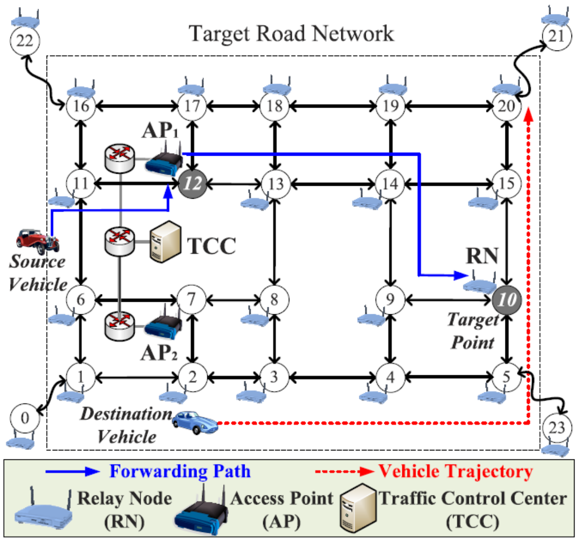

Fig. 1. Data forwarding in vehicular networks.

1 PROBLEM FORMULATION

In this section, we formulate the data forwarding in vehicular networks as follows: Given a road network with APs, our goal is to deliver packets reliably from the APs to a moving destination vehicle with a minimum End-to-End (E2E) delay.

1.1 Assumptions

This work is based on the following set of assumptions on the road network and vehicle settings.

●Access Point is a wireless network node connected to the wired network (e.g., the Internet) with DSRC device, storage and processor in order to provide vehicles with the wired network connectivity. For the cost effectiveness, as shown in Fig. 1, APs are sparsely deployed into road networks and are interconnected with each other through the wired network or wirelessly (as Mesh Network) for the data forwarding. The geographical location information of APs is available to vehicles.

●Traffic Control Center is a trustable entity that maintains vehicle trajectories without exposing the vehicle trajectories to other vehicles for privacy concerns. We can integrate vehicular networks to the existing TCCs used for the road traffic engineering. As shown in Fig. 1, TCC and APs are interconnected with each other through the wired network, such as the Internet. TCC selects an AP among multiple APs as the first hop for the data delivery toward the destination vehicle in terms of the shortest delivery delay to the destination vehicle.

●Relay Node is a temporary packet holder with DSRC device, storage and processor in vehicular ad hoc networks that is a stand-alone node without the wired network connectivity to APs, as shown in Fig. 1. For the sake of clarity, RN is assumed to be deployed at each intersection. This deployment is required to support the reliable data delivery from infrastructure node (i.e., AP) to mobile node (i.e., vehicle).

●Vehicles participating in VANET have DSRC devices. Nowadays many vehicle vendors, such as GM and Toyota, are planning to release vehicles with DSRC devices for the driving safety.

●Vehicles, TCC, APs, and RNs are installed with GPS based navigation systems and digital road maps. Traffic statistics, such as vehicle arrival rate λ and average vehicle speed v per road segment, are available via commercial navigation systems.

●Drivers input their travel destination into their GPS based navigation systems before their travel and so their vehicles can compute their future trajectory based on their current location and their final destination. Vehicles regularly report their trajectory information and their current location to TCC via APs, using vehicle-to-infrastructure data forwarding schemes, such as VADD, TBD, and SADV. These participant vehicles can be localized by TCC with their registered trajectories when an infrastructure node (i.e., AP) has data packets to send them.

1.2 Relay-Node-Assisted Forwarding

The data forwarding from vehicle to AP (i.e., fixed destination) has already been researched with stochastic models, such as VADD and TBD. These stochastic models try to forward packets opportunistically toward the packet destination using in-situ next carriers without relay nodes at intersections. For example, Fig. 1 shows the vehicle-to-infrastructure data forwarding from Source Vehicle to AP1 and for this data forwarding, we can use either VADD or TBD. Both VADD and TBD demonstrate the effectiveness of their approaches, mainly in the case where the destination is a fixed access point. However, the data forwarding from the AP to the vehicle (called reverse data forwarding) is a completely different story, such as the forwarding from AP1 to Destination Vehicle in Fig. 1. The success ratio of this reverse data forwarding highly depends on the accuracy of delay estimation, because only just-in-time packets can be delivered to a moving vehicle.

