use it for the travel time through a road segment.

4.1.2. Travel time on end-to-end path

Here we model E2E travel delay from one position to another position in a given road network. As discussed above, the link travel delay is modeled as the Gamma distribution of $d_i \sim \Gamma(\kappa_i, \theta_i)$ for road segment i. Given a specific traveling path, we assume the link travel delays of different road segments for the path are independent. Under this assumption, we approximate the mean (or variance) of the E2E travel delay as the sum of the means (or variances) of the link travel delays for the links along the E2E path. Note that in our target setting of light-traffic vehicular networks, a small number of vehicles are moving on road segments, and so the travel times on road segments can be assumed to be independent of each other. Assuming that the traveling path consists of N road segments, the mean and variance of the E2E travel delay D are computed as follows:

$$E[D] = \sum_{i=1}^{N} E[d_i] = \sum_{i=1}^{N} \mu_i, \quad (3)$$

$$Var[D] = \sum_{i=1}^{N} Var[d_i] = \sum_{i=1}^{N} \sigma_i^2. \quad (4)$$

With (3) and (4), the E2E travel delay D is approximately modeled as a Gamma distribution as follows: $D \sim \Gamma(\kappa_D, \theta_D)$ where κ_D and θ_D are calculated using $E[D]$ and $Var[D]$ using the formulas of (1) and (2). It is noted that our travel time prediction can accommodate any better E2E path delay distribution if it is available from either mathematical model or empirical measurement.

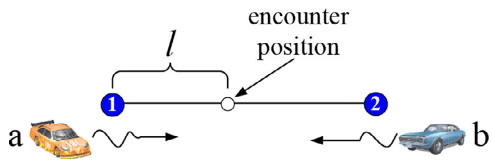


Fig. 2. Two vehicles a and b encountering on road segment $L_{1,2}$.

Let us discuss the relationship between the arrival time (denoted as T_{ak}) of vehicle V_a at a target intersection n_k and the E2E travel delay (denoted as $D_{aj,k}$) from V_a's current position n_j to the target intersection n_k. Let T^* be the current time. Let $T_{aj,k}$ be the arrival time at n_k for vehicle V_a's E2E travel from the current position n_j to the target intersection n_k. The arrival time $T_{aj,k}$ can be modeled as a Gamma distribution with Eqs. (3) and (4) such that $T_{aj,k} = D_{aj,k} + T^*$. This is because $T_{aj,k}$ is a linear combination of a Gamma random variable $D_{aj,k}$ and a constant value T^*. For simplicity, we denote $T_{aj,k}$ as T_{ak}, assuming that the vehicle V_a's current position is implicitly known by the GPS navigation systems. In the next section, we will explain encounter event prediction with arrival time random variable T_{ak} discussed in this section.

4.2. Encounter event prediction

4.2.1. Encounter probability on road segment

Based on the travel time prediction, the encounter event between two vehicles on a road segment can be predicted as follows. In Fig. 2, suppose that the trajectories of vehicles V_a and V_b overlap on road segment $L_{1,2}$ such that intersections n_1 and n_2 are endpoints. V_a will travel through $L_{1,2}$ from n_1 to n_2, while V_b will travel through road segment $L_{2,1}$ from n_2 to n_1. Assuming the initial time as 0, let T_{a1} and T_{a2} be the positive time instants 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 segment is computed as follows:

$$P(V_a \otimes_{1,2} V_b) = P(T_{a1} \le T_{b1} \cap T_{a2} \ge T_{b2}), \quad (5)$$

where "$\otimes_{1,2}$" means "encountering on road segment $L_{1,2}$".

As discussed above, T_{a1}, T_{b1}, T_{a2}, and T_{b2} are random variables following the Gamma distribution. Clearly, T_{a1} and T_{a2} are not independent, and T_{b1} and T_{b2} are not independent, either. This is because T_{a2} (or T_{b1}) is determined by T_{a1} (or T_{b2}) and the travel delay on $L_{1,2}$ (or $L_{2,1}$). Let $d_{1,2}$ be the link travel delay for $L_{1,2}$ and $d_{2,1}$ be the link travel delay for $L_{2,1}$. Now we have the following relationship between the link arrival time T_{a1} (or T_{b2}) and the link departure time T_{a2} (or T_{b1}) for road segment $L_{1,2}$ (or $L_{2,1}$):

$$T_{a2} = T_{a1} + d_{1,2}, \quad (6)$$

$$T_{b1} = T_{b2} + d_{2,1}. \quad (7)$$

With a Gamma distribution of link travel delay, we approximate the departure time from each road segment as follows:

$$T_{a2} = T_{a1} + t_{1,2}, \quad (8)$$

$$T_{b1} = T_{b2} + t_{2,1}, \quad (9)$$

where $t_{1,2} = E[d_{1,2}]$ and $t_{2,1} = E[d_{2,1}]$. Note that in our TPD model, the *link departure time* from n_2 for $L_{1,2}$ (or n_1 for $L_{2,1}$) is estimated by the *link arrival time* at n_1 for $L_{1,2}$ (or n_2 for $L_{2,1}$) plus the *average link travel time* $E[d_{1,2}]$ (or $E[d_{2,1}]$) of a Gamma distribution, as discussed in Section 4.1.1. Replace T_{a2} and T_{b2} in (5) by (8) and (9), we get:

$$P(V_a \otimes_{1,2} V_b) = P(T_{a1} \le T_{b1} \le T_{a1} + t_{1,2} + t_{2,1}). \quad (10)$$

Let $f(x)$ and $g(y)$ represent the probability density function (PDF) of Gamma random variables x and y for T_{a1} and T_{b1}, respectively [29]; note that a link travel delay can be modeled as a Gamma random variable, as discussed in Section 4.1.1. Because T_{a1} and T_{b1} are regarded as independent, we have:

$$P(V_a \otimes_{1,2} V_b) = \int_0^\infty \int_x^{x+t_{1,2}+t_{2,1}} f(x)g(y)dydx. \quad (11)$$

So far we have discussed how to calculate the encounter probability in one road segment. If the trajectories of two vehicles overlap for by more than one road segment, which means more than one encounter, we can calculate the overall encounter probability by the sum of encounter probabilities for the individual overlaps on the road segments by the superposition. This is because of our assumption that the trajectories of two vehicles are independent. However, for simplicity, the case of disjoint overlaps where two vehicles meet and diverge more than once is computed as if two vehicles can meet one time. This is because these disjoint overlaps happen rarely in reality.

4.2.2. Encounter probability at intersection

Based on the travel time prediction, the encounter event between two vehicles at an intersection can be predicted as follows. A packet carrier vehicle (called carrier) V_a can forward its packets to another vehicle V_b as a next carrier at an intersection along its travel path (called trajectory). We suppose that vehicles V_a and V_b can communicate with each other in communication range at an intersection. As shown in Fig. 3(a) and (b), those will communicate with each other at an intersection in each case. The probability of each case can be calculated in the similar way with the encounter probability on a road segment in Section 4.2.1. In Fig. 3(a), V_a will travel through a road segment $L_{i,5}$ from intersection n_i to intersection n_5 for $i = 1, \ldots, 4$ and V_b will travel through a road segment $L_{j,5}$ from intersection n_j to intersection n_5 for $j = 1, \ldots, 4$ where $i \neq j$. Let $T_{ai,5}$ be the arrival time at n_5 when V_a moves through $L_{i,5}$ and $T_{bj,5}$ be the arrival time at n_5 when V_b moves through $L_{j,5}$. Let S_a be the expected speed of vehicle V_a and S_b be the expected speed of vehicle V_b.

