A Static-Node Assisted Adaptive Routing Protocol in Vehicular Networks

Yong Ding
Department of Computer Science and Engineering
Michigan State University
East Lansing, MI 48824
dingyong@cse.msu.edu

Chen Wang
Department of Computer Science and Engineering
Michigan State University
East Lansing, MI 48824
wangchen@cse.msu.edu

Li Xiao
Department of Computer Science and Engineering
Michigan State University
East Lansing, MI 48824
lxiao@cse.msu.edu

ABSTRACT

Vehicular networks have attracted great interest in the research community recently, and multi-hop routing becomes an important issue. To improve data delivery performance, we propose SADV, which utilizes some static nodes at road intersections in a completely mobile vehicular network to help relay data. With the assistance of static nodes at intersections, a packet can be stored in the node for a while and wait until there are vehicles within communication range along the best delivery path to further forward the packet, which reduces the overall data delivery delay. In addition, we let adjacent nodes measure the delay of forwarding data between each other in real time, so that the routing decision can adapt to changing vehicle densities. Our simulation results show that SADV outperforms other multi-hop data dissemination protocols, especially under median or low vehicle density where the network is frequently partitioned.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless communication*; C.2.2 [**Computer-Communication Networks**]: Network Protocols—*Routing protocols*

General Terms

Algorithms, Design

Keywords

mobile ad-hoc networks, vehicular networks, geographic forwarding, trajectory based forwarding

1. INTRODUCTION

Vehicular networks have attracted great interest in the research community recently. Since FCC allocated 75 MHz of spectrum at 5.9GHz for Dedicated Short-Range Communications (DSRC) [1], many potentially useful applications have been envisioned in vehicular networks [2] [3]. These range from safety applications, such as vehicle collision avoidance, to other valuable applications such as real-time traffic estimation for trip planning, information retrieval, and media content sharing. Moreover, vehicular networks also have the prospect of improving sensing and wireless coverage in the future [4]. For example, by embedding sensors in vehicles, a mobile sensor network can be established to monitor road states and other environmental conditions in large areas. The vehicular networks can also act as "delivery networks" to transfer data from remote sensor-nets to Internet servers.

Most of the previous research on inter-vehicle communication is limited to vehicles within one hop or few hops away [2] [3] [5] [6] [7], such as communicating with nearby upstream traffic vehicles to avoid collision. However, it is also important to send data from a vehicle to a destination several miles away through multi-hop relay by a number of intermediate vehicles. For example, the sensing data from a vehicle may need to be sent to a sink that is deployed miles away, or a vehicle may want to send queries to a remote site such as gas station, restaurant, or parking area. Thus, a multi-hop routing algorithm is needed in a large vehicular network for these applications.

A vehicular network can be regarded as a special type of mobile ad hoc network (MANET) with some unique features. First, as vehicles move at high speeds the topology of the vehicular network changes rapidly. Second, unlike MANETs where an end-to-end connection is usually assumed, vehicular networks are frequently disconnected depending on the vehicle density. In addition, the movement of vehicles is constrained by the roads, which renders many topology holes in the network. These characteristics make the classical MANET routing algorithms inefficient in vehicular networks, and significantly influence the design of alternative routing protocols.

VADD [8] and MDDV [9] are two multi-hop routing protocols in vehicular networks. They abstract each road as a link where the packet delivery delay depends on the vehicle density on the road. Therefore, a packet will be delivered along the currently available shortest-delay trajectory to the destination.

There are two problems in the current routing protocols for vehicular networks. 1) The routing performance is quite sensitive to the vehicle density. Under high vehicle density,

VANET'07, September 10, 2007, Montréal, Québec, Canada.

there is high probability that vehicles are available along the shortest-delay trajectory towards the destination to further deliver the packet. However, when the vehicle density is median or low, the second best, third best, or even the worst path may be taken at an intersection, because there may not be any vehicles along the best path at the moment so that those worse paths are the only choices. This makes the actual packet delivery route deviate far from the optimal one, leading to a dramatic increase in packet delivery delay. 2) The real shortest-delay trajectory may not be taken under inaccurate delay estimation of each road. Previous studies estimate the packet delivery delay along each road based on some statistical parameters, such as the speed limit and the average vehicle density on the road. Nevertheless, as the vehicle density often varies with time, this statistical result may not be an accurate estimation of the current packet delivery delay along each road.

In this paper, we propose SADV, a Static-node assisted Adaptive data Dissemination protocol for Vehicular networks, which addresses these problems. We suggest employing mechanisms that enable the packet to wait at an intersection until the best path is available. To achieve this, we add static nodes at intersections that store and forward the packet when appropriate. Our simulation shows that this can dramatically improve the packet delivery performance. In addition, to get a more accurate delay estimation of forwarding packets along each road, we let the static nodes measure the packet forwarding delay in real time. Therefore, the routing decision in each static node can adapt to changing vehicle densities on the roads. Furthermore, we also study how multi-path routing can help decrease the packet delivery delay by increasing the probability of hitting the optimal trajectory under inaccurate delay estimation of each road.

The rest of the paper is organized as follows. Previous studies are summarized in Section 2. The motivation of our work is introduced in Section 3. The detailed description of our routing protocol SADV is in Section 4. In Section 5, we evaluate our proposed approach by simulation. We conclude our work in Section 6.

2. RELATED WORK

There have been many studies on delivering messages in sparse mobile ad hoc networks with sporadic connectivity and ever-present network partitions. In these networks with extreme conditions, traditional routing algorithms that assume the fully connected path between hosts become inefficient.

"Opportunistic forwarding" has been proposed for the case of random movement of mobile nodes [10] [11] [12]. Epidemic routing [10] ensures eventual message delivery by random pair-wise exchanges of messages between mobile hosts when they meet. The work in [11] used the motion of vehicles on a highway for message delivery, that is, the intermediate vehicle will store the message temporarily until it finds opportunities to forward the message further. The ZebraNet project [12] utilized the similar idea of carrying and forwarding the message on mobile nodes.