To investigate whether we can apply existing infrastructure-free forwarding technique such as VADD, we conduct simulations in the road network. As shown in Fig. 1, AP1 is placed at intersection n12 and the target point is intersection n10. AP1 at n12 generates 5,000 packets with the exponential distribution of 1-second interval toward the relay node (denoted as RN) at the target point n10. As shown in the figure, one of possible packet forwarding paths is n12 -> n13 -> n14 -> n9 -> n10.

TABLE 1
Delay Average Estimation of VADD

Protocol	Expected Delay	Actual Delay	Error
VADD	489.1sec	412.5sec	15.7%

TABLE 2
Delay Standard Deviation of VADD

Protocol	Expected STD	Actual STD	Error
VADD	10.1sec	139.2sec	1277.1%

Tables 1 and 2 show the statistics of VADD's packet delivery delay from the AP at n12 (denoted as AP1) to the relay node at the target point n10 (denoted as RN). Clearly, from Table 1, VADD has a very large delay estimation error in that the mean of the expected delivery delay is much different from that of the actual delivery delay. More noticeably, from Table 2, VADD has a standard deviation (STD) estimation error of 1,277.1 percent, a value that makes just-in-time delivery difficult, if not impossible. Such a large uncertainty is introduced by the stochastic forwarding at the intersection, where a vehicle might carry the packet along a wrong direction if no vehicle at the intersection moves toward the right direction.

1.3 Concept of Operation in TSF

Fig. 1 shows the data packet forwarding from an AP to a destination vehicle. Suppose that as shown in the figure, the destination vehicle has its vehicle trajectory consisting of seven intersections, that is, n2 -> n3 -> … -> n20 and has registered its vehicle trajectory into the Traffic Control Center via APs. Our goal is to deliver packets from the AP to the destination vehicle with a short delay. As shown in Fig. 1, our delivery strategy is to let the packets arrive earlier at a target point (i.e., intersection n10 on the destination vehicle's trajectory) along the forwarding path for the target point than the destination vehicle. Since there exists a relay node at the target point, the packets earlier arrived can wait for the destination vehicle. Thus, this target point is determined as a rendezvous point where the packet is highly expected to meet the destination vehicle with the shortest packet delay.

For the driving guidance services in vehicular networks, the data upload and download should be considered together for sharing road safety information among vehicles via APs. For the upload of road safety information collected by vehicles as well as the download, we can use 1) our TSF by regarding APs as packet destinations or 2) the existing data forwarding schemes (e.g., VADD and TBD) for the vehicle-to-infrastructure data delivery. This indicates that our TSF can support the vehicle-to-vehicle data delivery via APs, that is, the data delivery from Source Vehicle to Destination Vehicle via AP1 in Fig. 1.

2 TARGET POINT SELECTION FOR DATA DELIVERY

In this section, we explain how to select an optimal target point for the data delivery from an AP to a destination vehicle with the packet delay and vehicle delay distributions. The target point selection is based on the delivery probability that the packet will arrive earlier than the destination vehicle at the target point. This delivery probability can be computed with the packet's delivery delay distribution and the destination vehicle's travel delay distribution as follows: Let I be the set of intersections consisting of the destination vehicle's trajectory. Let i be a target point where $i \in I$. Let α be the user-required delivery probability. Let P_i be the packet delay that a packet will be delivered from AP to target point i. Let V_i be the vehicle delay that the destination vehicle will move from its current position to target point i. For example, in Fig. 1, P10 is the expected packet delay that a packet will be delivered from AP1 to target point n10 and V10 is the expected vehicle delay that Destination Vehicle will move from its current position n2 to target point n10. Thus, we can compute the delivery probability as $P[P_i \leq V_i]$

Given a user-required delivery probability threshold α, we select a target point intersection i with the minimum vehicle travel delay as an optimal target point such that $P[P_i \leq V_i] \geq \alpha$. Note that the minimum vehicle travel delay determines the destination vehicle's packet reception delay. More formally, we can select an optimal target point with a minimum delivery delay while satisfying the delivery probability α as follows:

$$i^* <- \arg\min_{i \in I} E[V_i] \ \text{ subject to } \ P[P_i \leq V_i] \geq \alpha \quad (1)$$

In (1), the delivery probability $P[P_i \leq V_i]$ is the probability that the packet will arrive earlier at target point I than the destination vehicle. Fig. 2 shows the distribution of packet delay P and the distribution of vehicle delay V.