For case 1 in Fig. 3(a), assume that the current carrier V_a and the next carrier V_b move toward n_5 and V_a arrives at n_5 earlier than V_b. The probability that V_a and V_b will communicate with each other at n_5 is computed as follows:

$$\mathrm{P}(V_a \otimes_5 V_b) = \mathrm{P}(T_{bj,5} \ge T_{ai,5} \cap (T_{bj,5} - T_{ai,5})S_b \le R), \quad (12)$$

where "$\otimes_5$" means "encountering at intersection n_5" and R is the communication range.

$$T_{ai,5} = T_{ai} + t_{i,5}. \quad (13)$$

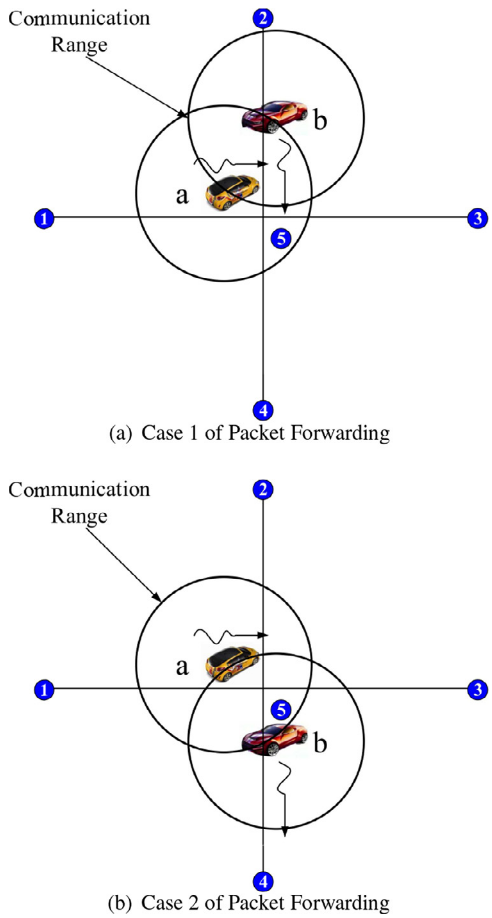


Fig. 3. Cases of packet forwarding at intersection.

Applying $T_{ai,5}$ in (13) to (12), the following equation is obtained:

$$\mathrm{P}(V_a \otimes_5 V_b) = P\left(T_{ai} + t_{i,5} \le T_{bj,5} \le T_{ai} + t_{i,5} + \frac{R}{S_b}\right). \quad (14)$$

For case 2 in Fig. 3(b), assume that the current carrier V_a and the next carrier V_b move toward n_5 and V_b arrives at n_5 earlier than V_a. The probability that V_a and V_b will communicate with each other at n_5 is computed as follows:

$$\mathrm{P}(V_a \otimes_5 V_b) = \mathrm{P}(T_{ai,5} \ge T_{bj,5} \cap (T_{ai,5} - T_{bj,5})S_b \le R). \quad (15)$$

Applying $T_{ai,5}$ in (13) to (15), the following equation is obtained:

$$\mathrm{P}(V_a \otimes_5 V_b) = P\left(T_{ai} + t_{i,5} - \frac{R}{S_b} \le T_{bj,5} \le T_{ai} + t_{i,5}\right). \quad (16)$$

To compute the probability of these two cases, the link travel delay of a Gamma random variable can be used in the similar with (11) as follows:

Case 1: In the case where the current carrier V_a arrives at the encountering intersection n_5 earlier than the next carrier V_b, the encounter probability is:

$$P(V_a \otimes_5 V_b) = \int_0^\infty \int_{x+t_{i,5}}^{x+t_{i,5}+\frac{R}{S_b}} f(x)g(y)dydx. \quad (17)$$

Case 2: In the case where the next carrier V_b arrives at the encountering intersection n_5 earlier than the current carrier V_a, the encounter probability is:

$$P(V_a \otimes_5 V_b) = \int_0^{\infty} \int_{x+t_{i,5}-\frac{R}{S_b}}^{x+t_{i,5}} f(x)g(y)dydx. \quad (18)$$

Finally, the encounter probability based on (17) and (18) is computed as follows:

$$P(V_a \otimes_5 V_b) = \int_0^{\infty} \int_{x+t_{i,5}-\frac{R}{S_b}}^{x+t_{i,5}+\frac{R}{S_b}} f(x)g(y)dydx. \quad (19)$$

4.3. Predicted encounter graph construction

To forward packets from a packet source vehicle to a packet destination using intermediate vehicles, we develop a graph model to predict the encounter sequence of vehicles that can be packet carriers. This graph model is called *predicted encounter graph*, based on probabilistic encounters defined by encounter probability in Section 4.2. To construct a predicted encounter graph, we need to compute the encounter sequence of intermediate vehicles (as packet carrier candidates), encountering each other with a certain level of encounter probability in a target road network.

First, we formally define a *predicted encounter graph* as a directed graph $G = (V, E)$ where V is the set of nodes (i.e., vehicles or packet destination) and E is the set of directed edges whose tail node is the packet carrier and whose head node is the next-hop vehicle for the tail node. This predicted encounter graph G originates from a packet source vehicle that intends to forward packets, and ends at the packet destination, which could be a moving vehicle or a static point on 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 node e, its child nodes are the vehicles it might encounter later after encountering its parent vehicle. These child nodes are sorted in the sequence of their expected encounter time instants with node e. That is, if the expectations of the encounter time between node e and its n child nodes satisfy $t_1 \le t_2 \le \ldots \le t_n$, these child nodes are sorted in the sequence $C_{t_1}, C_{t_2}, \ldots, C_{t_n}$, where C_{t_i} ($i \in [1, n]$) is the child whose expected encounter time with node e is t_i.

Next, we explain the construction procedure of a *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 node e into graph G, the child nodes of e as possible encounter events are subsequently inserted into G. We use a minimum priority queue Q to implement this node insertion where the key in Q is the expected encounter time of two vehicles. Also, a bitmap B is used to mark whether a vehicle is already visited in the graph G. Let $B[i]$ be the bitmap element for vehicle V_i. Initially, all the bitmap elements are initialized with 0, indicating that each vehicle is not used as a packet carrier yet. If vehicle V_i is visited and added to the graph G, the corresponding bitmap element $B[i]$ is set to 1, indicating that the vehicle V_i is used as a packet carrier. The algorithm is represented as follows:

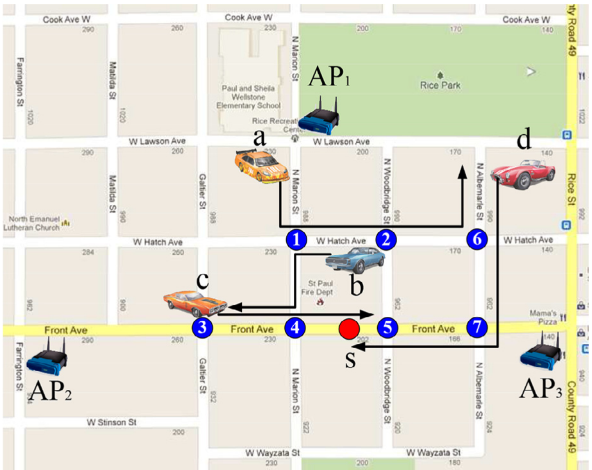


Fig. 4. Traveling vehicles for data forwarding in road network.

