VADD: Vehicle-Assisted Data Delivery in Vehicular Ad Hoc Networks

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Abstract—**Multi-hop data delivery through vehicular ad hoc networks is complicated by the fact that vehicular networks are highly mobile and frequently disconnected. To address this issue, we adopt the idea of carry and forward, where a moving vehicle carries the packet until a new vehicle moves into its vicinity and forwards the packet. Different from existing carry and forward solutions, we make use of the predicable vehicle mobility, which is limited by the traffic pattern and road layout. Based on the existing traffic pattern, a vehicle can find the next road to forward the packet to reduce the delay. We propose several vehicle-assisted data delivery (VADD) protocols to forward the packet to the best road with the lowest data delivery delay. Experimental results are used to evaluate the proposed solutions. Results show that the proposed VADD protocols outperform existing solutions in terms of packet delivery ratio, data packet delay and protocol overhead. Among the proposed VADD protocols, the H-VADD protocol has much better performance.**

I. Introduction

Vehicular ad hoc networks have been envisioned to be useful in road safety and many commercial applications [26], [28], [30]. For example, a vehicular network can be used to alert drivers to potential traffic jams, providing increased convenience and efficiency. It can also be used to propagate emergency warning to drivers behind a vehicle (or incident) to avoid multi-car collisions. To realize this vision, FCC has allocated 75 MHz of spectrum for dedicated short range communications (vehicle-vehicle or vehicle-roadside), and IEEE is working on standard specifications for intervehicle communication. As more and more vehicles are equipped with communication capabilities that allow for intervehicle communication, large scale vehicular ad hoc networks are expected to be available in the near future.

Quite a few researches have been done on intervehicle communication. Medium access control (MAC) issues have been addressed in [25], [18], [28], where slot-reservation MAC protocols [25], [18] and congestion control policies for emergency warning [28] are studied. Transportation safety issues have been addressed in [26], [30], where vehicles communicate with each other and with the static network nodes such as traffic lights, bus shelters, and traffic cameras. Data dissemination protocols [16], [27] have been proposed to disseminate information about traffic, obstacles, and hazard on the roads. Other applications such as real time video streaming between vehicles have been studied in [10].

Most of the aforementioned work is limited to one hop or short range multihop communication. On the other hand, vehicular ad hoc networks are also useful to other scenarios. For example, without internet connection, a moving vehicle may want to query a data center ten miles away through a vehicular ad hoc network. To further motivate our work, consider the widely deployed Wireless LANs or infostations [9] [11] which can be used to deliver advertisements and announcements such as sale information or remaining stocks at a department store; the available parking lot at a parking place; the meeting schedule at a conference room; the estimated bus arrival time at a bus stop. Since the broadcast range is limited, only clients around the access point can directly receive the data. However, these data may be beneficial for people in moving vehicles which are far away, as people driving may want to query several department stores to decide where to go; a driver may query the traffic cameras or parking lot information to make a better road plan; a passenger on a bus may query several bus stops to choose the best next stop for bus transfer. All these queries may be issued miles or tens of miles away from the broadcast site. With a vehicular ad hoc network, the requester can send the query to the broadcast site and get reply from it. In these applications, the users can tolerate up to seconds or minute of delay as long as the reply eventually returns.

Although aforementioned services can be supported by the wireless infrastructure (e.g., 3G), the cost of doing this is high and may not be possible when such an infrastructure does not exist or is damaged. From the service provider point of view, setting up a wireless LAN is very cheap, but the cost of connecting it to the Internet or the wireless infrastructure is high. From the user point of view, the cost of accessing data through the wireless carrier is still high and most of the cellular phone users are limited to voice service. Moreover, in case of disaster, the wireless infrastructure may be damaged, whereas wireless LANs and vehicular networks can be used to provide important traffic, rescue and evacuation information to the users.

Although the cost of setting up vehicular networks is high, many researchers and industry players believe that the benefit of vehicular networks on traffic safety and many commercial applications [26], [28], [30] should be able to justify the cost. In the near future, with such a vehicular network already in place, many of the proposed data delivery applications can be supported.

Multi-hop data delivery through vehicular ad hoc networks is complicated by the fact that vehicular networks are highly mobile and sometimes sparse. The network density is related to the traffic density, which is affected by the location and time. For example, the traffic density is low in rural areas and during night, but very high in the large populated area and during rush hours. Although it is very difficult to find an end-to-end connection for a sparsely connected network, the high mobility of vehicular networks introduces opportunities for mobile vehicles to connect with each other intermittently during moving. Namboodiri *et al.* [20] showed that there is a high chance for moving vehicles to set up a short path with few hops in a highway model. Further, a moving vehicle can carry the packet and forward it to the next vehicle. Through relays, carry and forward, the message can be delivered to the destination without an end-to-end connection for delay-tolerant applications.

This paper studies the problem of efficient data delivery in vehicular ad hoc networks. Specifically, when a vehicle issues a delay tolerant data query to some fixed site, how to efficiently route the packet to that site, and receive the reply within reasonable delay. The proposed vehicle-assisted data delivery (VADD) is based on the idea of carry and forward [8]. Different from existing carry and forwarding approaches [24], [8], [17], [31], we make use of the predicable mobility, which is limited by the traffic pattern and road layout. Extensive experiments are used to evaluate the proposed data delivery protocols. Results show that the proposed VADD protocols outperform existing solutions in terms of packet delivery ratio, data packet delay and protocol overhead.

The rest of this paper is organized as follows. Section II describes the related work on data delivery in sparsely connected ad hoc networks. Section III describes how to model the data delivery delay. The vehicle-assisted data delivery protocols will be presented in Section IV. Section V evaluates the performance of the proposed protocols. Section VI concludes the paper.

II. Data Delivery in Sparsely Connected Ad Hoc Networks

Data delivery in ad-hoc network heavily relies on the routing protocol, which has been extensively studied for many years. However, most protocols [13], [14], [21], [22] assume that intermediate nodes can be found to setup an end-to-end connection; otherwise, the packet will be dropped. To deal with disconnections in sparse ad hoc networks, researchers [8] adopt the idea of *carry and forward*, where nodes carry the packet when routes do not exist, and forward the packet to the new receiver that moves into its vicinity. There exist two categories of data delivery protocols that differ mainly on how much control is posed on the mobility in order to forward message from one node to another. One option is to follow the traditional ad hoc network literature, and add no control on mobility. The other option is to control the mobility of the mobile nodes to help message forwarding.

There are several protocols [24], [8] belong to the first category. The work by Vahdat and Becker [24] uses epidemic routing. Whenever two nodes meet, they exchange the data that they do not possess. The extensive data exchanges ensure eventual message delivery, given unbounded time and buffer, at the cost of many redundant packets. Epidemic routing seems to be an ideal solution to deal with partitioned network. However, to implement it in vehicular ad hoc network appears to be much more difficult than it seems, particularly in high density areas where infostations are usually deployed. Synchronizing these nodes to reduce collisions turns out to be a tough problem, and the excessively redundant data exchange easily leads to severe congestion at these areas, affecting both packet delivery ratio and delay. This limits its usefulness in large scale vehicular ad hoc networks. Davis *et al.* [8] improved the epidemic routing protocol by exploiting the mobility history to assist packet dropping to meet the buffer size constraint. However, they assume that nodes frequently met in the past should meet in the future, but this assumption may not hold in vehicular ad hoc networks where most vehicles meet only once even if they meet.

The protocols in the second category exploits controllable mobility. Li and Rus [17] proposed to have mobile nodes proactively modify their trajectories to transmit messages. Zhao *et al.* [31] proposed to add message ferry into the network, and control their moving trajectory to help data delivery. However, in vehicular networks, it is impossible to modify the trajectories of the moving vehicles or finding such ferries.