We model the distributions of packet delay and vehicle delay as the Gamma distributions such that $P \sim \Gamma(k_p, \Theta_p)$ and $V \sim \Gamma(k_v, \Theta_v)$.

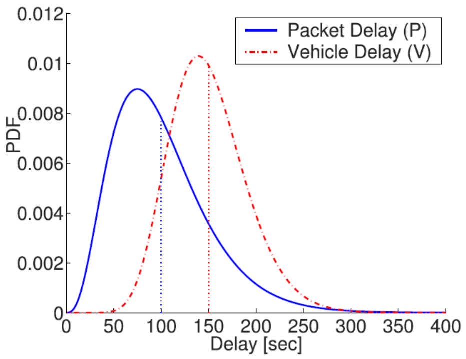

Fig. 2. Packet delay distribution and vehicle delay distribution.

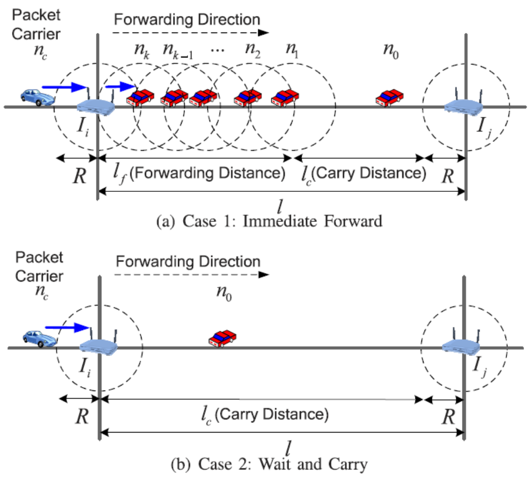

Fig. 3. Link delay modeling for road segment.

Given that the packet delay distribution and the vehicle delay distribution are independent of each other, the delivery probability $P[P_i \le V_i]$ is computed as follows:

$$P[P_i \le V_i] = \int_0^{TTL} \int_0^{v} f(p)g(v)dpdv \quad (2)$$

where $f(p)$ is the probability density function (PDF) of packet delay p, $g(v)$ is the PDF of vehicle delay v, and TTL is the packet's Time-To-Live (TTL); TTL is determined as the destination vehicle trajectory's lifetime that is the destination vehicle's travel time from its current position to its last position on the trajectory. Note that the delivery probability is computed considering the packet's lifetime TTL; that is, since the packet is discarded after TTL, the probability portion is zero after TTL. Clearly, the optimal target point selection depends on the packet delay model P and the vehicle delay model V.

3. DELAY MODELS

In this section, we describe two types of delay models: 1) Packet delay model and 2) Vehicle delay model. For the packet delay model, we first describe the link delay taken for the packet to be delivered over a road segment in Section 3.1 and then the E2E packet delay distribution from one position to another position on the road network in Section 3.2. For the vehicle delay model, we explain how to construct the vehicle delay distribution from the vehicle's current position to a target point in Section 3.3.

3.1 Link Delay Model

This section analyzes the link delay for one road segment with one-way road traffic given the vehicle interarrival time, the vehicle speed, and the communication range. It is supposed that one relay node for packet buffering is placed at each endpoint (i.e., intersection) of the road segment, as shown in Fig. 3. In this paper, for the simplified mathematical analysis of link delay, we focus on the link delay model in one-way road traffic. The link delay model in two-way road traffic will be investigated as future work, which can easily be integrated into our TSF design. Also, it should be noted that in the VANET scenarios, the carry delay is several orders-of-magnitude longer than the communication delay. For example, a vehicle takes 90 seconds to travel along a road segment of 1 mile with a speed of 40 MPH, however, it takes only 10 of milliseconds to forward a packet over the same road segment, even after considering the retransmission due to wireless link noise or packet collision; this short retransmission time is because the data rate in DSRC is 6 ~ 27 *Mbps* and transmission range can extend to almost 1,000 meters. Thus, since the carry delay is the dominating part of the total delivery delay, in our analytical model for the link delay we focus on the carry delay for the sake of clarity, although the small communication delay does exist in our design.