1. Insert packet source vehicle as root node into Q.
2. Take out the first node (denoted as node e) from Q.
3. Search for node e's child nodes *not visited yet* with a user-defined encounter probability threshold (e.g., 60%), using the trajectory information. That is, predict the possible encounters with other vehicles during its following travel and determine the child nodes likely to encounter e.
4. Insert the child nodes into Q such that the expected encounter time is earlier than Time-To-Live (TTL) that is the packet's lifetime. Note that all the nodes in the minimum priority queue Q are sorted in the nondecreasing order of the expected encounter time with their own parents.
5. If node e is the root node, it is the first node in the graph; otherwise, add node e into the graph by inserting it into its parent's child-list as a child node. Also, set the corresponding bitmap element $B[e]$ to 1, indicating that vehicle V_e is *visited*. The child nodes in the child-list are also ordered in the nondecreasing order of the expected encounter time.
6. If Q is not empty, go to Step 2; otherwise, the construction process is done.

We illustrate the construction process through an example. In Fig. 4, vehicles a, b, c, and d are moving in a target road network and nodes from 1 to 7 are intersections in the road network. For demonstration purpose, in Fig. 4, the static point s on roadside is selected as the packet destination. Of course, the destination could be a moving vehicle. Let us assume that vehicle V_a intends to forward packets to the static node s. First, the root node a is inserted into Q, as shown in Fig. 5(a). Next, as shown in Fig. 5(b), we take the node a out of Q. Since vehicle V_a expects to encounter vehicles V_b and V_d, nodes b and d are inserted into Q according to the expected encounter sequence, as shown in Fig. 5(c). Fig. 5(d) shows that when the first node b in Q is taken out, vehicle V_b could encounter vehicle V_c under the condition that V_a encounters V_b first, and so node c is inserted into Q after node b is added into the graph. Since the expected encounter time between V_b and V_c is earlier than the expected encounter

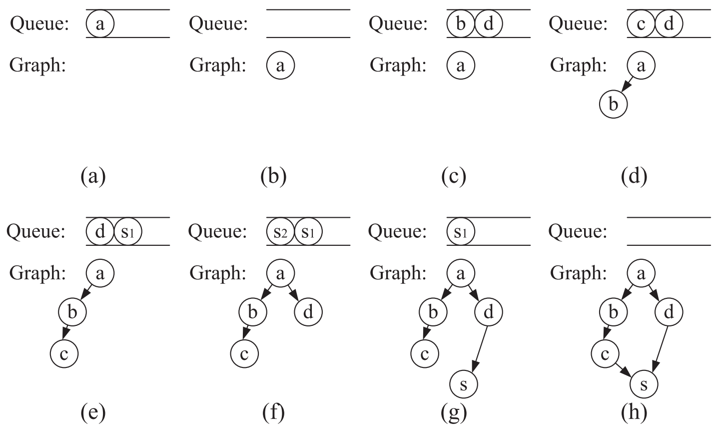


Fig. 5. Predicted encounter graph construction.

time between V_a and V_d, node c is ahead of node d in Q in Fig. 5(d). Fig. 5(e) shows the result when node c is taken out of Q. Note that the node s_1 in Q indicates that the destination node s could be encountered by node c. We differentiate the destination nodes in Q because they have the different delivery delays for the different paths along the *predicted encounter graph G*. As shown in Fig. 5(f), when node d is taken out of Q, its child node s_2 (differently denoted for the destination node s) is inserted into Q. Node s_2 is inserted ahead of s_1 because V_d is predicted to encounter the destination s earlier than V_c. Fig. 5(g) shows that vehicle V_d encounters the destination s earlier than vehicle V_c. Finally, as shown in Fig. 5(h), vehicle V_c is predicted to encounter the destination s.

When forwarding packets in a heavy-traffic road network, the graph construction might take more time. Some useful methods can be used to reduce this graph construction time, that is, 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 those nodes up to the root node is smaller than a threshold. More importantly, in the next section we will show that the expansion process of the graph can be finished earlier when the predicted encounter graph achieves the requested delivery ratio bound.

5. The design of travel prediction based data forwarding

Like other schemes such as VADD [2] and TBD [7], for the bandwidth efficiency, our TPD employs the unicast strategy, keeping only one copy of the message in the network. After constructing the predicted encounter graph, as shown in Fig. 5, each vehicle would usually 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 E2E packet delivery delay in the network, we will discuss how to minimize E2E packet delivery delay under a specific delivery ratio threshold by only selecting a subset of encountered vehicles for data delivery.

5.1. Calculating Expected Delivery Ratio (EDR)

In this section, we discuss how to calculate the Expected Delivery Ratio (EDR) based on a given predicted encounter graph. For a specific node (e.g., current packet carrier) in the predicted encounter graph, note that all of its child nodes are not necessarily selected as next-hop forwarders. This is because a subset of those child nodes can give the specific node an optimal EDR. Refer to Appendix A for the construction of *a subset of child nodes as next-hop forwarders* that is defined as *forwarding sequence*. For the specific node, these potential forwarders in the *forwarding sequence* are called the *forwarding vehicles*.

To send a packet toward the destination node, the packet carrier vehicle searches for the road segment where it will meet the first encountered vehicle in its *forwarding sequence* corresponding to its forwarding paths. If this carrier encounters the first forwarding vehicle successfully on the expected road segment, the packet is transmitted to the first one, and the carrier no longer needs to carry this packet. Otherwise, the carrier prepares for encountering the next vehicle in its *forwarding sequence* and tries to send it the packet again. This single-hop transmission process continues until the carrier successfully sends the packet to one of the forwarding vehicles in its *forwarding sequence*. If the carrier cannot forward the packet to any vehicle among its forwarding vehicles, the packet delivery fails, leading to the packet discarding.

