

Data Pouring and Buffering on The Road: A New Data Dissemination Paradigm for Vehicular Ad Hoc Networks

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Abstract— Vehicular ad hoc networks (VANET) have recently received considerable attention. To support VANET based applications, it is important to disseminate data from an information source (data center) to many vehicles on the road. Although disseminating data from a server to a large number of clients has been studied in the database community and the network community, many unique characteristics of VANET bring out new research challenges. In this paper, we propose a data pouring and buffering paradigm to address the data dissemination problem in VANET. In Data Pouring (DP), data are periodically broadcasted to vehicles on the road. In DP-IB, data poured from the source are buffered and rebroadcasted at the intersections. We provide analytical models to explore the dissemination capacity of the proposed schemes. The analytical models also provide guidelines on choosing the system parameters to maximize the dissemination capacity under different delivery ratio requirements. Simulation results show that the proposed DP-IB scheme can significantly improve the data delivery ratio and reduce the network traffic.

I. INTRODUCTION

Vehicular ad hoc networks (VANET) have been envisioned to provide increased convenience and efficiency to drivers on the road [1], [2], [3]. For example, an alert message on traffic accident or traffic jam can be propagated tens of miles along the road to help drivers select a better route. Department stores can disseminate sale advertisements to vehicles within vicinity to attract consumers as well as providing dining and parking information.

Through these applications, we can see that VANET is very useful for disseminating data from an information source (data center) to many vehicles on the road. Although disseminating data from a server to a large number of clients has been studied in the database community and the network community [4], [5], many unique characteristics of VANET bring out new research challenges. First, due to fast vehicle movement, the link topology changes rapidly [6], [7], [8]. As a result, many well studied structures for efficient data dissemination, such as tree, clustering, grid, are extremely hard to set up and maintain. Second, the conventional broadcast mechanism for data dissemination may lead to broadcast storm [9] because the network node density is usually quite high in the urban area, and extremely dense during rush hours or traffic jam. Third, the vehicle mobility is partially predictable since it is limited by the traffic pattern and the road layout [10].

Data dissemination techniques should address these unique characteristics of VANET.

Recently, researchers start to address data dissemination issues in VANET. Xu *et al.* proposes an opportunistic dissemination scheme [11] similar to gossip [12], [13], [14]. In this approach, the data center periodically broadcasts some data which will be received and stored by the passing by vehicles. Whenever two vehicles move into the transmission range of each other, they exchange data. This scheme does not rely on any infrastructure, and hence suitable for highly dynamic VANETs. However, after a data item has been propagated into the network, it is hard to remove the outdated information timely, especially when it is frequently updated. In addition, the performance of the opportunistic dissemination scheme is poor in areas with high vehicle density due to MAC layer collisions [15]. This can easily lead to severe congestion and significantly reduce the data delivery ratio. To mitigate the excessive transmissions and congestion, Korkmaz *et al.* [16] propose a link layer broadcast protocol to help disseminate the data. The protocol relies on link layer acknowledge mechanisms to improve the reliability of the multi-hop broadcast. More specifically, only one vehicle is used to forward and acknowledge the broadcast packet to reduce the broadcast storm problem. However, in case of network congestion, the link layer solution is not enough. Further, since many information sources may exist in a given urban area, the amount of broadcasted data from these sources can easily consume the limited bandwidth. Thus, it is important to study the maximum amount of data that can be disseminated in a given area (i.e., *the dissemination capacity*).

In this paper, we propose a data pouring and buffering paradigm to address the data dissemination problem in VANET. The proposed solution can reliably disseminate the data, efficiently utilize the limited bandwidth and maximize the dissemination capacity. In Data Pouring (DP), data are periodically broadcasted to the vehicles on the road. As data are poured along the roads, they are delivered not only to the vehicles on these roads, but also to vehicles on the intersecting roads when they move across the intersections. To further improve the performance, we propose an improved DP scheme called *DP with Intersection Buffering (DP-IB)*, which tries to reduce the amount of data poured from the source by buffering and rebroadcasting data at the intersection.