The link delay for one road segment can be computed by considering the following two cases for the communication range of the relay node at intersection Ii in Fig. 3:

- Case 1: Immediate Forward: There is at least one vehicle (i.e., $k > 0$) moving toward the intended next intersection along the packet's forwarding path. The current packet carrier n_c forwards its packets to the relay node at intersection I_i. As shown in Fig. 3a, the relay node forwards the packets to vehicle n_k right away and the packets are forwarded up to vehicle n_1, that is, by the forwarding distance l_f, which is the length of the connected ad hoc network consisting of vehicles n_i for $i = 1..k$. Vehicle n_1 will carry the packets up to the communication range of the relay node at I_j, that is, by the carry distance l_c.

- Case 2: Wait and Carry: There is no vehicle (*i.e.,* $k = 0$) moving toward the intended next intersection along the packet's forwarding path. As shown in Fig. 3b, the current packet carrier n_c forwards its packets to the relay node at intersection I_i. The relay node stores the packets at its local storage as a packet holder until a vehicle moves on the road segment (I_i, I_j). The average waiting time is $\frac{1}{\lambda}$ where the vehicle arrival rate is λ on the road segment (I_i, I_j); note that we will explain how to obtain λ later. After this average waiting, the new packet carrier will carry the packets by the carry distance $l_c(= l - R)$.

Thus, we can compute the expectation of the link delay with the link delays of these two cases as follows:

$$d = \begin{cases} \frac{l - l_f - R}{v} & for\ case\ 1{:}\ immediate\ forward, \\ \frac{1}{\lambda} + \frac{l-R}{v} & for\ case\ 2{:}\ wait\ and\ carry, \end{cases}$$ (3)

$$E[d] = E[link\ \ delay\ \mid\ forward] * P[forword] + E[link\ \ delay\ \mid\ wait] * P[wait] = (\frac{l-R-E[l_f]}{v}) * \beta + (\frac{1}{\lambda} + \frac{l-R}{v})(1 - \beta),$$ (4)

$$\mathrm{Var[d]} = E[d^2] - (E[d])^2 = ((l-R)^2 - 2(l-R)E\left[l_f\right] + E[l_f^2])/(v^2) * (\beta) + \left(\frac{1}{\lambda} + \frac{l-R}{v}\right)^2 (1-\beta) - \left(\frac{l-R-E\left[l_f\right]}{v} * (\beta) + \left(\frac{1}{\lambda} + \frac{l-R}{v}\right)(1-\beta)\right)^2$$ (5)

Now we explain how to obtain the vehicle arrival rate λ and the forwarding probability β per road segment. First, the vehicle arrival rate λ can be obtained with Fig. 3 as follows: Whenever a vehicle passes through the intersection I_i toward the neighboring intersection I_j, it reports its passing time stamp for the relay node at I_i. With a series of reported passing time stamps for the road segment (I_i, I_j), the relay node at the entrance intersection I_i can compute λ for the outgoing edge (I_i, I_j) by averaging the sum of the vehicle interarrival times and taking the reciprocal (each other) of the average. In the same way, the relay node at the exit intersection I_j can compute the arrival rate λ for the incoming edge (I_i, I_j) with the passing time stamps for I_j.

Second, the forwarding probability β can be computed with Fig. 3 as follows: Let T be the passing time from the intersection of a relay node to the communication range R of the relay node. When the vehicle speed is v, the passing time is computed as $T = \frac{R}{v}$. Suppose that the vehicle arrival at the directed edge (I_i, I_j) is Poisson process with vehicle arrival rate λ. The probability that at least one vehicle arrives at the entrance intersection I_i for the duration T means the forwarding probability. Thus, from the Poisson process probability that the arrival number N is at least one (*i.e.,* $N > 0$) for the unit time, the forwarding probability β can be computed as follows:

$$\mathrm{P[forward]} = P[N > 0] = \beta = 1 - e^{-\lambda T} = 1 - \mathrm{e}^{-\left(\frac{\lambda R}{v}\right)}.$$ (6)

Finally, with the mean $E[d]$ in (4) and variance $\mathrm{Var[d]}$ in (5) of the link delay, we model the link delay d as the Gamma distribution. Note that the Gamma distribution is usually used to model the positive continuous random variable, such as the waiting time and lifetime. Based on the Gamma distribution, a simplified mathematical model is used in this paper to obtain the packet's link delay distribution over a road segment, however, our design can accommodate an empirical link delay distribution if available through measurement. For this empirical distribution of link delay, adjacent relay nodes can periodically exchange probe packets with each other to obtain link delay samples. These samples are periodically processed by the relay nodes, which report the link delay statistics to TCC.