For the calculation of EDR, let p_{ei} be the *encounter probability* between vehicle V_e (i.e., node e) and its ith forwarder (denoted as V_i) in the first overlapped edge or intersection of V_e's trajectory and V_i's trajectory in the predicted encounter graph. Note that for such an overlapped edge or intersection, p_{ei} is $P(V_e \otimes_{x,y} V_i)$ in (5) or $P(V_e \otimes_z V_i)$ in (12) where x, y and z are intersections. Let $P_e(i)$ be the *forwarding probability* that a packet can be transmitted by node e to the ith forwarder because node e fails to encounter the former $i-1$ forwarders and encounters the ith forwarder such that:

$$P_e(i) = \left[\prod_{j=1}^{i-1} (1 - p_{ej}) \right] p_{ei}. \quad (20)$$

The EDR of a given node e (denoted as EDR_e) is the expected packet delivery ratio from node e to its destination. Assuming that node e has n children in its predicted encounter graph and the ith forwarder's EDR value is EDR_i, we

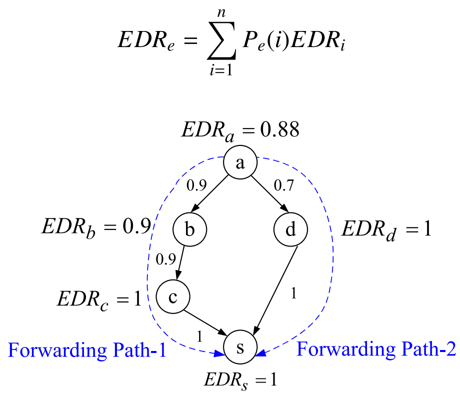


Fig. 6. EDR calculation of vehicle V_a.

have the following recursive equation for EDR_e:

$$EDR_e = \sum_{i=1}^{n} P_e(i)EDR_i. \tag{21}$$

To calculate the E2E Expected Delivery Ratio from the root node to the destination node in the predicted encounter graph G, a recursive process starts from the destination node s. First of all, let EDD_e be E2E Expected Delivery Delay (EDD) from node e to the destination node s. At the destination node s, obviously, $EDR_s = 1$ (i.e., no packet loss), while $EDD_s = 0$ because EDD_s is the EDD from node s to node s itself. To calculate the EDRs of all the nodes in the whole encounter graph G, we start from the destination node with known initial conditions and then recursively apply (21) to the other nodes toward the source node in G. That is, the whole process of calculating EDR values propagates upward from the destination node to the rest of the graph G until it finally reaches the root node in G, that is, the source node.

To illustrate the whole EDR calculation process for a predicted encounter graph, we show a walkthrough example in Fig. 6; note that this predicted encounter graph is constructed from Fig. 5. From Fig. 6, source node a can forward its data packets toward the destination s through *Forwarding Path-1* (i.e., $a \to b \to c \to s$) or *Forwarding Path-2* (i.e., $a \to d \to s$). The weights on the edges in Fig. 6 denote the encounter probability in (20) between two connected vehicles. At the initial state, the $EDR_s = 1$ at the destination node s. On the basis of (21), we can recursively calculate the EDR value for nodes c, d, and b, respectively. Finally, for source node a, we can calculate its EDR value as: $EDR_a = p_{ab}EDR_b + (1 - p_{ab})p_{ad}EDR_d = 0.9 * 0.9 + (1–0.9) * 0.7 * 1 = 0.88$ where the encounter time is estimated from Fig. 4, that is, node a encounters node b earlier than node d.

5.2. Optimizing Expected Delivery Delay (EDD) with delivery ratio constraint

In the similar way to calculate EDR, we can recursively calculate E2E Expected Delivery Delay (EDD) from the source node toward the destination node, based on the predicted encounter graph G. As a reminder, note that the EDD of a given node e (denoted as EDD_e) is the EDD of the packets from node e to the destination in the graph G.

EDD is defined on the basis of the condition that the packets are successfully transmitted to the destination as follows. To calculate the EDD value of node e (i.e., EDD_e), let $Q_e(i)$ be the conditional probability that the packet from node e is successfully delivered to the destination s via the ith forwarder of node e under the precondition that the packet from node e is successfully delivered to the destination s as follows:

$$\begin{aligned} Q_e(i) &= P[\text{packet from } e \text{ is delivered to } s \text{ via } i | \\ &\qquad \text{packet from } e \text{ is delivered to } s] \\ &= \frac{P_e(i)EDR_i}{EDR_e}. \end{aligned} \tag{22}$$

Let EDD_i be the EDD value for the ith forwarder (denoted as v_i^e) in the set of node e's n child nodes (denoted as V^e). Let d_i be the carry delay (i.e., packet carrying time) for node e to carry the packet until node e encounters forwarder v_i^e. We formulate EDD_e as follows:

$$EDD_e = \sum_{i=1}^{n} Q_e(i)(d_i + EDD_i). \tag{23}$$

In the minimization of the EDD, it is noted that even though a low delivery delay is preferable in a vehicular network, a user-required delivery ratio threshold (e.g., 90%) should be satisfied at the same time. In fact, if there is no required lower bound on the Expected Delivery Ratio (EDR), the optimal delay can be easily achieved by including only a single vehicle v_j^e that has the minimum $(d_j + EDD_j)$ value among all next-hop potential encountered vehicles in V_e. Because the corresponding delivery ratio may be very low, such an optimal solution is not suitable for practical applications requiring reliable data delivery. Therefore, we will focus on how to optimize the EDD metric for the node e under the constraint that the EDR metric is at least the delivery ratio threshold R.

For the optimization of EDD with the constraint of delivery ratio R, we propose the following construction of a predicted encounter graph G. Note that when a new node is added into the encounter graph G, all the encounter events (predicted to have happened earlier than the new node) must have already been included into the encounter graph G. Therefore, in this graph construction process, when the destination node is taken out from the ordered queue Q and added into the predicted encounter graph G for the first time, the first connected path from the source node to the destination node can be found. Because of the way that this graph is constructed, this path has a *minimal delay* as a local optimum EDD value for packet forwarding rather than the *minimum delay* as the global optimum EDD value. We then calculate the EDR of the root node (i.e., source node) at the current graph expansion by Eq. (21). If the EDR value is greater than the required lower bound R, the construction of the graph stops because an optimal path with the bound R 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 Time-To-Live (TTL) constraint. Finally, the approach of optimizing the delivery delay is integrated into the process of constructing a predicted encounter graph as follows:

1. In the process of constructing the graph G, when taking out the first node from Q and adding it into G (as shown in Fig. 5), judge whether this new node is the destination node.
2. If the newly added node is the destination node, we use a dynamic programming approach to calculate the maximum EDR of the source node toward the destination node, while pruning intermediate nodes in the encountered graph G that may decrease the EDR of the source node. Refer to Appendix A for the detailed dynamic programming for the optimization of the source node's EDR.
3. If the calculated EDR is smaller than the required EDR bound R, go to Step 1. Otherwise, the process stops because at the current graph expansion, the optimal forwarding paths have already met the required bound R with a minimal delivery delay at the same time.

When the graph expansion is over, the EDD value of the source node at the root can be calculated using (23). Note that because the optimal forwarding paths are acquired to satisfy the delivery ratio threshold R, the obtained EDD value is not necessarily the lowest delivery delay, that is, the global optimum EDD value, as mentioned before. However, based on the chronological graph expansion, the obtained EDD value is usually close to the lowest delivery delay. In the next subsection, we will show our TPD data forwarding protocol based on the EDR and EDD values per vehicle in a target road network.

5.3. TPD data forwarding protocol

Data forwarding in TPD is a *source-routing* based on a predicted encounter graph. When an AP needs to forward packets to a destination vehicle, it constructs a predicted encounter graph with the desired TTL and delivery ratio bound R, as shown in Figs. 4 and 5. When the AP has multiple vehicles as next carriers toward the destination vehicle, it selects a vehicle with the maximum EDR or minimum EDD according to its forwarding preference. The predicted encounter graph has the optimal forwarding paths toward the destination vehicle. TCC embeds the predicted encounter graph into a packet's header for source-routing in an efficient encoding format [30]. Basically, the forwarding can be guided by these optimal forwarding paths on the predicted encounter graph. Each packet carried by a packet carrier is forwarded to the next carrier according to the optimal forwarding paths until it is delivered to the destination vehicle. Thus, since TCC calculates a predicted encounter graph without exposing vehicle trajectories to other vehicles, there is no privacy issue as long as TCC having vehicle trajectories is trustworthy.