Some other studies employed controlled mobility to help message delivery [13] [14] [15]. In [13], a routing path between the source and destination is formed by recruiting the intermediate hosts to change their trajectories. This approach aims at minimizing the trajectory modification while getting the message across as fast as possible. Message Ferry [14] utilized special mobile nodes called message ferries, which move non-randomly in the deployed area, to help data delivery in a sparse network. Similarly, [15] introduced special hosts, which move in a coordinated way to sweep the motion space and act as intermediate pools, to facilitate message delivery to mobile users.

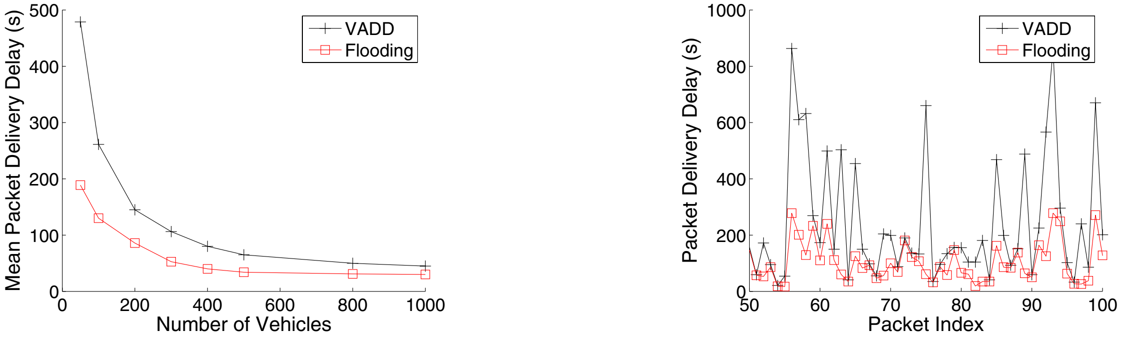
Vehicular network (VANET) is a special type of mobile ad hoc network (MANET). The most distinguished feature of VANET is that vehicles have some restricted mobility pattern. Specifically, all vehicle movements are constrained in roads, which have a static structure. Vehicles can only move in either direction on the road, and move at a speed restricted by the speed limit. In addition, some vehicles, such as buses, have pre-determined routes. Many algorithms have been proposed to utilize this predictable mobility for data delivery in VANET.

The authors of [16] suggest to utilize the non-randomness in the movement of mobile nodes. Vehicles can learn the movement pattern in the form of the meeting likelihood of pairwise nodes from the network, and use it to inform an adaptive routing strategy. [17] [18] used a similar idea and proposed routing protocols in the VANET formed by buses, whose mobility pattern can be well used to facilitate successful data delivery. "Trajectory based forwarding" [19] [20] further utilizes the static structure of road maps. It can be considered as an extension to geographic forwarding in that messages are forwarded greedily along a pre-defined trajectory.

MDDV [9] and VADD [8] are two multi-hop routing protocols, which well utilize the predictable mobility in VANET for data delivery. They abstract each road as a link whose delay is the time consumed to deliver a packet through the corresponding road by the multi-hop communication and the carrying of moving vehicles on this road. Therefore, packets will be delivered along the shortest-delay trajectory. In cases when no vehicles are available in the next road for data delivery along the optimal trajectory, VADD improves packet delivery reliability by making a routing decision at each intersection to select a best currently available trajectory. Different from MDDV and VADD, our work focuses on data delivery in VANET under low vehicle densities, where VADD experiences dramatic performance degradation in packet delivery delay, and MDDV even renders poor reliability.

There are also some protocols proposed for efficient flooding in VANET. [21] designed a reliable MAC broadcast protocol for omni-directional and directional transmissions. [22] proposed a multi-hop broadcast protocol, which utilizes the static structure of road maps to broadcast data directionally along roads. [23] proposed a geocast framework where the flooding of packets considers both spatial and temporal constraints. Our work is focused on unicast of packets from a mobile vehicle to a static location. Because of the highly mobile feature of VANET, broadcast is not used in routing discovery.

To evaluate routing protocols in VANET by simulation, various traffic mobility models have been studied. [24] [25] [26] present models to simulate vehicle movements in real road maps, while [27] evaluates routing protocols based on realistic public and private traffic over real regional road maps of Switzerland. We use the model in [24] to evaluate our protocol because we believe that it can capture the dynamics of the problem we want to address in this paper.



(a) Mean Packet Delivery Delay (b) Packet Delivery Delay under 100 Vehicles

Figure 1: Performance of VADD under Different Vehicle Densities

3. DATA DISSEMINATION UNDER DIFFERENT VEHICLE DENSITIES

In VADD [8], a routing decision is made each time a packet reaches an intersection and VADD will continue to forward the packet along the best currently available path towards the destination. A path is currently available if there are vehicles within wireless transmission range from the intersection at the moment to further deliver the packet along the path. In this section, we will evaluate the performance of VADD under different vehicle densities, which explains the motivation for our work.

To evaluate the performance of VADD with regard to packet delivery delay, we use the delay of epidemic flooding [10] as a baseline. In epidemic flooding, two vehicles exchange packets whenever they can communicate. Assume there is no packet loss due to transmission collision, epidemic flooding is the quickest way to deliver a packet to its destination. Therefore, we use this value as the lower bound in our analysis.