Thus, the distribution of the link delay d_i for the edge $e_i \in E(G)$ in the road network graph G is $d_i \sim \Gamma(k_i, \theta_i)$ such that $E[d_i] = k_i \Theta_i$ and $\mathrm{Var}[d_i] = k_i \theta_i^2$ for $d_i, k_i, \Theta_i > 0$. Since we have the mean and variance of the link delay, that is, $E[d_i] = \mu_i$ in (4) and $\mathrm{Var}[d_i] = \theta_i^2$ in (5), we can compute the parameters Θ_i and k_i of the Gamma distribution as follows:

$$\Theta_i = \frac{Var[d_i]}{E[d_i]} = \frac{\theta_i^2}{\mu_i}$$ (7)

In (7), the parameter Θ_i is computed by dividing the link delay variance by the mean link delay

$$\mathrm{k_i} = \frac{E[d_i]}{\Theta_i} = \frac{\mu_i}{\Theta_i} = \frac{\mu_i^2}{\Theta_i^2}$$ (8)

In (8), the parameter k_i is computed by dividing the mean link delay by the parameter Θ_i in (7).

Up to now, we have modeled the link delay for a directed edge corresponding to a road segment. Next, with the distribution of the link delay for each edge, we can compute the E2E packet delay from the AP to the target point, assuming the independence of the link delays for the road segments consisting of the E2E forwarding path from the AP to the target point.

3.2 E2E Packet Delay Model

In this section, we model the End-to-End Packet Delay from one position to another position in a given road network. As discussed in Section 3.1, the link delay is modeled as the Gamma distribution of $d_i \sim \Gamma(k_i, \Theta_i)$ for edge $e_i \in E(G)$ in the road network graph G. Given a forwarding path from AP to a target point, we assume that the link delays of edges consisting of the path are independent. From this assumption, the mean and variance of the E2E packet delay are computed as the sum of the means and the sum of the variances of the link delays along the E2E path, respectively. If the forwarding path consists of N edges, the mean and variance of the E2E packet delay distribution can be computed as follows:

$$E[P] = \sum_{i=1}^{N} E[d_i] = \sum_{i=1}^{N} \mu_i, \quad (9)$$

$$Var[P] = \sum_{i=1}^{N} Var[d_i] = \sum_{i=1}^{N} \sigma_i, \quad (10)$$

With (9) and (10), the E2E packet delay distribution can be modeled as $P \sim \Gamma(k_p, \Theta_p)$ such that $E[P] = k_p \Theta_p$ and $Var[P] = k_p \Theta_p^2$ for $P, k_p, \Theta_p > 0$.

3.3 Vehicle Delay Model

In this section, we model the Vehicle Delay from one

position to another position in a given road network. Given the road network graph G, the travel time for edge $e_i \in E(G)$ is modeled as the Gamma distribution of $t_i \sim \Gamma(k_i, \Theta_i)$; note that the travel time distribution for each road segment can be obtained through vehicular traffic measurement and is usually considered the Gamma distribution. The parameters k_i and Θ_i of the Gamma distribution are computed with the mean travel time μ_i and the travel time variance σ_i^2 using the relationship among the mean $E[t_i]$, the variance $Var[t_i]$, k_i, and Θ_i such that $E[t_i] = k_i \Theta_i$ and $Var[t_i] = k_i \Theta_i^2$ for $t_i, k_i, \Theta_i > 0$ as follows:

$$\Theta_i = \frac{Var[t_i]}{E[t_i]} = \frac{\Theta_i^2}{\mu_i}, \quad (11)$$

In (11), the parameter Θ_i is computed by dividing the travel time variance by the mean travel time

$$k_i = \frac{E[t_i]}{\Theta_i} = \frac{\mu_i}{\Theta_i} = \frac{\mu_i^2}{\Theta_i^{\ 2}}, \quad (12)$$

In (12), the parameter k_i is computed by dividing the mean travel time by the parameter Θ_i in (11).

Given a vehicle trajectory from the vehicle's current position to a target point, we suppose that the travel times of edges consisting of the trajectory are independent. Especially, this assumption is valid in light-traffic vehicular networks where vehicles are a little affected by other vehicles in their travel.