To support multihop vehicle-to-vehicle (V2V) data delivery, TPD can decompose the V2V data delivery into vehicle-to-infrastructure (V2I) and infrastructure-to-vehicle (I2V) data delivery. In the V2I data delivery, an AP nearest to a source vehicle is selected as the destination in the TPD data forwarding. When an AP receives a packet from a source vehicle, it constructs a predicted encounter graph for the corresponding destination vehicle, and then forwards the packet with the predicted encounter graph in the packet's header toward the destination vehicle through I2V data delivery. Thus, TPD can support V2I, I2V, and V2V data delivery in vehicular networks.

So far, we have explained our TPD data forwarding process, based on the source-routing. In the next section, we will evaluate our TPD protocol through extensive simulations under realistic road network settings.

6. Performance evaluation

This section evaluates the performance of TPD along with two baselines. In the performance evaluation, this paper focuses on multihop unicast-based data forwarding from an AP to a moving destination vehicle. As a baseline, an existing unicast-based data forwarding called TBR [14] is used, which uses vehicle trajectories for data forwarding through vehicle encountering. The major difference between TPD and TBR is that TBR does not consider Expected Delivery Ratio (EDR) to construct forwarding paths, but TPD considers EDR. As another baseline, Epidemic Routing (just called *Epidemic*) [16] is used where the current carrier forwards its packet copies to another vehicle that is encountered for the first time. As expected, Epidemic's delivery cost in terms of the number of transmissions is much more expensive than TPD's and TBR's because Epidemic works as a controlled flooding. We do not compare our TPD with TSF [8] for multihop I2V data forwarding. This is because TSF requires additionally infrastructure nodes (called relay nodes) and these relay nodes are not required by our TPD. Finally, the evaluation is based on the following settings:

Performance metrics: We use (i) average delivery ratio, (ii) average delivery delay, and (iii) average delivery cost as the performance metrics.

Parameters: We investigate the impact of (i) vehicle speed deviation, (ii) vehicle speed, (iii) communication range, (iv) vehicular density, and (v) trajectory-changing vehicle ratio.

In the simulation, a road network with 49 intersections is used. Each vehicle moves from a randomly selected source position to a randomly selected destination position. The movement pattern is determined by a *Hybrid Mobility model* of City Section Mobility model [31] and Man hattan Mobility model [32] suitable for vehicle mobility in urban areas having a rectangular road network topology, as shown in Fig. 1. Among the vehicles, one vehicle as a destination vehicle circulates in the perimeter of the road network according to its vehicle travel path during the simulation. All the vehicles including the destination vehicle register their travel paths into the TCC in the road network. Thus, the TCC in the simulator knows the accurate trajectories of all the vehicles all the time.

The vehicle speed follows the normal distribution of $N(\mu_v, \sigma_v)$ [33], and a vehicle may change its speed at each road segment. During the simulation, packets are dynamically generated from an AP 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.

6.1. The impact of vehicle speed deviation

As TPD is travel-prediction-based, the accuracy of prediction will affect its performance. Intuitively, traffic mainly

Table 1
Simulation configuration.

Parameter	Description
Road network	The number of intersections is 49 The area of the road map is 8.25 km × 9 km
Communication range	$R_c = 200$ m
Number of vehicles (N)	The number N of vehicles moving within the road network. The default of N is 200.
Time-To-Live (TTL)	The expiration time of a packet. The default TTL is the Expected Delivery Delay plus 500 s
Vehicle speed (v)	$v \sim N(\mu_v, \sigma_v)$ where $\mu_v = \{25, 30, \ldots, 65\}$ MPH and $\sigma_v = \{1, 2, \ldots, 9\}$ MPH. 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
Encounter probability threshold	The threshold of the encounter probability used to select an encounter for forwarding in the predicted encounter graph. The default value is 0.6
Requested EDR bound (R)	The requested EDR bound the forwarding should achieve. The default is $R = 0.6$

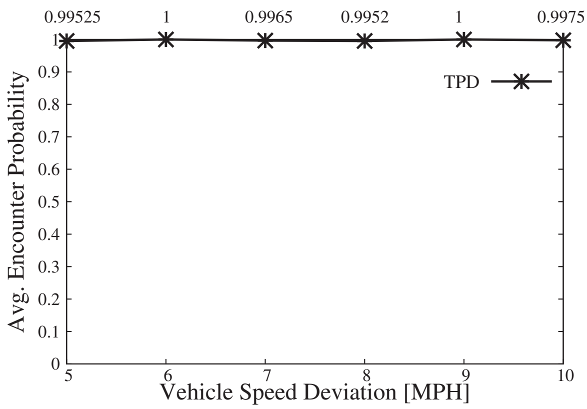


Fig. 7. Average encounter probability vs. vehicle speed deviation.

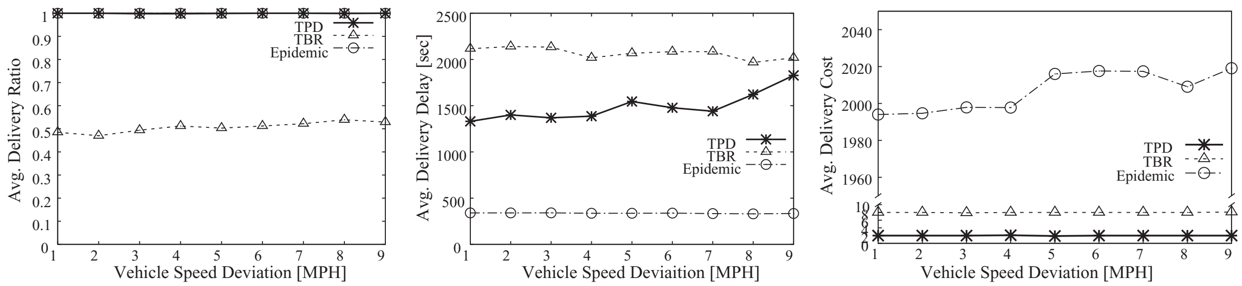
affects the traveling time, making the encounters probabilistic. In our simulation, for simplicity, we use vehicle speed deviation to reflect the traffic condition, and intend to study to what extent the speed deviation could affect TPD.

Fig. 7 shows average encounter probability that is defined as the probability that a carrier will actually encounter the next carrier in a predicted encounter graph during the simulation. The higher average encounter probability indicates the more occurrences of the predicted encounter events, that is, the higher reliability of the predicted encounter graph. As shown in Fig. 7, average encounter probability is always higher than 0.995 for the vehicle speed deviation from 5 MPH to 10 MPH. This figure shows that our predicted encounter graph allows for accurate encounter prediction. Note that TPD selects an encounter for a packet forwarding such that the encounter probability based on a Gamma distribution is greater than a given encounter probability threshold (e.g., 0.6).

Fig. 8 shows the impact of vehicle speed deviation on the E2E delivery ratio, delivery delay, and delivery cost. For the average delivery ratio, as shown in Fig. 8(a), TPD has the average delivery ratio close to 1 with Epidemic. On the other hand, TBR has the average delivery ratio of about 0.5. It is seen that by the selection of encounters based on the encounter probability threshold, TPD guarantees a higher E2E delivery ratio than TBR without using encounter probability.