Periodically pouring data on the road is necessary since vehicles receiving the data may move away quickly and vehicles coming later still need the data. With DP, the data are consistently available for vehicles crossing the dissemination area. In case there are large amount of data from many information sources to disseminate, it is important to increase the amount of data that can be disseminated on a given road. Thus, we provide analytical models to explore the dissemination capacity of the proposed schemes. The analytical models also provide guidelines on choosing the system parameters to maximize the dissemination capacity under different delivery ratio requirements. Extensive simulations are provided and used to evaluate the proposed methodology. Simulation results show that the proposed DP-IB scheme can significantly improve the data delivery ratio and reduce the network traffic.

The rest of this paper is organized as follows. Section II describes the data pouring and buffering schemes. Section III presents an analytical model to optimize the system parameters of our data pouring schemes. Performance evaluations are presented in Section IV. Section VI concludes the paper.

II. DATA POURING AND BUFFERING ON THE ROAD

In this section, we first describe our system model, and then present the data pouring and buffering schemes.

A. The System Model

VANET can be used to disseminate traffic accident or traffic jam to help drivers select better routes. It can also be used to disseminate sale advertisements to attract customers. One way of achieving this goal is to have a data center disseminate the data. The data center can be a computer with a wireless interface, a wireless access point, or an infostation [17]. A data center may have a list of data items to disseminate, referred to as the *dissemination data set (D-Set)*. The data center periodically broadcasts the D-Set so that each data item is broadcasted once in each cycle. The disseminated data are relayed by moving vehicles and poured to the desired area.

The data delivery information such as source id, source location, packet generation time, propagation direction and etc, is specified by the data center and placed in the packet header. The disseminated data are often spatial or/and temporal sensitive. For example, the traffic jam at downtown is not likely to be the interest of drivers thirty miles away, and will also be less helpful two hours later. Thus, a data item is attached with two more attributes: the *dissemination zone (D-Zone)* which is defined as a rectangle area and the *expiration time* which specifies the duration when the data item is valid. Vehicles outside of this D-Zone will discard the data to save bandwidth.

We assume vehicles communicate with each other and with the data center through short range wireless channel (100m-250m). 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. Vehicles use periodic beacon messages to report their moving velocity, direction and location, so each vehicle (including the data center) can get the information about their one-hop neighbors, and construct a neighbor list. To avoid overloading the channel with too many

beacons, a vehicle can adjust its beacon interval based on its moving velocity, e.g. two beacons per second when moving over 40 miles/hour, while one beacon every 10 seconds when moving below 5 miles/hour. Techniques to achieve this can be found in [18], [19].

B. Data Pouring (DP)

In this section, we first introduce the basic idea of the DP scheme and then propose solutions to make it more reliable.

1) *The Basic Idea:* The DP scheme makes use of the partially predictable vehicle mobility limited by the road layout. Instead of spreading data throughout the network, it broadcasts the data to one or several roads, called *axis roads (A-Roads)*. The A-Roads are selected from those main roads going through the data center and they normally have higher vehicle traffic density than other roads. The DP scheme also delivers data to vehicles moving on the roads that intersect with the A-Road, called *crossing roads (C-Roads)*. However, it does not proactively push data to the C-Roads. Since vehicles on the C-Roads moving towards the A-Roads will eventually reach a point intersecting with A-Roads, they will get the data. Therefore, the D-Zone of a data item only includes the A-Road where this data item is propagated to. Figure 1 shows the basic idea of the DP scheme. Both data centers, P and Q , select the horizontal road A-1 as the A-Road, and the vertical roads C-1 and C-2 as the C-Roads. The data are broadcasted along Road A-1. Figure 1 only shows the data broadcasted from the data center P ; the circles represent its broadcast coverage, which only covers Road A-1. Vehicles on Roads C-1 and C-2 receive the data when they go through the intersections.