Assuming that the trajectory consists of N edges, in the same way with the Packet Delay Model in Section 3.2, the mean $E[V]$ and variance $Var[V]$ of the E2E vehicle delay can be computed such that $E[V] = \sum_{i=1}^{N} \mu_i$ and $Var[V] = \sum_{i=1}^{N} \sigma_i$. Therefore, the E2E vehicle delay distribution can be modeled as $V \sim \Gamma(k_v, \Theta_v)$ such that $E[V] = k_v \Theta_v$ and $Var[V] = k_v \Theta_v^2$ $fo\ rV, k_v, \Theta_v$.

4 TSF PROTOCOL

In this section, we explain the protocol of our Trajectory-based Statistical Forwarding.

4.1 Forwarding Protocol

For the TSF forwarding protocol, the TSF packet format contains two important fields: 1) Forwarding Path and 2) Vehicle Trajectory. Forwarding Path is the list of the intersections for the source routing from AP to the target point. Vehicle Trajectory is the destination vehicle's trajectory, that is, the series of intersections on the destination vehicle's trajectory. With this TSF packet format, the data packets will be forwarded toward the destination vehicle.

First, the destination vehicle periodically reports its future trajectory and current position to TCC to receive data packets from APs through TCC. With this vehicle trajectory registered into TCC, TSF will forward the data packets from AP to the destination vehicle by the following two steps: 1) The First-Step Forwarding from AP to Target Point (in Section 4.1.1) and 2) The Second-Step Forwarding from Target Point to Destination Vehicle (in Section 4.1.2).

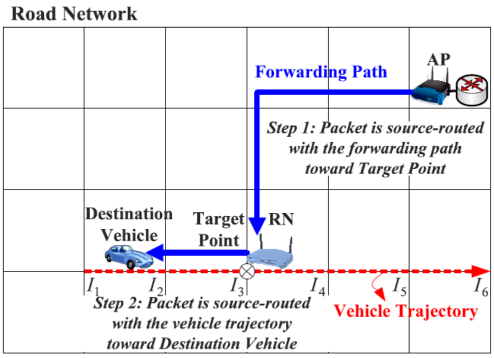

Fig. 4. TSF forwarding protocol.

4.1.1 The First-Step Forwarding from AP to Target Point

The first-step forwarding is to forward a packet through the source routing along the forwarding path from AP to the target point. When TCC has data packets to forward a destination vehicle, it computes the forwarding path for an optimal target point at the transmission time and forwards the data packets to an appropriate AP as the first hop. This first-hop AP will try to forward the packets to a vehicle moving along the forwarding path when the vehicle comes into the communication range of the AP. As shown in Fig. 4, the forwarding path is the shortest packet delay path from AP to the target point I3 determined by TCC with the optimization in (1). For example, as shown in Fig. 1, the forwarding path is n12 -> n13 -> n14 -> n9 -> n10. The relay nodes on the forwarding path are trying to forward the packets to carriers moving toward their neighboring relay nodes along the forwarding path.

During the forwarding process, it should be noted that only one packet copy exists in the vehicular network because TSF is a unicast data forwarding scheme. Thus, the current packet holder (i.e., AP, relay node, or current carrier) deletes its packet copy after forwarding the packet to the next hop (i.e., next carrier, relay node, or destination vehicle). In Fig. 1, the AP at n12 will try to forward the packets to a vehicle moving toward the neighboring relay node at n13 on the forwarding path. The intermediate relay nodes at n13, n14, and n9 will try to forward the packets to their neighboring relay node along the forwarding path. In this way, the packet will be delivered to the relay node corresponding to the target point n10 in Fig. 1.

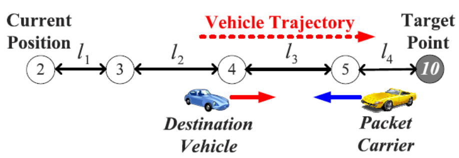

Fig. 5. Reverse path forwarding for vehicle trajectory.

6.1.2 The Second-Step Forwarding from Target Point to Destination Vehicle

The second-step forwarding is to forward a packet through the source routing along the reverse path of the vehicle trajectory from the target point toward the destination vehicle.