Briesemeister and Hommel [5] proposed a protocol to multicast a message among highly mobile vehicles. In this protocol, not all vehicles are equipped with wireless transceivers, and a vehicle is allowed to buffer the message until a new receiver moves into its vicinity. The idea of carry and forward has also been used in [7]. However, both papers [5], [7] did not give any protocol on how and when to carry and forward.

In summary, existing data delivery schemes either pose too much control or no control at all on mobility, and hence not suitable for vehicular networks. Different from the aforementioned work, we make use of the predictable vehicle mobility which is limited by the traffic pattern and road layout. For example, the driving speed is regulated by the speed limit and the traffic density of the road, the driving direction is predictable based on the road pattern, and the acceleration is bounded by the engine speed. Next, we propose protocols which exploit the vehicle mobility pattern to better assist data delivery. In this paper, we will not consider security issues and the motivation for vehicles to relay, which can be addressed by many existing techniques [6], [12], [19].

III. The VADD Model

In this section, we first give the assumptions, the overview of Vehicle-Assisted Data Delivery (VADD), and then present the VADD delay model.

A. Assumptions

We assume vehicles communicate with each other through short range wireless channel (100m-250m), and vehicles can find their neighbors through beacon messages. The packet delivery information such as source id, source location, packet generate time, destination location, expiration time, etc, is specified by the data source and placed in the packet header. A vehicle knows its location by triangulation or through GPS device, which is already popular in new cars and will be common in the future.

We assume that vehicles are equipped with pre-loaded digital maps, which provide street-level map and traffic statistics such as traffic density and vehicle speed on roads at different times of the day. Such kind of digital map has already been commercialized. The latest one is developed by MapMechanics [3], which includes road speed data and an indication of the relative density of vehicles on each road. Yahoo is also working on integrating traffic statistics in its new product called SmartView [1], where real traffic reports of major US cities are available. We expect that more detailed traffic statistics will be integrated into digital map in the near future. Note that the cost of setting up such a vehicular network can be justified by its application to many road safety and commercial applications [26], [28], [30], which are not limited to the proposed delay tolerant data delivery applications.

B. VADD overview

VADD is based on the idea of carry and forward. The most important issue is to select a forwarding path with the smallest packet delivery delay. Although geographical forwarding approaches such as GPSR [14] which always chooses the next hop closer to the destination, are very efficient for data delivery in ad hoc networks, they may not be suitable for sparsely connected vehicular networks.

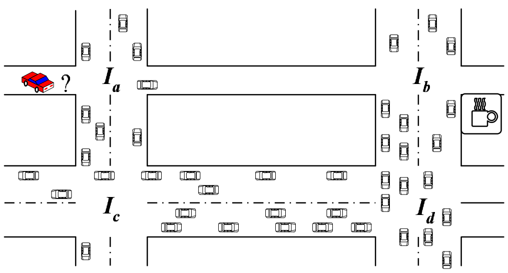


Fig. 1. Find a path to the coffee shop

As shown in Figure 1, suppose a driver approaches intersection I_a and he wants to send a request to the coffee shop (to reserve a sandwich) at the corner of intersection I_b. To forward the request through $I_a \rightarrow I_c$, $I_c \rightarrow I_d$, $I_d \rightarrow I_b$ would be faster than through $I_a \rightarrow I_b$, even though the latter provides geographically shortest possible path. The reason is that in case of disconnection, the packet has to be carried by the vehicle, whose moving speed is significantly slower than the wireless communication.

In sparsely connected networks, vehicles should try to make use of the wireless communication channel, and resort to vehicles with faster speed otherwise. Thus, our VADD follows the following basic principles:

1. Transmit through wireless channels as much as possible.
2. If the packet has to be carried through certain roads, the road with higher speed should be chosen.
3. Due to the unpredictable nature of vehicular ad-hoc networks, we cannot expect the packet to be successfully routed along the pre-computed optimal path, so dynamic path selection should continuously be executed throughout the packet forwarding process.

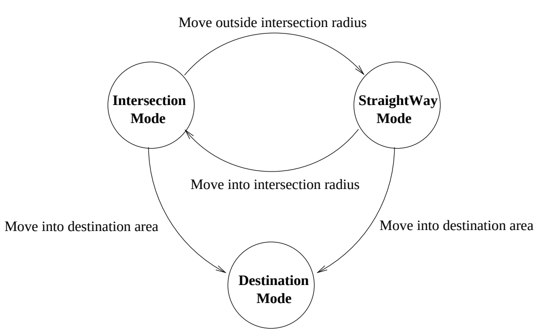


Fig. 2. The transition modes in VADD

As shown in Figure 2, VADD has three packet modes: *Intersection, StraightWay, and Destination* based on the location of the packet *carrier* (i.e., the vehicle that carries the packet.) By switching between these packet modes, the packet carrier takes the best packet forwarding path. Among the three modes, the Intersection mode is the most critical and complicated one, since vehicles have more choices at the intersection.

C. The VADD Delay Model

To formally define the packet delivery delay, we need the following notations.

- r_{ij}: the road from I_i to I_j.
- l_{ij}: the euclidean distance of r_{ij}.
- ρ_{ij}: the vehicle density on r_{ij}.
- v_{ij}: the average vehicle velocity on r_{ij}.
- d_{ij}: the expected packet forwarding delay from I_i to I_j.

$$d_{ij} = \begin{cases} \alpha \cdot l_{ij}, & \text{if } \frac{1}{\rho_{ij}} \leq R \\ \frac{l_{ij}}{v_{ij}} - \beta \cdot \rho_{ij}, & \text{if } \frac{1}{\rho_{ij}} > R \end{cases} \tag{1}$$

where R is the wireless transmission range. Equation 1 indicates that if the average distance between vehicles is smaller than R, wireless transmission is used to forward the packet. Otherwise, vehicles are used to carry the data. Even in this case, it is still possible to occasionally have wireless transmissions, and hence $\beta \cdot \rho$ is used as a correction factor.

One way to view the VADD delay model is to represent the vehicular network as a directed graph, in which nodes represent intersections and edges represent the roads connecting adjacent intersections. The direction of each edge is the traffic direction. The packet forwarding delay between two adjacent intersections is the weight of the edge. Given the weight on each edge, a naive optimal forwarding path selection scheme is to compute the shortest path from source to destination by applying *Dijkstra's* algorithm. However, this simple solution does not work, since we cannot freely select the outgoing edge to forward the packet at an intersection. Only those edges with vehicles on it to carry packets can be the candidate path for packet forwarding. However we can not know for sure which direction the packet will go at the next intersection. In other words, it is impossible to compute the complete packet forwarding path.

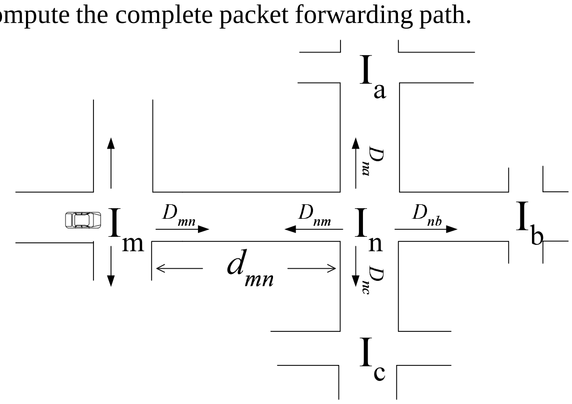


Fig. 3. An example of VADD Delay Model

To address this problem, we propose a stochastic model to estimate the data delivery delay, which is used to select the next road (intersection). We first introduces the following notations:

- D_{ij}: The expected packet delivery delay from I_i to the destination if the packet carrier at I_i chooses to deliver the packet following road r_{ij}.
- P_{ij}: the probability that the packet is forwarded through road r_{ij} at I_i.
- $N(j)$: the set of neighboring intersections of I_j.