Fig.1 illustrates the performance of VADD under different vehicle densities. We extract a regional road map from TIGER [28], which is shown in Fig.8. The simulation is performed on this road topology with different numbers of vehicles. The detailed experiment setting is explained in Section 5. As shown in Fig.1(a), when the vehicle density is high, the mean packet delivery delay of VADD is close to that of Epidemic Flooding. However, the gap increases with the decreasing vehicle density. Moreover, VADD becomes unstable under low vehicle densities. Fig.1(b) shows the comparison of the delivery delay of individual packets between VADD and Epidemic Flooding when 100 vehicles are simulated in the area. We can observe that the packet delivery delay of some packets is much larger than that of Epidemic Flooding while the delay of some other packets is close or even equal to the optimal value.

There are two reasons for this performance degradation. 1) VADD chooses the best currently available path at each intersection. However, when the vehicle density is low, the optimal path may not always be available at the moment. Thus, VADD has to deliver packets via detoured paths. In the worst case, the packet may go through a much longer path as indicated by the peaks in Fig.1(b). 2) The estimation of packet forwarding delay through each road is based on some statistical data such as the average vehicle density, because it is expensive to have each vehicle get up-to-date vehicle densities from some infrastructures. As the vehicle density on each road may vary with time, which greatly influences the packet forwarding delay, the shortest-delay path calculated based on the statistical data may not reflect the real optimal one. Due to these reasons, we propose SADV in this paper, which can improve the performance of data dissemination under low vehicle densities in VANET.

4. SADV DESIGN

Since the best path is not always available at the moment a packet reaches an intersection, we can deploy a static node at each intersection to assist packet delivery. The static node can store the packet for some time until the best path becomes available to deliver the packet. As illustrated in Fig.2, a packet is forwarded by wireless communication through vehicles A, B to the static node S. When the packet reaches S, the best path to deliver it is northward. However, there are no vehicles within communication range along this road at that time. Thus, S will store the packet for a while, and forward it to the vehicle C when C passes the intersection and enters the northward road. From the figure, we can see that without the help of the static node, the packet will be carried by B to the eastward road if B does not meet C at the intersection, which may lead to a much longer packet delivery path.

We assume that each vehicle knows its location through the GPS service, which is already available in most new cars and will be common in the future. In addition, each static node has a digital street map, based on which the packet forwarding trajectory is determined. In this section, we will present the design of SADV, a Static-node assisted Adaptive data Dissemination protocol for Vehicular networks. SADV consists of three modules: SNAR (Static Node Assisted Routing), LDU (Link Delay Update) and MPDD (Multi-Path Data Dissemination). SNAR utilizes static nodes at intersections to store and forward data through optimal paths, while LDU and MPDD further decrease the packet delivery delay in VANET.

4.1 Static Node Assisted Routing

Assume the static node deployed at intersection v_i is s_i. Let s_i and s_j be two adjacent static nodes, then the expected delay of delivering a packet from s_i to s_j through road v_iv_j

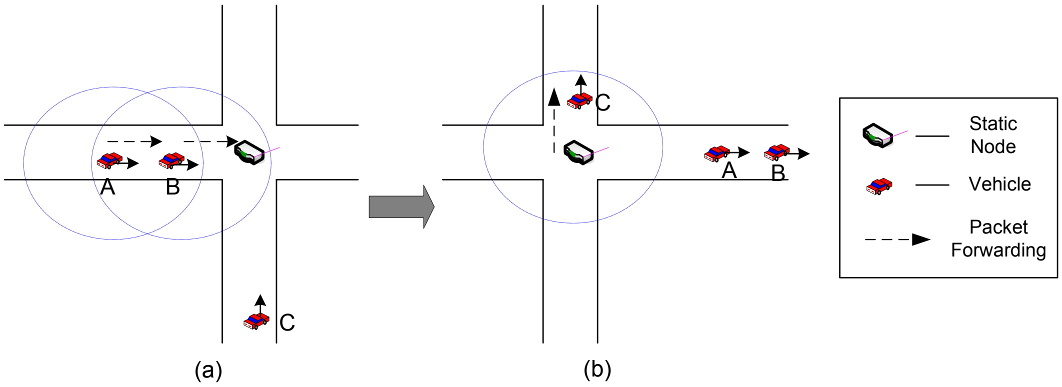


Figure 2: Static Node Assisted Routing in VANET

can be calculated as:

$$d(s_i s_j) = w(s_i s_j) + t(v_i v_j)$$

where $w(s_i s_j)$ denotes the expected waiting time of a packet at s_i for vehicles coming into communication range to deliver the packet toward s_j along $v_i v_j$, and $t(v_i v_j)$ denotes the expected time taken to deliver a packet through $v_i v_j$ given that vehicles are currently available for transmitting the packet at s_i along $v_i v_j$.

Suppose vehicles enter road $v_i v_j$ with an average rate of λ, then

$$\lambda = speed(v_i v_j) \times density(v_i v_j)$$

where $speed(v_i v_j)$ and $density(v_i v_j)$ represent the average speed and average vehicle density on the road, respectively. Therefore, the expected waiting time can be calculated as:

$$w(s_i s_j) = \frac{1}{\lambda} = \frac{1}{speed(v_i v_j) \times density(v_i v_j)}$$

On the other hand, $t(v_i v_j)$ is dependent on the vehicle density, average speed, and length of the road, that is,

$$t(v_i v_j) = f(density(v_i v_j), speed(v_i v_j), length(v_i v_j)) \quad (1)$$

In the extreme case where there are very few vehicles in the road, packets are delivered only by the carrying of vehicles. Thus the packet delivery delay equals $length(v_i v_j)/speed(v_i v_j)$. While in the case of very high vehicle density, the packet will be delivered through multi-hop wireless communication, whose delay is negligible with regard to the former case. In this paper, we use the formula in [8] to evaluate this value.