As shown in Fig. 4, when the packet arrives at the relay node corresponding to the target point I_3, the relay node will hold the packet until a vehicle passes it. If a vehicle is heading for the next intersection I_2 on the reverse path of $I_3 \rightarrow I_2 \rightarrow I_1$, the relay node at I_3 will forward its packet to the vehicle.

For example, in Fig. 5, if the relay node corresponding to the target point n10 finds a vehicle moving reversely on the destination vehicle's trajectory (i.e., on n10 -> n5), it will forward its packet to the vehicle as next carrier. Note that the packet copy at the relay node is deleted after it is forwarded to the next carrier. The current carrier carries and forwards the packet to the next carrier moving toward the destination vehicle. As a reminder, when the packet is received by the next carrier, the packet copy at the current carrier is deleted. If the carrier goes out of the vehicle trajectory at n5 in Fig. 5 and there is not any other vehicle moving toward the destination, it forwards its packet to the relay node at n5 on the vehicle trajectory before its leaving from the vehicle trajectory. The relay node at n5 that takes over the packet will try to forward the packet to another carrier moving toward the destination vehicle along the reverse path of the vehicle trajectory. This process is repeated until the packet can be delivered to the destination vehicle.

The rationale of the reverse-path forwarding is that the optimization for a target point in (1) provides an optimal target point with the minimum packet delivery delay while satisfying the required delivery probability. This indicates that the packet will hit the destination vehicle along the destination vehicle's trajectory if the packet follows the reverse path of the vehicle trajectory. Of course, there is some probability that the packet arrives at the target point later than the destination vehicle. In this case, the packet will not hit the destination vehicle, so will be discarded after its TTL expiration.

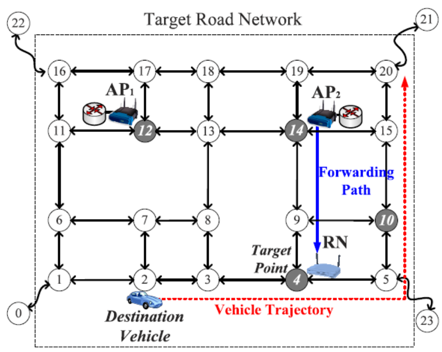

Fig. 6. Data forwarding with multiple APs.

4.2 Data Forwarding with Multiple APs

In a large-scale road network, multiple APs are usually required to accommodate the infrastructure-to-vehicle data delivery. In this case, an AP with the minimum delivery delay can send the packets to a destination vehicle among the multiple APs; note that the multiple APs are interconnected with each other via the wired network (e.g., the Internet), so the communication delay among the APs is negligible compared with the carry delay with the time unit of second. Also, note that the multiple APs share the estimated link delays of road segments (discussed in Section 3.1) to compute the E2E packet delay from their position to a target point. We can easily extend our data forwarding framework for this multiple-AP road network as follows: We determine *the Expected Vehicle Delay (EVD) of the destination vehicle for the multiple APs as the minimum among the EVDs for the APs* as follows:

$$\mathrm{EVD}^* \leftarrow \min_{k \in AP} EVD_k \quad , (13)$$

where AP is the set of APs and EVD_k is the EVD of the destination vehicle for access point AP_k; note that the AP with the minimum EVD will try to send packets to the destination vehicle. For example, Fig. 6 shows the road network graph with two access points AP1 and AP2. The EVD^* is $\min\{\mathrm{EVD}_1, \mathrm{EVD}_2\}$ where EVD_1 and EVD_2 can be computed using (1) to satisfy the required delivery probability α, respectively. In this figure, as a target point, AP1 and AP2 select n10 and n4, respectively. Thus, the packet from AP1 to n10 can be received after EVD1 and the packet from AP2 to n4 can be received after EVD2. Since EVD2 < EVD1, only AP2 will send the packet toward its target point n4.

Note that APs can be interconnected via wireless links as Mesh Networks. In this case, the road segments within the coverage of these APs have no carry delay. That is, the link delay of these road segments can be considered zero. Even for this setting, our TSF protocol can still be used by adjusting the link delays in the road network graph.

In a large-scale road network, one TCC might not scale up to provide many vehicles with the reverse data forwarding. For this system scalability, TCC can have multiple servers having the replicas of the trajectories and also the large-scale road network can be divided into multiple regions that have their own TCC for the TSF data forwarding. Each TCC per region performs the reverse data forwarding in the centralized way with the trajectory information.