As shown in Figure 3, for a packet at I_m, the expected delay of delivering the packet through road r_{mn} is:

$$D_{mn} = d_{mn} + \sum_{j \in N(n)} (P_{nj} \times D_{nj}) \tag{2}$$

Figure 4 illustrates how to apply Equation 2 to a simple triangle road, which only contains three intersections I_a, I_b, and I_c. Suppose a data packet reaches I_a, and the destination is I_c. The forwarding scheme needs to decide whether to forward the packet through the road to I_c or I_b. This is done by computing the value of D_{ac} and D_{ab}, and choosing the smaller one. By applying Equation 2, we have the following linear equations:

$$\begin{cases} D_{ac} = d_{ac} \\ D_{ab} = d_{ab} + P_{ba} \cdot D_{ba} + P_{bc} \cdot D_{bc} \\ D_{ba} = d_{ba} + P_{ab} \cdot D_{ab} + P_{ac} \cdot D_{ac} \\ D_{bc} = d_{bc} \\ D_{cb} = 0 \\ D_{ca} = 0 \end{cases} \tag{3}$$

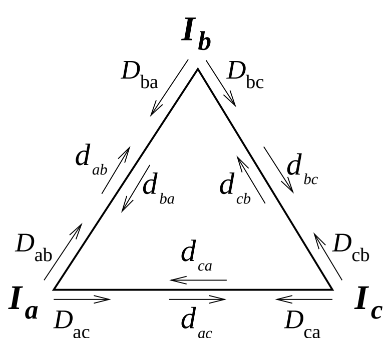


Fig. 4. One Road Graph

Note that both d_{cb} and d_{ca} are equal to 0, since the packet already arrives at destination c, and will not be forwarded anymore. We can easily solve Equation 3 and get D_{ac} and D_{ab}:

$$\begin{aligned} D_{ac} =& d_{ac} \\ D_{ab} =& \frac{1}{1 - P_{ab} \cdot P_{ba}} \times \\ & (d_{ab} + P_{ba} \cdot d_{ba} + \\ & P_{ba} \cdot P_{ac} \cdot d_{ac} + P_{bc} \cdot d_{bc}) \end{aligned}$$

Unfortunately, to find the minimum forwarding delay between two arbitrary intersections is impossible, since it involves unlimited unknown intersections. However, by placing a boundary including the source and the destination in a connected graph, we are able to find the expected minimum forwarding delay between them. Figure 5 shows one such boundary which includes the sender and the destination (hot spot). Certainly there are many other ways to place the boundary, as long as the destination has to be enclosed. Since only the roads within the boundary are used as available paths to compute the delay, a large boundary covering more high-density streets can generally find more close-to-optimal paths, but with more computation cost. Thus, there is a tradeoff between computation complexity and accuracy in delay estimation when selecting the boundary. Since this is not the major concern of this paper and it does not affect the correctness of our algorithms, we will not further discuss it in this paper.

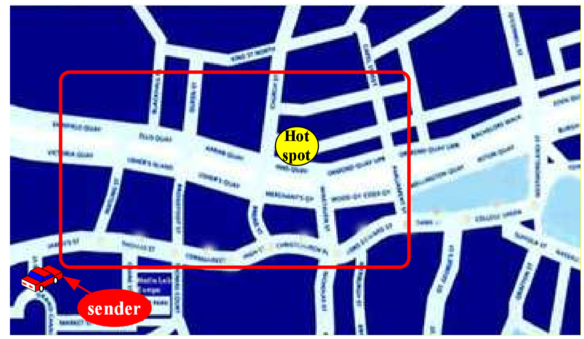


Fig. 5. Add a boundary

Since the number of intersections inside the boundary is finite, we can derive Equation 2 for each outgoing edge of every intersection within the boundary (similar to the method used to derive Equation 3). In this way, a $n \times n$ linear equation system is generated.

To follow the general representation of linear equation systems, we rename the unknown D_{ij} as x_{ij}, rename the subscript ij of d_{ij} and x_{ij} with a unique number for each pair ij, and rename the subscript of P_{ij} by its position in the equations. Then, we can derive n linear equations with n unknowns $x_1, x_2, \cdots, x_n$, where n equals to the number of roads within the boundary:

$$\begin{aligned} x_1 =& d_1 + P_{11}x_1 + P_{12}x_2 + \cdots + P_{1n}x_n \\ x_2 =& d_2 + P_{21}x_1 + P_{22}x_2 + \cdots + P_{2n}x_n \\ &\vdots \\ x_n =& d_n + P_{n1}x_1 + P_{n2}x_2 + \cdots + P_{nn}x_n \end{aligned}$$

It can be easily transformed to the following matrix.

$$\begin{aligned} (P_{11} - 1)x_1 + P_{12}x_2 & + \cdots + P_{1n}x_n & = -d_1 \\ P_{21}x_1 + (P_{22} - 1)x_2 & + \cdots + P_{2n}x_n & = -d_2 \\ & \vdots & \\ P_{n1}x_1 + P_{n2}x_2 & + \cdots + (P_{nn} - 1)x_n & = -d_n \end{aligned}$$

which is equivalent to

$$P \cdot X = -D \tag{4}$$

where $P = \begin{bmatrix} P_{11} - 1 & P_{12} & \cdots & P_{1n} \\ P_{21} & P_{22} - 1 & \cdots & P_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ P_{n1} & P_{n2} & \cdots & P_{nn} - 1 \end{bmatrix}$

$$X = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \quad \text{and} \quad D = \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_n \end{bmatrix}$$

The typical way to solve this equation is to use the *Gaussian Elimination* algorithm, which is known to be solved in time $\Theta(n^3)$.

By solving Equation 4, we get D_{ij} for the current intersection I_i. The packet carrier can sort D_{ij} for each neighboring intersection I_j, and forward the packet to the road with smaller delay. As a result, among all the vehicles within communication range (called *contacts*) available at the intersection, the packet will be forwarded to the one on the road with the smallest delay. If no contact is available or all available contacts are going through roads with longer delay than the packet carrier's next traveling road, the packet carrier passes the intersection with the packet, and looks for the next forwarding opportunity.

IV. VEHICLE-ASSISTED DATA DELIVERY PROTOCOLS

In this section, we present the VADD protocols. We first present protocols used in the Intersection mode and the contact model. Then we present protocols on the Straightway and protocols for data return.

A. VADD Protocols Used in the Intersection Mode

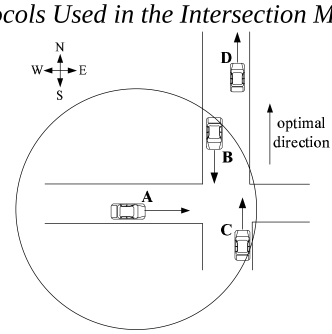


Fig. 6. Select the next vehicle to forward the packet

By deriving and solving Equation 4 at the intersection, the packet carrier can sort all the outgoing directions and check if there is a contact available to help forward through that direction. However, to determine the next hop among all available contacts and ensure a packet to go through the pre-computed direction is not trivial. As shown in Figure 6, vehicle A has a packet to forward to certain destination. Assume the optimal direction for this packet is North. There are two available contacts for the packet carrier: B moving south and C moving north. A has two choices on selecting the next hop for the packet: B or C. Both choices aim at forwarding the packet towards North: selecting B because B is geographically closer towards North and provides better possibility to exploit the wireless communication (e.g. B can immediately pass the packet to D, but C cannot;) whereas selecting C because C is moving in the packet forwarding direction. These two choices lead to two different forwarding protocols: *Location First Probe (L-VADD)* and *Direction First Probe (D-VADD)*.