Given the road map of the region and assuming there is a static node at each intersection, we can abstract the vehicular network as a directed graph $G(V, E)$, where V is the set of static nodes and E is the set of directed roads. Weight d on E is the expected packet forwarding delay between adjacent static nodes. As the movement of vehicles is directional, the packet forwarding delay from s_i to s_j, denoted as $d(s_i s_j)$, is often different from the forwarding delay in the reverse direction, denoted as $d(s_j s_i)$. As each static node has a digital map of the region, it can abstract the map as a directed graph and thus generate a delay matrix, which contains the packet forwarding delay between adjacent static nodes. Therefore, SNAR tries to deliver a packet through the minimum-weight path, or the shortest expected delay path to the destination. The packet delivery service will be accomplished by the relay of both intermediate vehicles and static nodes at intersections along the optimal path.

SNAR operates in two modes, that is, in-road mode and intersection mode. When a packet is carried by a vehicle in a road, the SNAR stack in the vehicle operates in in-road mode, using geographic forwarding to deliver the packet greedily to the static node at the next intersection. When a packet is in a static node at an intersection, the SNAR stack in the node operates in intersection mode. It determines the optimal route to deliver the packet based on its delay matrix, and stores the packet until vehicles are available to forward the packet to the next-hop static node.

For the in-road mode, two strategies can be used for geographic forwarding with regard to whether it should resort to the vehicles running in the opposite direction on the same road for packet forwarding. As shown in Fig.3, if these vehicles are used, the packet may be delivered to the next intersection faster through the chance that the vehicle running in the opposite direction may have wireless connection to a further vehicle in the same direction. Otherwise, however, the packet may be delivered back to the original vehicle when it turns out to be closer to the intersection than the vehicle in the opposite direction, which incurs greater packet delivery overhead.

Fig.4 shows the state transition diagram of the intersection mode. Upon arrival of new packets, SNAR scans adjacent roads for delivery opportunities. If SNAR finds that the road along the optimal path of the packet is available currently, that is, there are vehicles within communication range in this road that may deliver the packet further, it will transmit the packet to the farthest vehicle. Otherwise, SNAR will enter a waiting state and check for delivery opportunities some time later. As packets may be stored in the static node for some time before being delivered further, buffer management is a critical issue when the buffer turns out to be full in the static node. In this case, some packets must be eliminated from the buffer. Instead of being directly dropped, these packets can be delivered immediately through the best currently available paths, without decreasing the packet delivery reliability.

Several buffer management strategies can be used:

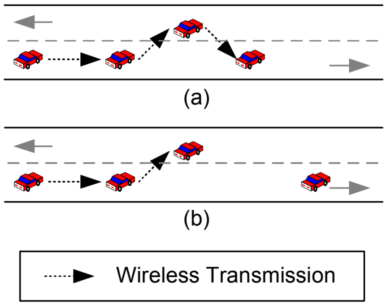


Figure 3: In-road Geographic Forwarding

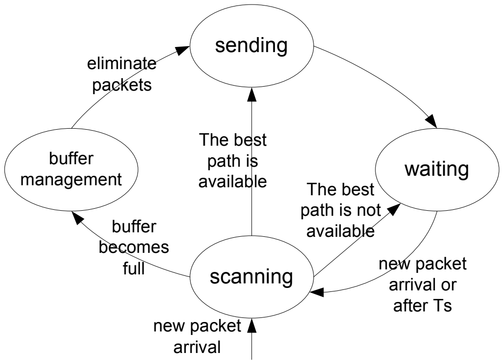


Figure 4: State Transition Diagram of the Intersection Mode

(1) FIFO (First In First Out), where the packets that stay the longest in the buffer are eliminated first. However, this is not a good strategy because these packets may have more chance of being forwarded along the optimal path after waiting for quite a long time in the static node.
(2) FILO (First In Last Out), where the most recently arrived packets are eliminated first. However, as these packets have just arrived, the best or even the second best path is possibly not available yet. As a result, the packets may be routed along some much longer paths.
(3) The elimination strategy we used in SNAR is called *least delay increase*, which aims at reducing the increase in the overall packet delivery delay caused by sending packets along sub-optimal paths. The basic idea is as follows. Suppose the static node is at intersection v_i. In this node, we define a priority vector $[p_1, p_2, ..., p_m]$ for each packet, where m is the number of adjacent roads of v_i, and p_j is the ranking of the optimality of the corresponding road. For example, if v_i has 4 adjacent roads, $[2, 1, 3, 4]$ means the first adjacent road corresponds to the second best path, while the second adjacent road corresponds to the best path, and so on. The static node will scan for currently available roads, thus the rank of the currently best path can be determined for each packet, which we call *instant rank*. As for the example above, if the first and fourth adjacent roads are available, then the first road corresponds to the currently best path of delivering the packet, and thus the instant rank is 2. In our strategy, the packets with the highest instant rank will be eliminated from the buffer first. Instead of being directly dropped, these packets will be forwarded along the best currently available paths. Intuitively, this strategy tries to forward some packets along sub-optimal paths in the hope that they will not differ significantly from the optimal paths. Therefore, this strategy is favorable to preserve low packet delivery delay in VANET.

4.2 Link Delay Update

In the previous section, the routing decision is made on a delay matrix, where the delay of each link is estimated based on the statistical vehicle density in each road. However, our simulation shows that the packet forwarding delay varies with time because of the variation of vehicle density on the road. In addition, as the vehicle density is quite stable during a period of time, the packet forwarding delay also remains at different stable levels during different periods of time. In order to let static nodes obtain a more accurate packet forwarding delay estimation for each link, we introduce LDU module in this section, which measures the delay of each link in real time and propagates the up-to-date estimation among static nodes.

Let s_i and s_j be two adjacent static nodes, and assume a packet is to be forwarded from s_i to s_j. To measure the packet forwarding delay $d(s_i s_j)$, we insert a single field *stime* into the packet head. When s_i receives the packet for further delivery, it immediately records the current time in *stime*. Then when the packet reaches s_j, s_j can calculate the measured packet forwarding delay:

$$d'(s_i s_j) = etime - stime$$

where *etime* is the current time. Therefore, each static node s_j is able to obtain the measured delay of all its incoming links $\{s_i s_j\}$.