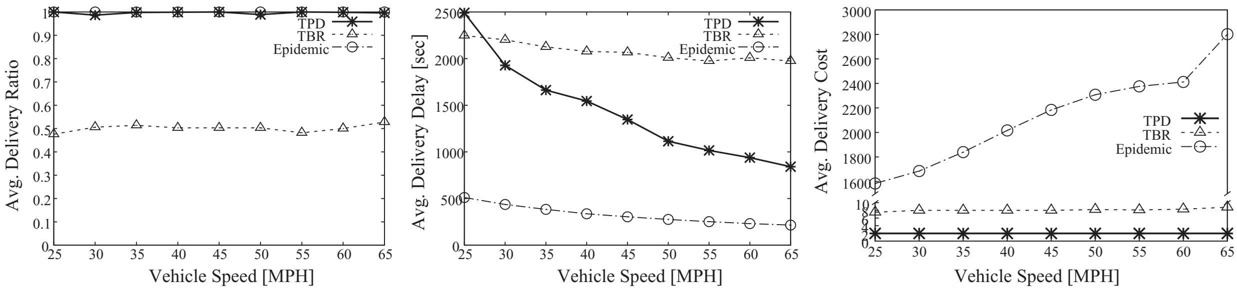
For the average delivery delay, as shown in Fig. 8(b), Epidemic has the shortest delay around 340 s, as expected. For all the range of vehicle speed deviation, TPD outperforms TBR in the E2E delivery delay. For the vehicle speed deviation of 5 MPH, the average delivery delay of TPD is 1546 s, but that of TBR is 2067 s. That is, TPD reduces 25% of the delivery delay of TBR. Note that in our evaluation, when a packet is delivered to the destination vehicle 500 s later than the Expected Delivery Delay, it is regarded as a packet loss. In this case, the delivery delay for the packet is counted as 3000 s due to the packet loss. Note that 3000 s is the destination vehicle's travel delay along its vehicle trajectory in the target road network. Thus, the higher packet loss ratio (e.g., 0 – average delivery ratio) leads to the higher E2E delivery delay (e.g., 3000 s).

For the average delivery cost, as shown in Fig. 8(c), in average, TPD and TBR have 2 transmissions and 8 transmissions, respectively. On the other hand, Epidemic has about 2000 transmissions due to the frequent packet copy operations. Looking at the tradeoff between delivery delay and delivery cost in the vehicle speed deviation of 5 MPH, TPD has 4.6 times the delivery delay of Epidemic where TPD's delay is 1546 s and Epidemic's delay is 336 s. However, Epidemic



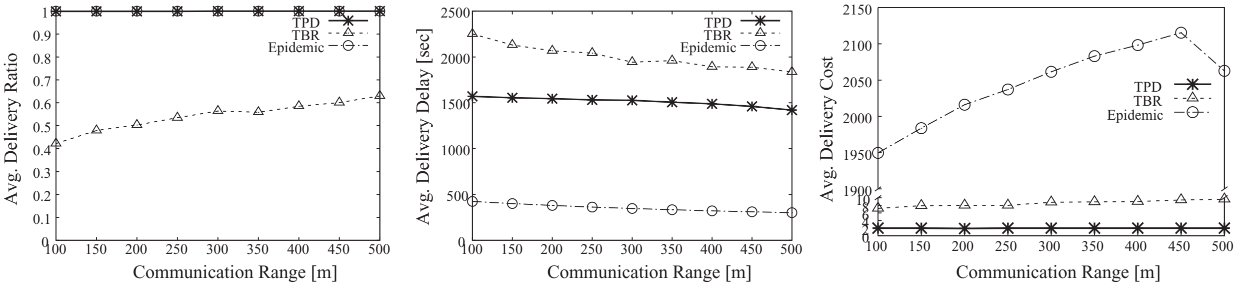
(a) Delivery Ratio vs. Speed Deviation (b) Delivery Delay vs. Speed Deviation (c) Delivery Cost vs. Speed Deviation

Fig. 8. The impact of vehicle speed deviation.



(a) Delivery Ratio vs. Speed (b) Delivery Delay vs. Speed (c) Delivery Cost vs. Speed

Fig. 9. The impact of vehicle speed.



(a) Delivery Ratio vs. Comm. Range (b) Delivery Delay vs. Comm. Range (c) Delivery Cost vs. Comm. Range

Fig. 10. The impact of communication range.

has 1008 times the delivery cost of TPD where TPD's cost is 2 transmissions and Epidemic's cost is 2016 transmissions. Thus, TPD can support the most cost-effective delivery with a reasonable delivery delay.

6.2. The impact of vehicle speed

This subsection investigates the impact of vehicle speed on the performance. As expected, as the vehicle speed is faster, the performance of all the three schemes is getting better due to the faster packet carry by packet carriers. As shown in Fig. 9(a), all the three schemes have stable delivery ratio curves according to vehicle speed from 25 MPH to 65 MPH. TPD and Epidemic have the delivery ratio of at least 0.98 and 1, respectively. On the other hand, TBR has the delivery ratio of about 0.5.

As shown in Fig. 9(b), the delivery delay of all the three protocols tends to decrease according to vehicle speed. This is because a faster vehicle speed allows for a more opportunity that a carrier can encounter other vehicles as next carriers and also faster movement. Thus, packets are forwarded more quickly toward the destination vehicle.

For the delivery cost, as shown in Fig. 9(c), TPD and TBR have 2 transmissions and 8 transmissions in average, respectively. On the other hand, Epidemic's delivery cost tends to quickly increase according to vehicle speed by the increase of encounter opportunity between vehicles.

6.3. The impact of communication range

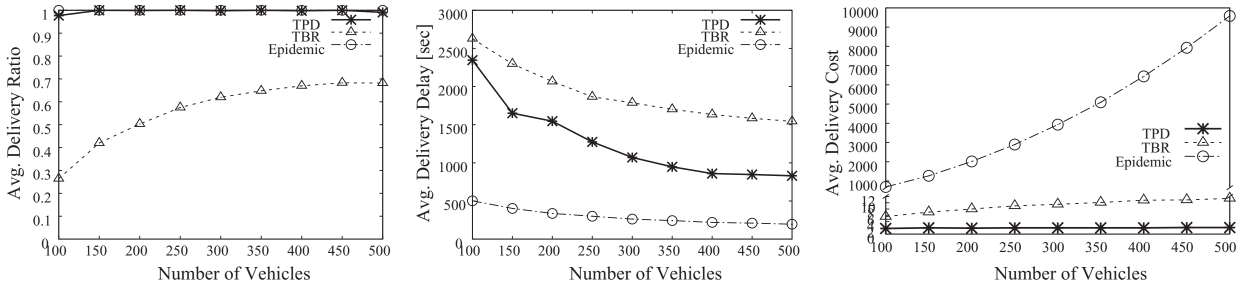
This subsection investigates the impact of communication range on the performance. As expected, as the communication range is longer, the performance of all the three schemes is getting better due to the higher encounter probability. As shown in Fig. 10(a) and (b), the delivery ratio of TBR tends to increase, and the delivery delay of all the three protocols tends to decrease. This is because a longer communication range allows for a more opportunity that a carrier can encounter other vehicles as next carriers. Thus, packets have a higher chance to be forwarded to the destination vehicle.