A.1 Location First Probe (L-VADD)

Given the preferred forwarding direction of a packet, L-VADD tries to find the closest contact towards that direction as the next hop. First, based on Equation 4, D_{ij} can be obtained for each outgoing road r_{ij} at intersection I_i. As a result, each outgoing road is assigned a priority where smaller D_{ij} has higher priority. Next, the packet carrier checks the outgoing directions starting from the highest priority. For a selected direction, the packet carrier chooses the next intersection towards the selected direction as the *target* intersection, and apply geographical greedy forwarding towards the target intersection to pass the packet. If the current packet carrier cannot find any contact to the target intersection, it chooses the direction with the next lower priority and re-starts the geographical greedy forwarding towards the new target intersection. This process continues until the selected direction has lower priority than the packet carrier's current moving direction. At this time, the packet carrier will continue carrying the packet.

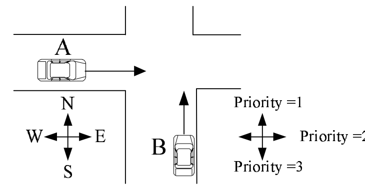


Fig. 7. A scenario of routing loop

As shown in Figure 6, vehicle A forwards the packet to B. Seems like this is better than selecting C as the next hop, since B can immediately forward packet to D. Even if D does not exist, selecting B seems as good as selecting C, since B will meet C shortly and the packet can be passed to C anyway. However, L-VADD may result in *routing loops*. Figure 7 shows one such scenario. Assume the North direction has the highest priority and East has the second highest priority. A first checks North and can not find any contact. Then, it checks East, and finds B which is closer towards East. Thus, it forwards the packet to B. Upon receiving the packet, B checks the North direction first and finds A is closer towards North, and then passing the packet back to A. There is a loop between A and B.

A simple solution to break the routing loop is to record the previous hop(s) information. As in the above example, A records its own id as the $previous\_hop$ before forwarding the packet to B. When B receives the packet, and decides to forward the packet to A, it checks the previous hop record and finds that A is the previous hop. To avoid a routing loop, B will not forward the packet to A, and look for the next available contact.

A routing loop may involve $n (n > 2)$ nodes. To detect such a routing loop, all these previous n hops should be recorded. However, such loop detection mechanism dramatically degrade the forwarding performance, since the detection mechanism may prevent many valid nodes from being considered as the next hop. As shown in Figure 7, if A is the packet carrier after a routing loop has been detected, and there is no other contact available except B. Suppose after both A and B pass the center of the intersection, A continues going East and B to North. The packet should be forwarded to B since B will move towards the best direction, and the path between A and B becomes loop-free. However, as the packet records B as the previous hop, forwarding the packet to B is not allowed. Therefore, even though we can record previous hop information to detect routing loops, many valid forwarding paths cannot be used.

A.2 Direction First Probe (D-VADD) and Multi-Path Direction First Probe (MD-VADD)

Routing loop occurs because vehicles do not have an unanimous agreement on the order of the priority, and then do not have an agreement on who should carry the packet. To address this issue, D-VADD ensures that everyone agrees on the priority order by letting the vehicle moving towards the desired packet forwarding direction carry the packet.

In D-VADD, the direction selection process is the same as L-VADD. For a selected direction, instead of probing by location (in L-VADD), D-VADD selects the contacts moving towards the selected direction. Among the selected contacts, the one closest to the selected direction is chosen as the next hop. As shown in Figure 6, D-VADD selects C as the next hop when the selected direction is North. Since B is not moving North, it will not be considered. Therefore, D-VADD only probes vehicles moving towards the direction whose priority is higher than or equal to the moving direction of current packet carrier. As the probing strictly follows the priority order of the direction, D-VADD has the following property: Any subsequent packet carrier moves towards the direction whose priority is higher than or equal to that of the current packet carrier.

Theorem 1: D-VADD is free from routing loops at intersection areas.

Proof: By contradiction, suppose a routing loop occurs and node A and B are in the circle, which indicates that at least one packet forwarded from A passes through B and returns to A. Consider the first case that A and B are moving in the same direction, and the packet is forwarded from A to B. It indicates that B is closer towards the destination direction than A, while packet passing back to A indicates the reverse. In the second case, if A and B move towards different direction, packet forwarded from A to B indicates B is moving towards the direction of higher priority than A's, while packet passing back to A shows A's direction has higher priority. Both cases lead to contradictions. Therefore, there is no routing loop in D-VADD. ■

In D-VADD, if there are available contacts which can help forward the packet, the packet may pass through the intersection quickly (in milliseconds). However, most likely, a vehicle entering an intersection passes the packet to a contact moving towards a sub-optimal direction before it meets the contact moving towards the optimal direction. It would be better if the packet carrier can carry the packet a little bit longer and pass the packet to the optimal direction. Certainly, this packet carrier should not hold the packet longer than the packet delay of going through the sub-optimal direction.

MD-VADD is inspired by this idea. In order to increase the chance of finding contacts to the optimal direction, the packet carrier does not delete the packet from its own buffer until it is forwarded towards the direction of the highest priority. More specifically, after a contact is selected as the next hop by D-VADD, the packet carrier passes a copy of the packet to the selected contact, and continues buffering the packet. In addition, it marks the packet as $SENT$, and record d_{sent} as the moving direction of the contact to which the packet has just been passed. Later, if the packet carrier meets another contact at the same intersection moving towards the direction whose priority is higher than d_{sent}, it sends another copy to the contact, and updates d_{sent} accordingly. Only when d_{sent} reaches the direction of the highest priority, the packet is deleted from the buffer. Immediately after the vehicle exits the Intersection Mode, it checks all buffer entries, and removes all packets that have been marked as $SENT$. Figure 8 illustrates the details of the MD-VADD protocol.

Notations:
- $\boldsymbol{I_n}$: the current intersection
- $\boldsymbol{p}$: the packet to forward
- $\boldsymbol{E}$[]: a list of all outgoing roads at I_n, sorted by the order of priority to forward p
- $\boldsymbol{N_n}$: the number of outgoing roads at I_n
- $\boldsymbol{V_{next}}$: next hop vehicle for p
- $\boldsymbol{P(r)}$: the priority of road r to forward packet p
- $\boldsymbol{I_{next}(r_{nj})}$: the neighbor intersection I_j (connected to I_n by r_{nj})

Enter Intersection:
  $d_{sent} \Leftarrow$ moving direction of the current packet carrier
Periodic Probing:
  i = 0
  while $i < N_n$ **and** $P(E[i]) \geq P(d_{sent})$ **do**
    $S \Leftarrow$ all neighbors moving towards road $E[i]$
    $V_{next} \Leftarrow$ the closest node to $I_{next}(E[i])$ in S
    $i++$
    if V_{next} is found **then**
      break
    end if
  end while
  if V_{next} is found **then**
    send a copy of the packet p to V_{next}
    if $P(E[i])$ is the highest priority at I_n **then**
      delete the packet from the buffer
    else
      mark the packet as *SENT*
      $d_{sent} \Leftarrow E[i]$
      continue to hold packet
    end if
  else
    continue to hold packet
  end if
  Repeat *Periodic Probing* at the next probing interval
Leave Intersection:
  purge all packets which have been marked *SENT*

Fig. 8. MD-VADD Protocol at Intersection I_n

In MD-VADD, some packets may be forwarded through multiple paths and a vehicle may receive a packet which is already in its buffer. In this case, the vehicle simply discards the duplicated packet. MD-VADD is expected to have better packet delivery ratio and lower packet delay than D-VADD. In the worst case, it has the same performance as D-VADD, since at least one copy of the packet will use the currently available contacts as in D-VADD. However, MD-VADD may involve multiple paths and create duplicate packets, which requires more buffer space and generates more network traffic.

A.3 Hybrid Probe (H-VADD)

Comparing to other VADD protocols, L-VADD without loop detection can minimize the packet forwarding distance and hence the delay if there is no loop. However, the routing loop in L-VADD severely affects the performance and leads to a low packet delivery ratio. Loop detection mechanism can remove the routing loop, but may also increase the forwarding delay. D-VADD and MD-VADD are free from routing loops; however, they give priority to the moving direction and may suffer from long packet forwarding distance, and hence long packet delivery delay.