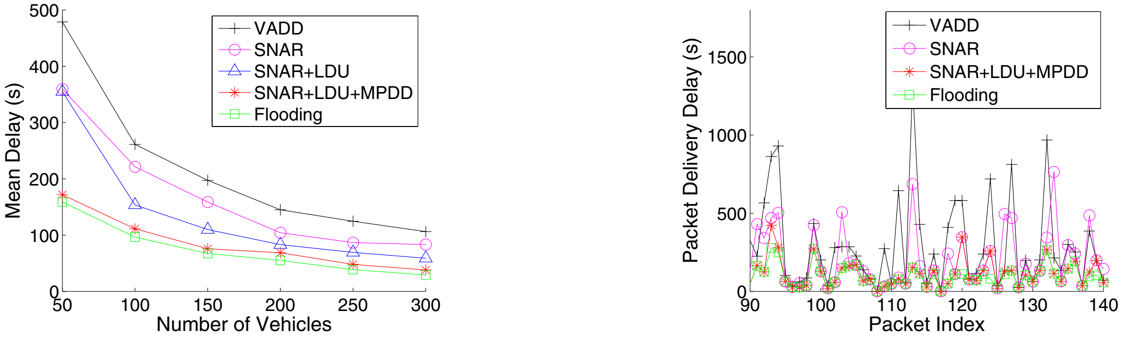
Let the delay matrix maintained by each s_i be d^i. Initially, the delay of each link in the matrix is calculated by formula (1) based on statistical data. Let $\overline{d'}(s_j s_i)$ be the mean of the measured delay $d'(s_j s_i)$ over time interval I. Thus, each s_i can obtain $\overline{d'}(s_j s_i)$ for all of its incoming links in each interval. In SADV, each static node exchanges with other nodes the mean measured delay it has observed during each interval I, so that each node gets a more complete up-to-date delay matrix.

The propagation of the mean measured delay observed in each static node is in the form of *delay update message*, which consists of records in the following form:

< *src_id, dst_id, delay, seq, expire* >

where *src_id* and *dst_id* are the IDs of the starting and ending static node, *delay* is the mean measured packet forwarding delay during interval I from *src_id* to *dst_id*, *seq* is the sequence number indicating the freshness of the message, and *expire* denotes the time when the information in the message becomes invalid.

Once each static node s_i obtains $\overline{d'}(s_j s_i)$, it encapsulates them into the *delay update message*, and informs other nodes by broadcast. The broadcast is realized by the carry and forward of vehicles from one static node to its adjacent nodes.



(a) Mean Packet Delivery Delay

(b) Packet Delivery Delay for Individual Packets

Figure 5: Performance of SADV Under Different Vehicle Densities

The process is similar to *Link-State Broadcast* [29]. To reduce overhead, each static node only broadcasts the freshest delay measurement for the same link, which is identified by *seq*, and each message is broadcasted only once at each node. Upon receiving a delay update message, each static node modifies its delay matrix accordingly. Suppose s_k receives the delay measurement of the link $s_m s_n$, then d^k will be modified by the following formula.

$$d^k(s_m s_n) = k_1 \cdot d^k(s_m s_n) + k_2 \cdot \overline{d'}(s_m s_n)$$

where k_1 and k_2 are two coefficients satisfying $k_1 + k_2 = 1$.

4.3 Multi-Path Data Dissemination

In classical studies, multi-path routing has often been used to improve data delivery reliability or achieve load balance in network communications. In this paper, we are interested in decreasing the packet delivery delay by routing packets through multiple paths.

In the VANET, if the packet forwarding delay between each two adjacent static nodes cannot be estimated correctly, the shortest-delay path computed based on the estimated delay matrix may not be the real optimal one. This motivates us to utilize multi-path routing, when the packet load in the VANET is not high, to decrease the packet delivery delay by trying to hit a faster path than the single-path routing.

Packets are delivered through multiple paths only at intersections. Therefore, multi-path routing can be realized by only some additional support in static nodes, without any modifications of the protocol stack in vehicles. Assume a packet is in s_i at present. Let $N(s_i)$ be the set of static nodes that are adjacent to s_i. According to some strategy, s_i selects a subset of $N(s_i)$, denoted by $N_s(s_i)$. s_i will send a copy of the packet to each static node in $N_s(s_i)$, and thus the packet will be delivered along multiple paths. In order to reduce the overhead caused by multi-path routing, we let each static node s_i remember the packets it has sent out for some time T_m. If the same packet arrives at s_i from other paths later, it simply ignores this packet.

We use the following strategy to choose $N_s(s_i)$ out of $N(s_i)$. Let s_i compute the priority vector $[p_1, p_2, ..., p_m]$ for the packet. Then s_i will send the packet through the roads corresponding to the best and second best paths. For example, if the priority vector is $p = [2, 3, 1, 4]$, then the packet will be forwarded to both the first and third adjacent static nodes. This strategy applies when the estimation of the link delay is not accurate, so that it will increase the chance of hitting a better or even the real optimal path.