For the delivery cost, as shown in Fig. 10(c), TPD and TBR have 2 transmissions and 8 transmissions in average, respectively. On the other hand, Epidemic's delivery cost tends to increase according to the communication range by the increase of encounter opportunity between vehicles except the communication range of 500 m.

6.4. The impact of vehicular density

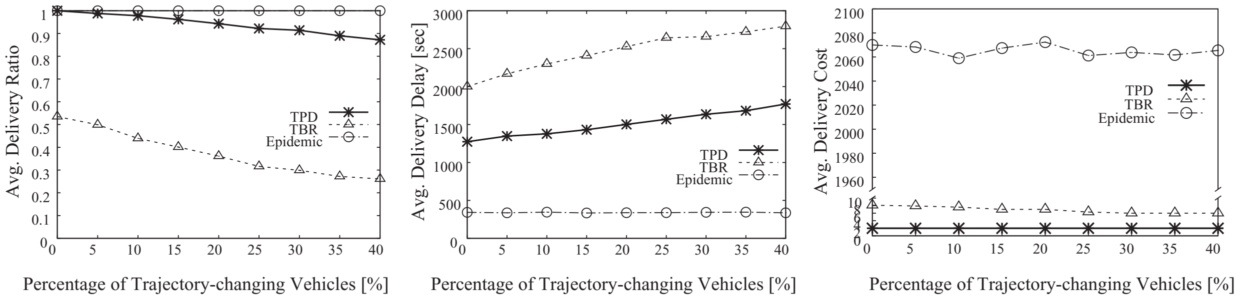
This subsection investigates the impact of vehicular density on the performance. As expected, as the vehicular density in the road network increases, the performance of TPD and TBR is getting better due to the higher encounter probability. As shown in Fig. 11(a) and (b), the delivery ratio of TPD and TBR tends to increase, and the delivery delay of all the three protocols tends to decrease. This is because more vehicles in the road network allow for a more opportunity that a carrier can encounter other vehicles as next carriers. Thus, packets have a higher chance to be forwarded to the destination vehicle through better forwarding sequences.

For the delivery cost, as shown in Fig. 11(c), TPD has 2 transmissions in average. On the other hand, the delivery cost of TBR and Epidemic tends to increase according to the



(a) Delivery Ratio vs. Vehicle Number (b) Delivery Delay vs. Vehicle Number (c) Delivery Cost vs. Vehicle Number

Fig. 11. The impact of vehicle number.



(a) Delivery Ratio vs. Change Percent (b) Delivery Delay vs. Change Percent (c) Delivery Cost vs. Change Percent

Fig. 12. The impact of trajectory-changing percentage.

vehicular density by the increase of encounter opportunities. Especially, Epidemic's cost increases quickly according to the vehicular density. This indicates that Epidemic requires much higher cost than TPD, so it is not appropriate for data delivery in vehicular networks. However, TPD can provide better delivery according to the increase of vehicular density with a bounded delivery cost.

6.5. The impact of trajectory-changing percentage

This subsection investigates the impact of the percentage of trajectory-changing vehicles on the performance. Note that trajectory-changing percentage is the percentage of vehicles that do not follow their original trajectory reported to the TCC. As expected, as the trajectory-changing percentage increases, the performance of TPD and TBR is getting worse due to the lower encounter probability. As shown in Fig. 12(a) and (b), according to the increase of the trajectory-changing percentage, the delivery ratio of TPD and TBR tends to decrease, and the delivery delay of TPD and TBR tends to increase. This is because a higher trajectory-changing percentage in the road network leads to a less opportunity that a carrier can encounter other vehicles as next carriers. Thus, packets have a lower chance to be forwarded to the destination vehicle through worse forwarding sequences.

For the delivery cost, as shown in Fig. 12(c), TPD has 2 transmissions in average. On the other hand, TBR's cost tends to decrease according to the percentage by the decrease of encounter opportunities. Epidemic's cost is around 2070 transmissions according to the percentage. This indiates that TPD outperforms TBR even under the change of trajectories. Thus, it can be expected that in the real road network, TPD will be able to provide good data delivery service with a bounded delivery cost.

Therefore, through the simulations, it can be concluded that TPD is a promising data forwarding without additional infrastructure nodes, such as relay nodes, by supporting an efficient V2I, I2V or V2V data delivery in unicast with a bounded delivery cost.

7. Practical issues

We have so far shown that the trajectory information plays an important role that directly affects the feasibility and effectiveness of TPD. Now we discuss the following practical issues associated with trajectory sharing through TCC: (i) The utilization of APs as a backbone network and (ii) Communication overhead for source-routing.

7.1. Interconnected APs as backbone network

In practice, we can easily extend our TPD to take advantage of the interconnection between APs as a wormhole backbone used to expedite I2V or V2V delivery process. We can reconstruct the topology of a road network such that road segments between APs have zero delay. As stationary vehicles, APs can participate in TPD forwarding process, as discussed in Section 5.3. Thus, through this remodeling of the vehicular network with the backbone of APs, the TPD design can be used along with multiple APs without any modification. For evaluation purpose, we let a single AP be involved in the data forwarding in order to show the effectiveness of the vehicle trajectory sharing through TCC at the level of microscopic information. Clearly, the performance will be improved by involving APs in the data forwarding.

7.2. Communication overhead

TPD uses source-routing with forwarding sequences in a predicted encounter graph. TCC can encode the predicted encounter graph with next carrier candidates into a packet's header, using an efficient encoding scheme [30]. When a target road network is partitioned into multiple regions with a reasonable size with a dedicated AP, the predicted encounter graph can be bounded to a reasonable size fitting a packet's header. On the performance evaluation, both TPD and TBR use a predicted encounter graph, so the evaluation condition is fair. Even though Epidemic does not require such a predicted encounter graph, the packet duplication leads to high delivery cost.

8. Conclusion

This paper proposes an infrastructure-to-vehicle (I2V) or vehicle-to-vehicle (V2V) data delivery called Travel Prediction-based Data Forwarding (TPD) in vehicular networks, using vehicle trajectories. With the vehicle trajectories, TPD can support multihop unicast I2V or V2V data delivery even under a road network without relay nodes for temporary packet holding as infrastructure nodes during packet forwarding process. This means the reduction of the infrastructure cost for vehicular data delivery. In TPD, a predicted encounter graph is constructed to determine forwarding sequences from a packet source to a packet destination, considering the encounter probability of two vehicles that is a carrier and the next carrier. Through optimal forwarding path computation, optimal forwarding sequences are used to achieve the maximum Expected Delivery Ratio (EDR). Through simulation, it is shown that TPD outperforms legacy forwarding schemes in terms of the tradeoff among delivery ratio, delivery delay, and delivery cost. In addition to the efficient data forwarding, our travel time model and predicted encounter graph can be used for better navigation and more precise safety notification because they can facilitate the prediction of the rendezvous of vehicles in road networks.