An ideal VADD protocol should minimize the geographic forwarding distance and does not have routing loops. To achieve this goal, we design a scheme called Hybrid Probe (H-VADD), which works as follows. Upon entering an intersection, H-VADD behaves like L-VADD. If a routing loop is detected, it immediately switches to use D-VADD (or MD-VADD) until it exits the current intersection. In this way, H-VADD inherits the advantage of using the shortest forwarding path in L-VADD when there is no routing loop, and use D-VADD (or MD-VADD) to address the routing loop problem of L-VADD.

B. Calculating P_{ij}

In this section, we provide solutions to calculate P_{ij} used in Section III. Specifically, we choose MD-VADD as the data delivery protocol, because of its simplicity in modeling the packet forwarding process. Certainly, other protocols such as L-VADD and D-VADD can be modeled to calculate P_{ij} in a similar way. Our simulation results show that the P_{ij} value calculated under MD-VADD model also serves well enough for the other VADD protocols. The reason is that different VADD protocols follow similar principle, and would suggest similar optimal packet forwarding path.

We focus on the normal traffic layout, where each road has one-way or two-way traffic and intersections are either signalized or isolated [4]. Throughout this section we assume vehicle arrivals at intersections follow Poisson distribution.

The expected time that a packet carrier stays in the Intersection Mode is referred to as the *contacting time*. The contacting time at a signalized intersection I_i, denoted as t_i, is only related to the length of the signal interval at I_i. In an isolated intersection, vehicles in all directions can smoothly go through without being stopped. For a vehicle at I_i, we assume the average vehicle speed going through the intersection as the average vehicle speed at the outgoing road. Let R_{int} denote the radius of the intersection area which is a circle area with the intersection point as the center. Formula 5 computes the contacting time of a packet carrier which currently enters intersection I_i, and moves towards neighbor intersection I_j.

$$T_{ij} = \begin{cases} t_i, & I_i \text{ is signalized} \\ \frac{2R_{int}}{v_{ij}}, & I_i \text{ is isolated} \end{cases} \tag{5}$$

The packet carrier is able to forward the packet towards road r_{ij} at I_i, only if it can meet at least one contact going towards road r_{ij}. Next, we calculate the probability of meeting at least one contact towards road r_{ij}.

$$\begin{aligned} CP_{ij} =& P(N(T_{ij}) \geq 1) \\ =& 1 - P(N(T_{ij}) = 0) \\ =& 1 - e^{-\lambda_{ij} T_{ij})} \frac{(\lambda_{ij} T_{ij})^0}{0!} \\ =& 1 - e^{-\lambda_{ij} T_{ij}} \end{aligned}$$

where λ_{ij} is the average rate of contacts *leaving* I_i and moving towards road r_{ij}.

In MD-VADD, the packet carrier does not immediately remove the packet which has been passed to another carrier, and it may send the packet to multiple contacts towards different directions. In this protocol, although duplicated packets may be sent at the intersection, P_{ij} is only relevant to the packet expected to experience the shortest delay, and it is the copy going through the best possible direction at the intersection. If intersection I_i only has two outgoing roads r_{ia} and r_{ib} and satisfies $D_{ia} < D_{ib}$ with contacting probability CP_{ia} for contacts towards road r_{ia} and CP_{ib} for contacts towards road r_{ib} respectively, P_{ia} would be equal to CP_{ia}, and P_{ib} would be $CP_{ib} - CP_{ia} \cdot CP_{ib}$. This is due to the reason that the path with expected minimum delivery delay will count the packet forwarded to road r_{ia} instead of the packet to road r_{ib}, if both contacts are available when the packet carrier passes the intersection I_i. Therefore, to compute P_{ij} at I_i, we need to first sort CP_{ij} for all $j \in N(i)$ by the non-decreasing order of D_{ij}, the sorted list looks like:

$$CP_{ij_1}, CP_{ij_2}, CP_{ij_3}, \cdots, CP_{ij_n}; \qquad \text{where } n = |N(i)|$$

The subscripts of j_is implicitly indicates a meaningful order:

$$D_{ij_1} \leq D_{ij_2} \leq D_{ij_3} \leq \cdots \leq D_{ij_n} \tag{6}$$

By using basic probability, we can calculate the probability of a packet being forwarded to road r_{ij} at I_i. This result is denoted as P'_{ij}.

$$\begin{aligned} P'_{ij_1} &= CP_{ij_1} \\ P'_{ij_2} &= CP_{ij_2} - CP_{ij_1} \cdot CP_{ij_2} \\ P'_{ij_3} &= CP_{ij_3} \\ &\quad - (CP_{ij_1} \cdot CP_{ij_3} + CP_{ij_2} \cdot CP_{ij_3}) \\ &\quad + CP_{ij_1} \cdot CP_{ij_2} \cdot CP_{ij_3} \\ &\quad \vdots \end{aligned}$$

Suppose the packet carrier will move to road r_{ij_c} (either go straight or make a turn) after passing I_i, the packet will only be forwarded to the road that has higher or equal priority. That is, for a road r_{ij_k}, if $k > c$, P_{ij_k} equals to zero, since the carrier will continue to buffer data instead of forwarding it towards lower priority roads. Thus, under the condition that the packet carrier goes to road r_{ij_c} after leaving I_i, the probability that road r_{ij_p} will be chosen as the packet forwarding direction can be defined as the following conditional probability:

$$P_{ij_p|ij_c} = Prob\{\text{packet forwarded to } r_{ij_p} | \text{ carrier goes to } r_{ij_c}\}$$

and

$$P_{ij_p|ij_c} = \begin{cases} P'_{ij_p}, & \forall p < c \\ 1 - \sum_{s=1}^{c-1} P'_{ij_s}, & p = c \\ 0, & \forall p > c \end{cases} \tag{7}$$

Let Q_{ic} denote the probability of a vehicle moving (going straight or turning) from the current intersection I_i towards the next adjacent intersection I_c. P_{ij} can be calculated by the following:

$$P_{ij} = \sum_{c \in N(i)} Q_{ic} \times P_{ij_p|ij_c} \tag{8}$$

C. Data Forwarding in the StraightWay Mode

Data forwarding in the StraightWay mode is much simpler than the intersection scenario, since the traffic is at most bi-direction. We can simply specify a target location and then apply the geographically greedy forwarding. To specify the target location, a simple scheme is to use the intersection ahead as the target. A better solution needs to identify whether taking the intersection ahead or the one behind as the target location. The intersection behind may have shorter delay in case the packet carrier failed to meet any contact in the previous intersection, and the chances to meet any one at the next intersection ahead is even less. In this case, we use Equation 2 to compute the expected delay of forwarding data to these two intersections, and pick the one with the smallest expected delay as the target. There is one minor modification when using Equation 2. Originally, d_{ij} is the expected forwarding delay between two neighbor intersections. Now it is the delay between the current location and the selected intersection: the one ahead or the one behind. d_{ij} can still be computed by applying Equation 1, using the distance between the current location and the selected intersection.

If the identified target intersection is the intersection ahead, the packet is forwarded to the target intersection by geographical routing [14]. If there is no vehicle available to forward ahead, the current packet carrier continues to carry the packet. If the identified target intersection is the intersection behind, the packet carrier keeps holding the packet, and waits for a vehicle in the opposite direction. Upon meeting one, it immediately forwards the packet.

D. Protocols for Query Data Return

In the previous sections, we have discussed VADD for delivering packets from a moving vehicle to a fixed location (information server), which provides information and answers the query. Next, we discuss how to send the query data back to the moving vehicle. This is different from the previous data delivery protocol since the destination is moving. There are some previous work on delivering data to mobile sinks in sensor networks [15][29]. However, these work implicitly assumes a short round trip time since end-to-end connection normally exists in sensor network, and the mobile sink can not move too far away from its source in such a short time. However, the assumption may not hold in our environment.