5. PERFORMANCE EVALUATION

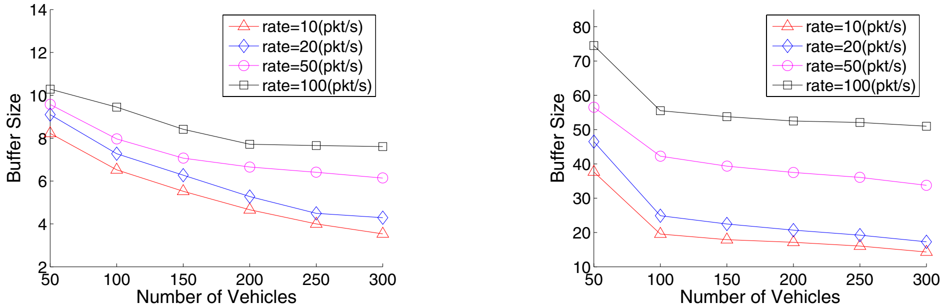
In this section, we evaluate the performance of SADV as compared with VADD. We perform the simulation on a real street map, which we extract from TIGER [28]. The Tiger database contains detailed information of each road, such as the positions of the two ends of each road and the type of each road. As shown in Fig.8, we extract a regional urban area from the Tiger database with the range of $4000m \times 5000m$, which contains 70 intersections. The speed limit of each road is determined based on the road type. In the figure, there are two high-speed roads (painted in bold) with speed limits over $50mph$, and the other roads are of local speed ranging from $25mph$ to $45mph$. As the Tiger database does not identify one-way streets, we regard all roads in the map as two-way streets.

We simulate different numbers of vehicles in the area to test our protocol. The mobility model for each vehicle is based on [24]. When the simulation starts, each vehicle determines a random destination, and then selects a quickest path or a shortest path with equal probability to the destination. Upon arriving at its destination following the predetermined path, each vehicle reselects a random destination and moves on again. In our experiments, we assume that each vehicle has a wireless communication range of $200m$.

5.1 Packet Delivery Delay of SADV

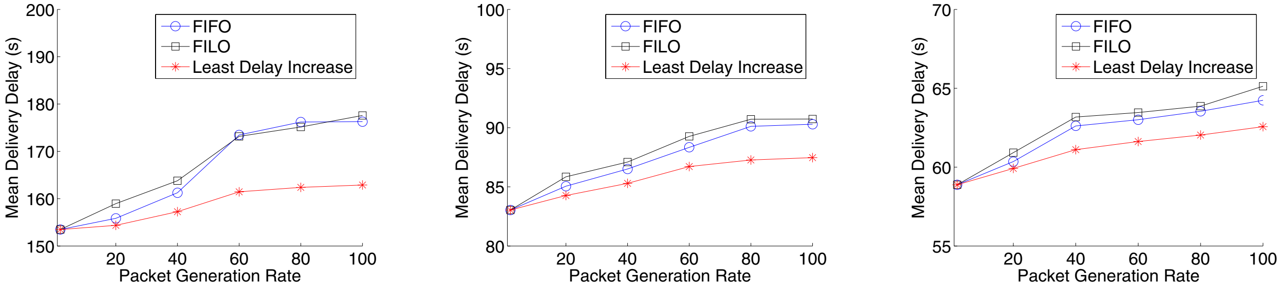
In our simulation, we randomly select vehicles to generate packets with random destinations in the map. We control the total packet generation rate in the map at 10 packets per second. We use different data dissemination protocols to deliver the packets, and finally compute the mean packet delivery delay of all the packets in order to compare different protocols. In the simulation, we assume that each static node has enough buffer such that no packet elimination occurs. We will evaluate SADV with limited buffer capacity of static nodes later. The total simulation time is set to one hour. The simulation is repeated under different vehicle densities, and the results are shown in Fig.5.

As shown in Fig.5(a), the bottom curve corresponds to the performance of Epidemic Flooding, which has the lowest



(a) Mean Buffer Size over All Static Nodes (b) Maximum Average Buffer Size

Figure 6: Buffer Size in Static Nodes



(a) 100 vehicles (b) 200 vehicles (c) 300 vehicles

Figure 7: Performance of SADV under Different Packet Sending Rates

packet delivery delay. The curve in this figure differs slightly with Fig.1(a), because in this simulation the flooding process utilizes both vehicles and static nodes. Therefore, this can be regarded as the lower bound of packet delivery delay in the vehicular network where a static node is deployed at each intersection.

In the figure, we show the performance of VADD, SNAR, SNAR + LDU, and SNAR + LDU + MPDD. VADD suffers from high packet delivery delay, especially under low vehicle densities. When 50 simulated vehicles are in the area, the mean packet delivery delay of VADD is more than twice the lower bound. This is because VADD may route packets through detoured paths instead of the optimal paths. SNAR delivers packets with the assistance of static nodes at intersections. If LDU is not used, the packet forwarding delay through each link can only be estimated by the statistical vehicle density, which is similar to VADD. We can observe that SNAR decreases the packet delivery delay to some extent, which indicates that the static nodes can help improve the packet delivery performance. If we use LDU to inform the static nodes of the up-to-date packet forwarding delay through each link, the performance can be further improved. One exception is that when the traffic density is very low, such as below 100 vehicles, LDU does not benefit the packet delivery performance that much, because the link delay update message may not be propagated to the nearby static nodes in time under low vehicle densities before it becomes out-of-date. Furthermore, when MPDD is used, the performance can be further improved, which is close to that of epidemic flooding. As can be seen from Fig.5(a), both LDU and MPDD can help reduce the packet delivery delay. They achieve the same goal through different methods. LDU tries to help static nodes choose the real optimal path by providing a more accurate delay estimate of each link, while MPDD tries to hit the optimal path through multi-path delivery.

Fig.5(b) shows the delivery delay of individual packets using different routing protocols. In this experiment, the traffic density is fixed at 100 vehicles. As can be seen from the figure, VADD sometimes experiences very large delay, which is indicated by the peaks. In contrast, SNAR is much better at avoiding delivering packets through very long paths. However, we can observe that the delay of SNAR is higher than VADD for a few packets. This is because SNAR did not compute the real optimal paths for these packets due to the inaccurate link delay estimations. However, if LDU is used with SNAR, the packet delivery delay is lower than VADD for each packet. Moreover, if LDU and MPDD are both used, the packet delivery delay of most packets is close or equal to the lower bound.