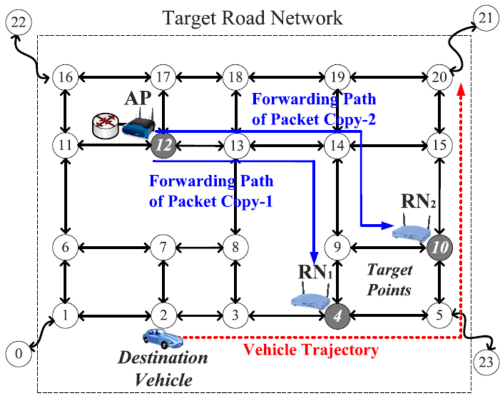

Fig. 7. Data forwarding with multiple target points.

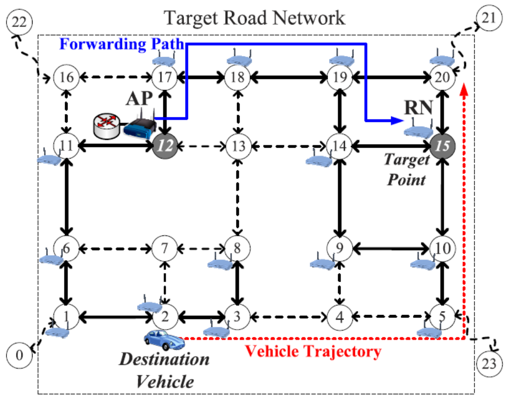

Fig. 8. The partial deployment of relay nodes.

4.3 Data Forwarding with Multiple Target Points

Up to now we have discussed the data forwarding for a single target point. However, under the light vehicular traffic, the forwarding with a single target point may not provide the reliable data delivery by guaranteeing the user-required data delivery ratio α. In this case, we can select multiple target points to satisfy α and send one copy of a packet to each target point. In this section, we discuss how to select multiple target points for the given α.

In the multiple target point selection, our objective is to select a minimum number of target points (i.e., a minimum number of packet copies) to satisfy the delivery probability α. For this objective, the following optimization is used: Let I be the intersection set on the destination vehicle's trajectory. Let $\mathrm{f}(\mathrm{S})$ be the multi-target-point objective function such that $\mathrm{f}(\mathrm{S}) = D(S) + c|S|$ for target point set $\mathrm{S} \in \mathrm{I}$ and $c > 0$ where $D(S)$ is the average delivery delay for S. Note: for the detailed derivation of $D(S)$. The coefficient c is set to a positive value such that a small subset S_a always has a smaller objective function value than a large subset S_b; that is, $f(S_a) < f(S_b)\ for\ |S_a| < |S_b|$. For the detailed computation of c; c is set to

$|E|[V_n] - E[V_1]$ (i.e., the difference between the maximum delivery delay and the minimum delivery delay). Thus, the following optimization is used for an optimal target point set S^* :

$$S^* \leftarrow argmin_{S \subset I} f(S) \ \ subject \ \ to \ \ 1 - \prod_{i \in S} P[P_i > V_i] \geq \ \ \alpha. \quad (14)$$

For example, Fig. 7 shows the selection of multiple target points under the delivery probability threshold ▯. In this figure, according to (14), intersections n4 and n10 are target points to minimize the delivery delay with the delivery success probability no less than α.

In (14), the searching of a minimum set of target points may be costly in terms of computation because the searching considers the possible combinations of target points. For a practical purpose, we can limit the upper bound of the number of target points (as maximum target point number) that can give a reasonable delivery probability for the given threshold α. Note that this multiple-target-point data forwarding can be performed in road networks with multiple APs through the combination of (13) and (14).

4.4 The Partial Deployment of Relay Nodes

In this section, we discuss data forwarding under the partial deployment of relay nodes in the given road network; that is, some intersections might not have their own relay nodes. In this case, we filter out the edges without RN from the road network graph, as shown in Fig. 8. In the figure, the dotted edges are the filtered ones. With this filtered graph, we can run our target point selection algorithm in Section 2 without any change. Note that the subgraph with the solid edges is used to cover the road network for the reverse data delivery. Clearly, as the number of relay nodes decreases, the data delivery probability from the AP to the destination vehicle will decrease. In the partial deployment of relay nodes, it is important to investigate how to deploy a certain number of relay nodes to guarantee the required delivery delay and delivery ratio.