Our solution is based on the predictable vehicle mobility. It is natural to assume the vehicle is moving with pre-specified trajectory, at least unchanged for a short time period due to the road layout. If GPS is used, the GPS system already knows the destination of the vehicle and can figure out the trajectory of the vehicle. These moving trajectory can be added to the query packet. After the information server receives the query, it attaches the moving trajectory with the query reply. Intermediate vehicles that delivering the query reply needs to calculate the destination position, and deliver the query reply to that position. To save computation overhead, the information server can calculate the expected position of the requester based on the moving trajectory. During the calculation, the information server can use the query delivering time to estimate the query reply delivering time. As this is only an estimate, and the requester may have changed its position, a broadcast can be used. To reduce the broadcast overhead, an expanding ring based approach where the number of flooding hops slowly increases from 1 to a threshold. Since the focus of this paper is on delivering the data to the information center, we will leave protocols for data return as our future work.

V. Performance Evaluations

In this section, we evaluate the performance of the four VADD protocols L-VADD, D-VADD, MD-VADD and H-VADD. Since L-VADD may have routing loops, we evaluate two versions of them: L-VADD (with loop) and L-VADD (loop-free), where L-VADD (loop-free) records previous three hops information to avoid intersection routing loops. H-VADD is a hybrid of L-VADD and D-VADD. Though we apply D-VADD in H-VADD for simplicity, it does not exclude the possibility of using MD-VADD in H-VADD. We compare the performance of the VADD protocols to several existing protocols: DSR protocol [13], the epidemic routing protocol [24] and GPSR [14]. Since GPSR is not proposed for sparsely connected networks, its performance is very poor in vehicular ad hoc networks. To have a fair comparison, we extend GPSR by adding buffers. In this way, GPSR (with buffer) can be considered as a simple carry and forward protocol. For all protocols, if we consider limited buffer size, simple FIFO replacement is used to manage the buffer space.

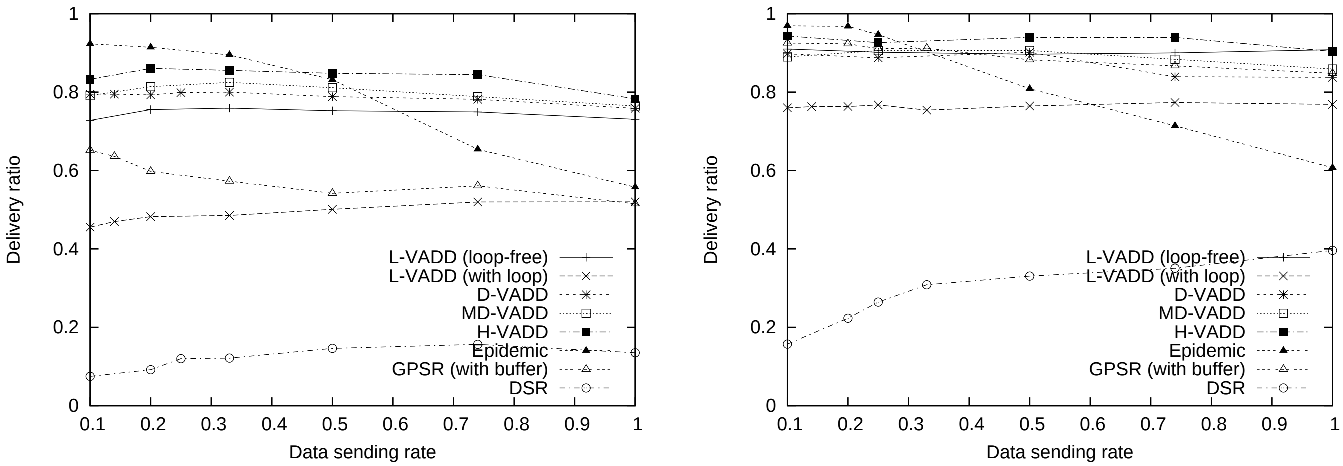
TABLE I
SIMULATION SETUP

Parameter	**Value**
Simulation area	$4000m \times 3200m$
# of intersections	24
Number of vehicles	150, 210
# of packet senders	15
Communication range	200m
Vehicle velocity	15 - 80 miles per hour
Buffer size (in packet)	10, 20, 50, 100, 200, 500, unlimited
CBR rate	0.1 - 1 packet per second
Data packet size	10 B - 4 KB
Vehicle beacon interval	0.5 sec

The experiment is based on a $4000m \times 3200m$ rectangle street area, which presents a grid layout. The street layout is derived and normalized from a snapshot of a real street map in Topologically Integrated Geographic Encoding and Referencing (TIGER) database [2] from U.S. Census Bureau. These map data are transformed into the data format that can be used by ns2, based on techniques presented in [23].

Different number of vehicles are deployed to the map, and the initial distribution follows the predefined traffic density. Then, each vehicle randomly chooses one of the intersection as its destination, and move along the road to this destination. The average speed ranges from 15 to 80 miles per hour, depending on the speed limit of the specific road it travels on, with a variance of 5 miles per hour. Figure 9 shows a snapshot of the simulation area.

Certain roads are chosen to go through with higher probability to produce uneven traffic density. Among all vehicles, 15 of them are randomly chosen to send CBR data packet to fixed sites during the move. To evaluate the performance on different data



(a) 150 nodes

(b) 210 nodes

Fig. 10. Data delivery ratio as a function of data sending rate

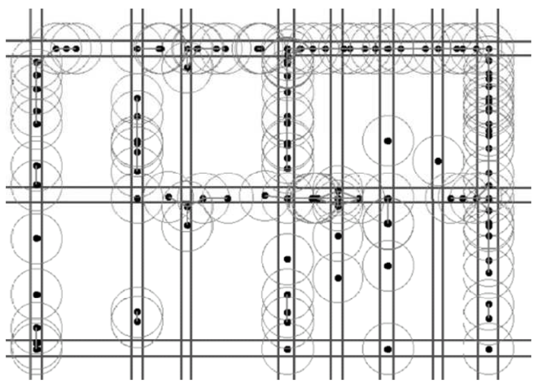


Fig. 9. A snapshot of the simulation setup area

transmission density, we vary the data sending rate (CBR rate) from 0.1 to 1 packet per second. All experiment parameters are shown in Table I. For a packet to reach a certain destination, the priority ranking of the outgoing roads at the intersections are pre-computed and loaded to the vehicle as the simulation starts. The performance of the protocols are measured by the data delivery ratio, the data delivery delay, and the generated traffic overhead.

A. The Data Delivery Ratio

In this section, we compare the performance of VADD protocols with epidemic routing, GPSR (with buffer), and DSR in terms of data delivery ratio, and examine how it is affected by data transmission density and vehicle density.

Figure 10 shows the data delivery ratio as a function of the data sending rate with unlimited buffer size, and compare the performance under different vehicle density settings. As shown in the figure, DSR has the lowest data delivery ratio and is not suitable for sparsely connected vehicular networks. Although GPSR (with buffer) is implemented in a carry and forward way, it is not a good choice since the geographical approach sometimes leads to void areas with few vehicles passing by, and it cannot make use of the traffic patterns. Therefore, its delivery ratio is poor when vehicle density is low, as shown in Figure 10(a). However, when vehicle density is high (in Figure 10(b)), where the connectivity is much better than the previous scenario, GPSR achieves very good delivery ratio, since the node mobility will help carry and forward the packets which temporarily reach the void zone. Intuitively, epidemic routing explores every possible path to the destination, and should represent the upper bound of the data delivery ratio. This is true when the data sending rate is low (e.g., when the data rate is 0.1 packet per second), and the node density is low. However, as the data sending rate increases, epidemic routing underperforms most of VADD protocols. This is due to MAC layer collisions. As the number of data requests increases, the network traffic dramatically increases in epidemic routing (see Figure 13), thus increasing the number of collisions and reducing the packet delivery ratio. At more densely deployed network as Figure 10(b), the delivery ratio of epidemic protocol drops even faster. While epidemic routing is very sensitive to the data rate and nodes density, VADD protocols, particularly H-VADD, steadily hold the close-to-optimum delivery ratio at different settings.