5.2 Buffer Management in Static Nodes

In our experiments, we also analyze the buffer size in the static nodes. In the simulation, we first assume that the buffer of each static node is large enough such that no packet elimination occurs. We set different packet generation rates, and record the buffer size of each static node at different times. The statistical results are shown in Fig.6. In Fig.6(a), we compute the mean buffer size over all static nodes, which reflects how many packets on average reside in a static node each time in the vehicular network. As we can see, the mean

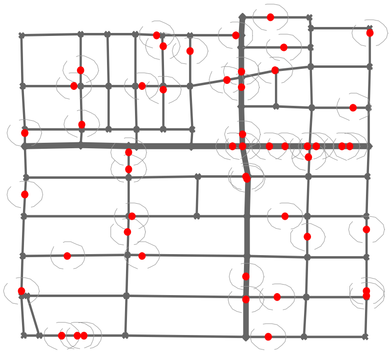


Figure 8: Road Topology used in the Simulation

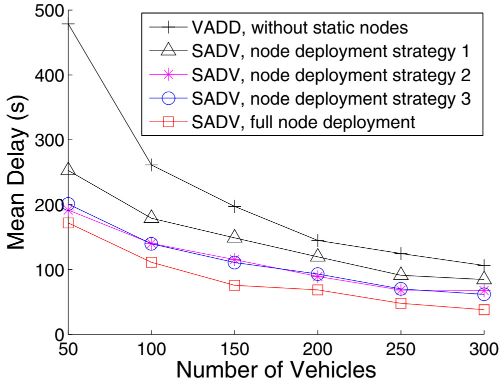


Figure 9: Performance of SADV under Different Node Deployment Strategies

buffer size increases with the packet generation rate. In addition, when the traffic density increases, the mean buffer size decreases, because the packets in buffers have higher chances to be further delivered when there are more vehicles around. Fig.6(b) illustrates the maximum average buffer size among all static nodes under different traffic densities and packet generation rates. We can observe the same trend as Fig.6(a).

In the previous experiment of SADV evaluation, we assume that the buffer size is large enough in each static node. In this section, we limit the buffer capacity of each static node, and evaluate SADV (SNAR+LDU) with different packet elimination strategies under different vehicle densities. We set the buffer capacity to 55 for each static node, which equals the maximum average buffer size under 100 vehicles, and then simulate SADV on the road topology setting with 100, 200 and 300 vehicles respectively. Under a specific vehicle density, we vary the total packet generation rate in the network, and compare the mean packet delivery delay corresponding to different packet elimination strategies. The simulation results are shown in Fig.7. As can be seen in the figure, when the packet generation rate is low, the buffer is rarely overflowed. Thus, the performance is similar for different elimination strategies. However, when the packet generation rate is increased, the Least Delay Increase strategy apparently outperforms the other two strategies.

5.3 SADV under Partial Deployment of Static Nodes

In this section, we evaluate the performance of SADV when only part of the intersections are equipped with static nodes to assist data delivery. We study three node deployment strategies.

- Uniform Deployment: Deploy static nodes uniformly based on space.
- High-degree Preferred: The intersections with more connected roads have priority to be equipped with static nodes.
- High-speed Preferred: The intersections along high-speed roads have priority to be deployed with static nodes.

As shown in Fig.8, there are a total of 70 intersections on the road map. We deploy 35 static nodes based on the three different strategies, and simulate SADV under different vehicle densities. The results are shown in Fig.9. The bottom curve corresponds to SADV when each intersection is deployed with a static node, and the top curve corresponds to VADD, where the results are the same as in the previous section. We can observe that the resulting performance depends on the node deployment strategies. In the figure, node deployment strategies 1, 2, 3 correspond to Uniform Deployment, High-degree Preferred, and High-speed Preferred strategies respectively. The performance of SADV under High-degree Preferred and High-speed Preferred strategies is better than SADV under Uniform Deployment strategy. The simulation results indicate that, given a specific number of static nodes, placing static nodes at high-degree and high-speed intersections both have better effect of reducing data delivery delay.

The reason why the latter two deployment strategies are better can be explained as follows. If the degree of the intersection is high, a packet has more choices of routes to be forwarded along when it reaches the intersection. Thus, the deployment of static nodes in these intersections has more chance of leading to a dramatic improvement in packet delivery performance. In addition, there are usually more vehicles in the high-speed roads because vehicles tend to take these faster roads to get to their destinations. The packet delivery delay through these roads is usually lower than the other small roads. If we place static nodes at these intersections, we can guarantee that the packet will not be routed through other small roads and that it will not miss the best delivery path.

6. CONCLUSION

As the vehicular network is completely composed of mobile nodes, the multi-hop data delivery performance may degrade under median or low vehicle densities where the network is frequently disconnected. In such cases, the performance may be improved by adding some static nodes at intersections to assist data delivery. In this paper, we present SADV, a Static-node assisted Adaptive data Dissemination protocol for Vehicular networks, which reduces the data delivery delay through three mechanisms. In SNAR

(Static Node Assisted Routing), when a packet reaches an intersection, it will be stored in the static node until the best delivery path becomes available to further deliver the packet. In LDU (Link Delay Update), the adjacent static nodes measure the link delay between each other in real time, so that the routing decision can be made adaptive to the changing vehicle densities. In addition, MPDD (Multi-Path Data Dissemination) can be used to further decrease the packet delivery delay by trying to hit a faster delivery path. Our simulation results show that SADV outperforms other routing protocols under median and low vehicle densities. We also evaluate SADV under partial deployment of static nodes.

7. ACKNOWLEDGEMENT

This work was supported in part by the US National Science Foundation under grants CCF-0514078, CNS-0551464, and CNS-0721441.