As future work, we will investigate the data forwarding in the road network where only parts of vehicles share their vehicle trajectories through TCC. Also, we will extend our TPD protocol for the multicast to allow for the efficient data sharing among vehicles in vehicular networks. As another future work, we will investigate a transport layer for the reliable data delivery in vehicular networks. For the reliable data exchange between vehicles in vehicular networks, we will design and implement a transport layer for vehicular networks, including both acknowledgment and data retransmission.

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Appendix A. Optimal forwarding path computation

We introduce a *dynamic programming* approach to find the optimal forwarding paths within the predicted encounter graph with a maximum Expected Delivery Ratio (EDR); note that this dynamic programming approach uses the dynamic programming model proposed in Dynamic Switch-based Forwarding for wireless sensor networks [34]. The basic idea is to decide whether a child node v_i should be included in the forwarding paths in terms of the maximization of EDR. That is, when vehicle V_e carries the packet and encounters the ith forwarder v_i, the question is "Does the exclusion of v_i from the forwarding paths have a greater EDR than the inclusion of v_i in the forwarding paths?". For this optimization, our strategy is to check how many chances are left to successfully forward the packet using the rest of forwarders in the predicted encounter graph.

Let us define *forwarding sequence* as the sequence of next forwarder candidates that may be actual next forwarders for the current packet carrier V_e. Let V^e be the forwarding sequence of vehicle V_e's n child nodes such that $V^e = (v^e_1, v^e_2, \ldots, v^e_n)$; note that the forwarders in V^e are sorted in the nondecreasing order of the expected encounter time with V_e. Let $V^e(k)$ be a *forwarding sequence* of the last k forwarders in V^e such that $V^e(k) = (v^e_{n-k+1}, v^e_{n-k+2}, \ldots, v^e_n)$. Let $V^e_{opt}(k)$ be an optimal *forwarding subsequence* of $V^e(k)$ in terms of the maximization of EDR of vehicle V_e toward the destination node. Note that $V^e_{opt}(k)$ *has not necessarily all of the forwarder candidates in* $V^e(k)$ *because the exclusion of some candidates may lead to a better EDR*; the rationale of this optimization will be discussed later. Let $EDR_e(V^e_{opt}(k))$ be the EDR value of vehicle V_e computed by Eq. (21) for $V^e_{opt}(k)$.

Now we show that $V^e_{opt}(k)$ has the optimal EDR of the packet carrier V_e. To use dynamic programming, a problem must have an *optimal substructure* property [35] such that *an optimal solution of the problem consists of the optimal solutions of its subproblems*. First of all, we show that the selection of all the forwarder candidates by the current packet carrier V_e may not be optimal with an example. As shown in Fig. A.1, vehicle V_e has two forwarder candidates, such as V_b and V_c. Let T_{ij} be the expected encounter time of vehicles V_i and V_j. As $T_{eb} < T_{ec}$, it is assumed that V_e is expected to encounter V_b earlier than V_c. Let us assume that the encounter probability for both forwarder candidates is 100% and that the EDR of V_b is 20% and the EDR of V_c is 100%. Let $V^e(2)$ be a subsequence including both V_b and V_c such that $V^e(2) = (V_b, V_c)$. Let $V^e(1)$ be a subsequence including only V_c such that $V^e(1) = (V_c)$. By Eq. (21), let us calculate the EDRs of $V^e(2)$ and $V^e(1)$: $EDR_e(V^e(2)) = 1 * 0.2 + 0 * 1 = 20\%$ and $EDR_e(V^e(1)) = 1 = 100\%$. The inclusion of only the last one V_c has a greater EDR than that of both V_b and V_c. Therefore, a subsequence should be optimally selected from the given forwarding sequence for the maximum EDR of V_e.

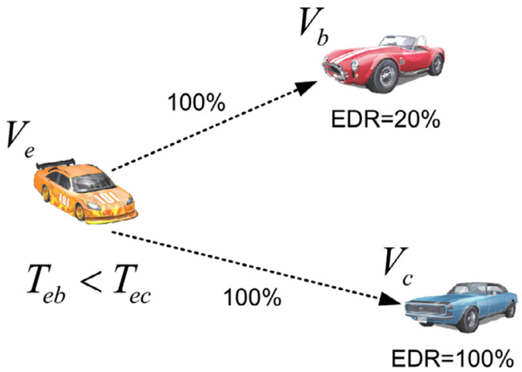

Fig. A.1. Example for optimal forwarding subsequence computation.

For $V^e_{opt}(k)$, we construct a solution by attempting to add vehicles in $V^e(k)$ backward one by one. Clearly, the last vehicle v^e_n must be added to $V^e_{opt}(k)$ because it is the last resort to carry the packet(s) of V_e before the forwarding failure of V_e may occur. To compute an optimal solution of $V^e_{opt}(n)$, the following procedure is repeated for $k = 1..n$ where for $k = 0$, we have $V^e_{opt}(0) = ()$ as empty sequence:

1. If the last kth vehicle (i.e., v^e_{n-k+1}) in V^e can contribute to the increase of the EDR in addition to $V^e_{opt}(k-1)$, then append v^e_{n-k+1} in front of $V^e_{opt}(k-1)$ for $V^e_{opt}(k)$.
2. Otherwise, exclude vehicle v^e_{n-k+1} as a forwarder for $V^e_{opt}(k)$.

To show the optimal substructure for $k = 1..n$ in the above procedure, *recursive formulas* for the optimal EDR and the optimal forwarding subsequence are represented with a concatenation operator $\oplus$, inserting node v^e_{n-k+1} in front of the sequence $V^e_{opt}(k-1)$ as follows:

$$EDR_e(V^e_{opt}(k)) = \begin{cases} 0 \quad \text{for } k = 0, \\ \max\{EDR_e(v^e_{n-k+1} \oplus V^e_{opt}(k-1)), \\ EDR_e(V^e_{opt}(k-1))\} \quad \text{for } 1 \le k \le n. \end{cases} \tag{A.1}$$

$$V^e_{opt}(k) = \begin{cases} v^e_{n-k+1} \oplus V^e_{opt}(k-1) \\ \text{if } EDR_e(v^e_{n-k+1} \oplus V^e_{opt}(k-1)) \\ \quad > EDR_e(V^e_{opt}(k-1)), \\ V^e_{opt}(k-1) \quad \text{otherwise.} \end{cases} \tag{A.2}$$

In (A.2), the optimal substructure is that an optimal subsequence $V^e_{opt}(k)$ for the problem $V^e(k)$ is determined by (i) the last kth vehicle in $V^e(k)$ and (ii) an optimal subsequence $V^e_{opt}(k-1)$ for the subproblem $V^e(k-1)$ of $V^e(k)$. The time complexity of the dynamic programming algorithm in (A.2) is $O(n^3)$ by Eqs. (20), (21), and (A.2) where n is the number of the next forwarder candidates for the current packet carrier V_e.

For the optimal EDR calculation of the packet carrier vehicle, we apply Eq. (A.2) to each node in the predicted encounter graph (as shown in Fig. 6) from the node for the destination vehicle (denoted as s) toward the node for the source vehicle (denoted as a) in the bottom-up fashion. Therefore, in this way, we can calculate the optimal EDR of the packet carrier (e.g., EDR_a in Fig. 6) and an optimal forwarding subsequence (e.g., $V^a_{opt}(n)$ for $V^a(n)$).

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