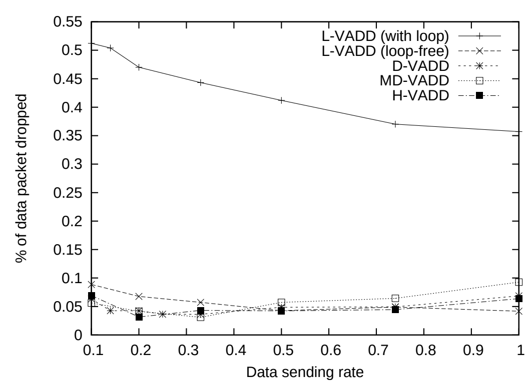
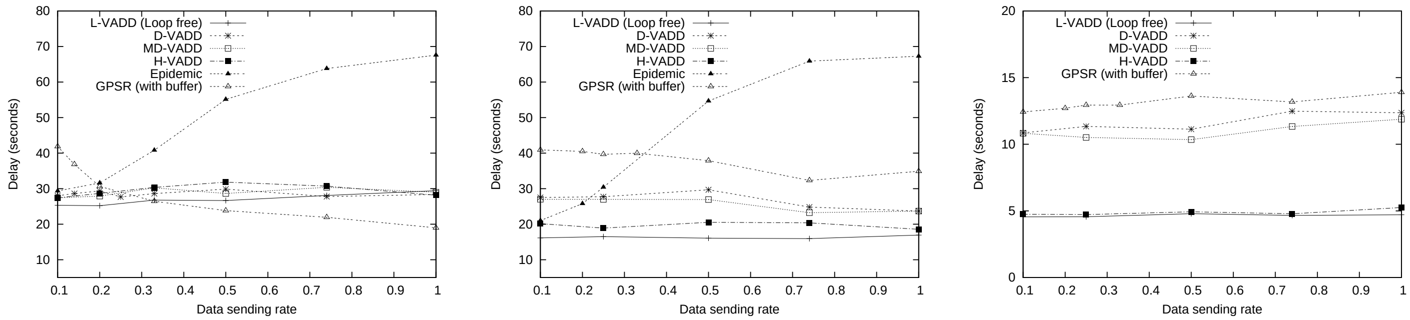


Fig. 11. Percent of data packets dropped due to routing loops or MAC layer packet collisions (150 nodes)

Figure 10 also compares several VADD protocols. Among them, H-VADD has the benefits of both L-VADD and D-VADD, presenting the best delivery ratio. MD-VADD shows slightly bet-



(a) 150 nodes

(b) 210 nodes

(c) The lowest 75% delivery delay (210 nodes)

Fig. 12. Data delivery delay as a function of data sending rate

ter delivery ratio than D-VADD and loop-free L-VADD at lower vehicle density, and approximately the same ratio at high vehicle density. As discussed in the previous section, loop detection prevents some packets from being sent to loop vulnerable neighbors, which reduces the chance of using some valid good paths. However, with a high vehicle density, intersection routing loops do not occur frequently, and L-VADD (loop-free) does not need to exclude too many innocent nodes to recover from the loop, and its delivery ratio becomes higher.

L-VADD (with loop) has the lowest data delivery ratio among the VADD protocols, and performs especially poor when the node density is low, since routing loops frequently happen and lead to packet drops. Figure 11 compares the percentage of data packet dropped due to TTL or MAC layer collision at 150-node setting. It also verifies the effectiveness of the routing loop detection mechanism used by loop-free L-VADD.

B. The Data Delivery Delay

In this section we compare the data delivery delay from moving vehicles to fixed sites using carry and forward schemes. Here, we do not consider DSR since its data delivery ratio is too low. Similarly, we do not consider the L-VADD protocol due to its low delivery ratio compared to MD-VADD and D-VADD. Note that a low delivery ratio may reduce the average data delivery delay since most undelivered packets may result in long delay. This is especially true in the DSR protocol, which only forwards packets through wireless communication whereas other carry and forward protocols may also rely on the vehicle movement.

Figure 12 shows the change of data delivery delay by increasing the data sending rate. Epidemic routing presents optimum delivery delay only when the data rate is very low. As the data sending rate increases, the delay of epidemic routing also increases, since epidemic routing generates many redundant packets. As the traffic load increases, many packets may be dropped. Even though the redundant copies can help the packet be eventually delivered, the delay increases. GPSR has relatively low data delivery delay at low node density (Figure 12(a)), but it is not meaningful simply because of its low delivery ratio. A valid comparison is when GPSR, epidemic routing and VADDs have similar delivery ratio, e.g., at data rate below 0.4 in Figure 12(b). In this case, GPSR shows much longer delivery delay since it does not consider the vehicle traffic pattern when making decisions.

H-VADD presents similar delivery delay as MD-VADD when the vehicle density is low, since it relies more on D-VADD for loop recovery because of more routing loops. When the vehicle density is high, the delay of H-VADD is lower than MD-VADD, but close to that of L-VADD. This shows that it behaves more like L-VADD, but has better packet delivery ratio than loop free L-VADD. These results verify that H-VADD effectively captures the advantages of both L-VADD and D-VADD.

The delivery delay is affected by the delivery ratio, and some extreme long-delay packets may greatly increase the mean value. To better study the delivery delay, we examine the "The lowest 75% delivery delay", which is the average delay of the lowest 75% packets. As shown in Figure 12(c), the delay of H-VADD is only half of the D-VADD (or MD-VADD). It is similar to L-VADD since it behaves more like L-VADD when the node density is high. MD-VADD shows slightly lower delivery delay than D-VADD since MD-VADD issues multiple copies to increase the chance of forwarding the packet through the best road.

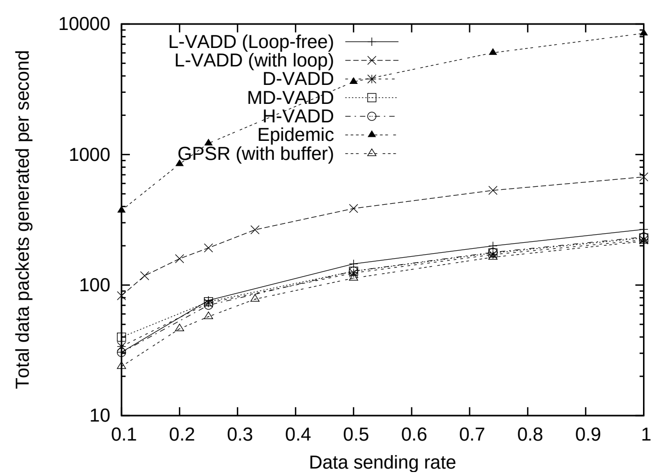
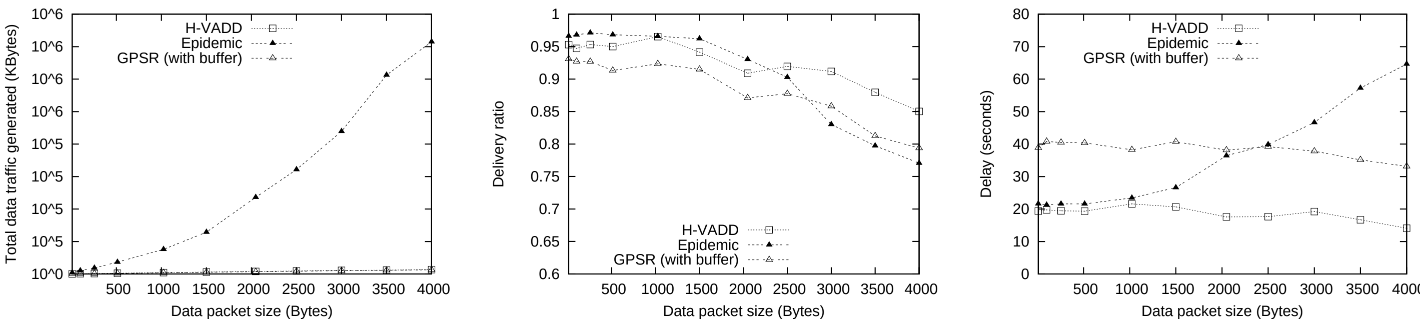