8. REFERENCES

[1] "Dedicated Short Range Communications (DSRC) home," http://www.leearmstrong.com/dsrc/dsrchomeset.htm.

[2] Q. Xu, T. Mark, J. Ko, and R. Sengupta, "Vehicle-to-vehicle Safety Messaging in DSRC," in *Proceedings of VANET*, October, 2004.

[3] J. Yin, T. ElBatt, G. Yeung, B. Ryu, S. Habermas, H. Krishnan, and T. Talty, "Performance Evaluation of Safety Applications over DSRC Vehicular Ad Hoc Networks," in *Proceedings of VANET*, October, 2004.

[4] B. Hull, V. Bychkovsky, Y. Zhang, K. Chen, M. Goraczko, E. S. A. Miu, H. Balakrishnan, and S. Madden, "CarTel: A Distributed Mobile Sensor Computing System," in *4th ACM SenSys*, November 2006.

[5] X. Yang, J. Liu, F. Zhao, and N. Vaidya, "A Vehicle-to-Vehicle Communication Protocol for Cooperative Collision Warning," in *Int'l Conf. on Mobile and Ubiquitous Systems: Networking and Services (MOBIQUITOUS)*, August, 2004.

[6] T. Nadeem, P. Shankar, and L. Iftode, "A Comparative Study of Data Dissemination Models for VANETs," in *Int'l Conf. on Mobile and Ubiquitous Systems: Networks and Services (MOBIQUITOUS)*, July 2006.

[7] S. Ghandeharizadeh, S. Kapadia, and B. Krishnamachari, "PAVAN: A Policy Framework for Content Availabilty in Vehicular Ad-hoc Networks," in *Proceedings of VANET*, 2004.

[8] J. Zhao and G. Cao, "VADD: Vehicle-Assisted Data Delivery in Vehicular Ad Hoc Networks," in *InfoCom*, 2006.

[9] H. Wu, R. Fujimoto, R. Guensler, and M. Hunter, "MDDV: Mobility-Centric Data Dissemination Algorithm for Vehicular Networks," in *Proceedings of VANET*, 2004.

[10] A. Vahdat and D. Becker, "Epidemic routing for partially connected ad hoc networks," Tech. Rep., 2000.

[11] Z. Chen, H. Kung, and D. Vlah, "Ad Hoc Relay Wireless Networks over Moving Vehicles on Highways," in *MobiHoc*, 2001.

[12] P. Juang, H. Oki, Y. Wang, M. Martonosi, L. Peh, and D. Rubenstein, "Energy-efficient computing for wildlife tracking: Design tradeoffs and early experiences with zebranet," in *ASPLOS*, Oct. 2002.

[13] Q. Li and D. Rus, "Sending messages to mobile users in disconnected ad-hoc wireless networks," in *Mobile Computing and Networking*, 2000.

[14] W. Zhao, M. Ammar, and E. Zegura, "A message ferrying approach for data delivery in sparse mobile ad hoc networks," in *MobiHoc*, 2004.

[15] I. Chatzigiannakis, S. Nikoletseas, and P. Spirakis, "An Efficient Communication Strategy for Ad-Hoc Mobile Networks," in *DISC*, 2001.

[16] J. A. Davis, A. H. Fagg, and B. N. Levine, "Wearable computers as packet transport mechanisms in highly-partitioned ad-hoc networks," in *ISWC '01: Proceedings of the 5th IEEE International Symposium on Wearable Computers*, 2001.

[17] B. Burns, O. Brock, and B. Levine, "MV Routing and Capacity Building in Disruption Tolerant Networks," in *InfoCom*, 2005.

[18] J. Burgess, B. Gallagher, D. Jensen, and B. N. Levine, "Maxprop: Routing for vehicle-based disruption-tolerant networking," in *InfoCom*, 2006.

[19] J. Tian, L. Han, K. Rothermel, and C. Cseh, "Spatially Aware Packet Routing for Mobile Ad Hoc Inter-vehicle Radio Networks," in *Proc. of the IEEE 6th Intl. Conf. on Intelligent Transportation Systems (ITSC)*, 2003.

[20] D. Niculescu and B. Nath, "Trajectory Based Forwarding and Its Applications," in *MobiCom*, 2003.

[21] R. Yadumurthy, A. Chimalakonda, M. Sadashivaiah, and R. Makanaboyina, "Reliable MAC Broadcast Protocol in Directional and Omni-Directional Transmissions for Vehicular Ad Hoc Networks," in *Proceedings of VANET*, 2005.

[22] G. Korkmaz and E. Ekici, "Urban Multi-Hop Broadcast Protocol for Inter-Vehicle Communication Systems," in *Proceedings of VANET*, 2004.

[23] C. Maihofer, T. Leinmuller, and E. Schoch, "Abiding Geocast: Time-stable Geocast for Ad Hoc Networks," in *Proceedings of VANET*, 2005.

[24] A. K. Saha and D. B. Johnson, "Modeling Mobility for Vehicular Ad Hoc Networks," in *Proceedings of VANET*, 2004.

[25] R. Mangharam, D. Weller, R. Rajkumar, D. Stancil, and J. Parikh, "GrooveSim: A Topography-Accurate Simulator for Geographic Routing in Vehicular Networks," in *Proceedings of VANET*, 2005.

[26] D. Choffnes and F. Bustamante, "An Integrated Mobility and Traffic Model for Vehicular Wireless Networks," in *Proceedings of VANET*, 2005.

[27] V. Naumov, R. Baumann, and T. Gross, "An evaluation of inter-vehicle ad hoc networks based on realistic vehicular traces," in *MobiHoc*, 2006.

[28] http://www.census.gov/geo/www/tiger/.

[29] J. F. Kurose and K. W. Ross, *Computer Networking: A Top-Down Approach Featuring the Internet.*