Fig. 13. The number of packets generated

C. Data Traffic Overhead

In this section, we evaluate the overhead of the carry and forward protocols by using the number of packets generated per



(a) Total amount of data traffic generated (b) Data delivery ratio (c) Data delivery delay

Fig. 14. Impact of data packet size

second, which is a summation of individual packet-hops. For example, if a generated packet is forwarded 10 hops, the packet overhead is counted as 10 packet-hops. All results shown in this section are based on the 210-node deployment scenario. Figure 13 shows the generated packet overhead as a function of the data sending rate with unlimited buffer. As the sending rate increases, the number of packets generated by all protocols also increases. However, the increasing trend is different. The overhead of epidemic routing increases much faster than other protocols due to the redundant packets generated.

For the VADD protocols, L-VADD (with loop) has the highest overhead due to loops whereas all the other VADD protocols have about the same low overhead. Compared to D-VADD, MD-VADD generates a little bit more traffic since it sometimes probe multiple paths to find the best road.

D. The Impact of Data Packet Size

Figure 14 illustrates the impact of data packet size on the performance of GPSR, epidemic routing protocol, and H-VADD. Larger packet size consumes more bandwidth and generates more contention for the limited wireless channel. As shown in Figure 14(a), the total injected data traffic using epidemic protocol increases much faster than GPSR and H-VADD. We intentionally choose the setting at a very low data sending rate (0.1 per second), where the delay of epidemic routing is close to H-VADD, and the delivery ratio is slightly better than H-VADD at the starting size (10 Bytes) due to the help of large amount of redundant packets. The delivery ratio of the epidemic routing protocol drops much faster than H-VADD as the data size increases (see Figure 14(b)). As shown in Figure 14(c), the delivery delay of the epidemic protocol increases dramatically as the packet size increases due to the congestion caused by the huge traffic load. The delay of GPSR slightly decreases as the packet size increases since some long delay packets are dropped. From the figure, we can also see that H-VADD has the lowest data delivery delay for different data sizes.

E. The Impact of Buffer Size

While all the previous results implicitly assumes unlimited buffer size for each node, Figure 15 and Figure 16 illustrate how these protocols react to the limited buffer size in terms of delivery ratio and delay. To make fair comparison, we choose the 210 nodes deployment scenario with data sending rate of 0.25 (see Figure 10(b)), where GPSR, epidemic routing and VADDs all have similar delivery ratio (around 90%).

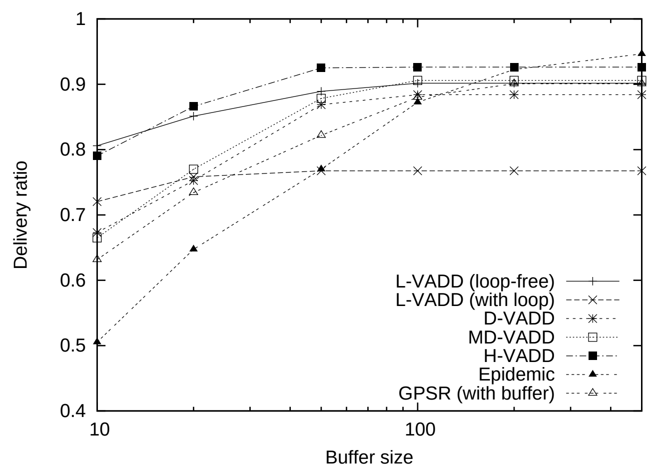


Fig. 15. Data delivery ratio at different buffer sizes

Generally speaking, as the buffer size increases, the data delivery ratio increases. This is due to the reason that increasing the buffer space increases the chance for the packet carrier to find a vehicle to relay the data. On the other hand, with limited buffer size, new data packets may replace the old undelivered packets, resulting in packet drops and low delivery ratio. As shown in both Figure 15 and 16, epidemic routing is more sensitive to the buffer size compared to other protocols because it generates many redundant packets which need much more buffer space. Epidemic routing has the lowest delivery ratio when the buffer size is small. As the buffer space increases, its delivery ratio increases much faster than other protocols. However, its delivery delay suffers as the buffer size increases. The reason is that larger buffer size leads to more data packet exchange between peers, so the chance of congestion also increases. In this case, even though the packet can reach the destination due to the redundant copies, the packet going through the shortest path is often dropped. Figure 16 shows that the delivery delay of epidemic routing also increases much faster as the buffer size increases.

Among all VADDs, MD-VADD is more sensitive to the buffer size than others because it needs to generate redundant copies;

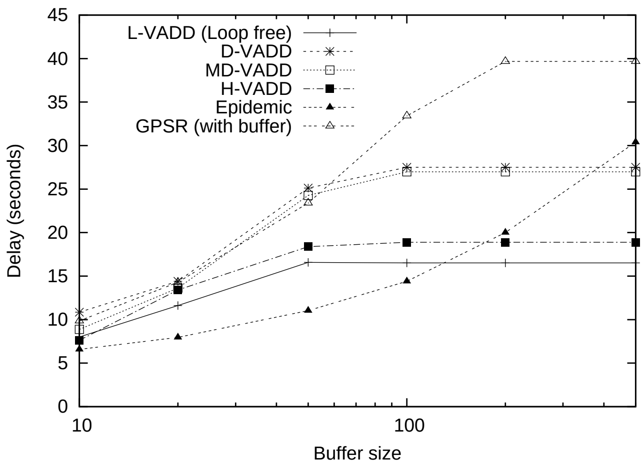


Fig. 16. Data delivery delay at different buffer sizes

its delivery ratio and delay can reach the steady state at a much smaller buffer size than the epidemic routing protocol. H-VADD only needs very small amount of buffer to reach the optimum delay and delivery ratio. Also, it outperforms epidemic routing protocol in both delay and packet delivery ratio most of time. As expected, GPSR still has the longest delay.

VI. Conclusions

Many researchers and industry players believe that the benefit of vehicular networks on traffic safety and many commercial applications [26], [28], [30] should be able to justify the cost. With such a vehicular network, many data delivery applications can be supported without extra hardware cost. However, existing protocols are not suitable for supporting delay tolerate applications in sparsely connected vehicular networks. To address this problem, we adopted the idea of carry and forward, where a moving vehicle carries the packet until a new vehicle moves into its vicinity and forwards the packet. Different from existing carry and forward solutions, we make use of the predicable vehicle mobility, which is limited by the traffic pattern and road layout. We proposed several vehicle-assisted data delivery (VADD) protocols: L-VADD, D-VADD, MD-VADD and H-VADD based on the techniques used for road selection at the intersection. Experimental results showed that the proposed VADD protocols outperform existing solutions in terms of packet delivery ratio, data packet delay and traffic overhead. Among the proposed VADD protocols, the H-VADD protocol has much better performance.

As future work, we will consider using vehicles from nearby road, although this will be more complex. We will also address issues on designing protocols for query data return.

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