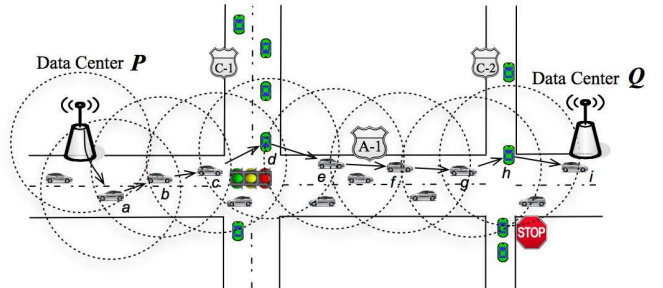


Fig. 1. Directional Broadcast

In the DP scheme, the data center specifies the road to propagate data based on D-Zone, and adds this information to the packet header. Then it designates a passing by vehicle to broadcast the data (for example, vehicle a in Figure 1). To propagate the data to the desired road, the data item needs to be consecutively broadcasted along the road by other vehicles such as $a \rightarrow b \rightarrow c \rightarrow d \rightarrow e \rightarrow f \rightarrow g \rightarrow h$ in Figure 1. To deal with the broadcast storm problem [9], each designated broadcasting vehicle selects one vehicle that is farther away in the data propagation direction from its neighbor list, and designates the selected neighbor as the next broadcast node by adding it to the packet header. After receiving the data, the designated vehicle (the forwarder) rebroadcasts the data. In this way, the data are poured to vehicles on the A-Roads. A

forwarder delivers the data to all potential receivers within its one hop range, and designates one vehicle as the next forwarder to broadcast the data father along the propagation direction.

Data invalidation [20] in the DP scheme is simple, because vehicles do not cache the data. If the disseminated data are updated, the data center broadcasts the updated version, and vehicles will get the updated data.

2) *Reliable DP*: The broadcasted data may be lost due to interference, packet collisions and hidden node problem. To ensure vehicles receiving the disseminated data, vehicles use RTS/CTS handshakes to reduce collisions and hidden node problem. To make the broadcast more reliable, after the broadcasting, the sender holds the data packet for a short period of time in case retransmissions are needed. The rebroadcast from the next forwarder is used as an implicit acknowledge to the previous forwarder. If the sender does not hear the rebroadcast from the next forwarder within a pre-specified time period, it selects another neighbor as the next forwarder and rebroadcasts the data.

When the sender is waiting for the rebroadcast by the next forwarder, it may receive some other broadcasted data towards the same direction. In this case, the sender has to buffer the data until the pending acknowledgement has been received from the next forwarder. There are two reasons for blocking the packet forwarding. First, if the selected next forwarder does not broadcast within a given period of time, it may indicate that there is an error on the selected next forwarder; e.g., the sender has selected an incorrect next forwarder or the selected forwarder is no longer within the transmission range. This may happen if the neighbor list is outdated or the sender mis-estimate the position of the selected forwarder. As a result, it should choose a different forwarder. Second, even if the next forwarder is correct, it may not be able to rebroadcast when the broadcasting load is too high. Adding more traffic may create congestion and result in more packet loss.

The reliable DP scheme can improve the data delivery ratio even if data are disseminated many hops away from the data center. However, it complicates the transmission with more control messages and backoff procedures, reducing the broadcast throughput. For example, when large amount of data are poured from many data centers independently, the data collision probability is very high. The reliable transmission mechanisms will be frequently used, and lots of bandwidth will be wasted by backoff timers, control messages, and RTS/CTS handshake. This will affect the dissemination capacity.

3) *Dissemination Capacity*: One desired goal of data dissemination is to maximize the dissemination capacity while ensuring a good data delivery ratio. Simply increasing the D-Set size is not an effective way to increase the dissemination capacity since most data may not be successfully delivered to vehicles if the D-Set size is too large.

Data delivery is subject to two constraints. The first constraint is the *data broadcast cycle*, i.e. the time interval between broadcasting the same data item on an axial road. To deliver data to moving vehicles, the data are periodically broadcasted. If a vehicle is on the A-Road, it will receive the

disseminated data sooner or later. However, vehicles on the C-road can only get the broadcasted data during a short time period; i.e., when they go cross the intersection. During this time period (t_i), the vehicle should stay inside the wireless coverage centered at the intersection. Thus, t_i is decided by the wireless coverage and the vehicle moving speed. A vehicle may miss the data if the broadcast cycle is longer than t_i . Although reducing the broadcast cycle time can solve this problem, it reduces the dissemination capacity and increases the network traffic. The second constraint is the bandwidth limit. Given a data broadcast cycle time, only limited amount of data can be broadcasted within one cycle. Disseminating data over this limit will cause collisions and data loss. As a result, the *dissemination capacity (DC)* within the given D-Zone is equal to the maximum number of data items that can be broadcasted to the D-Zone in one cycle, which is given by Equation 1.

$$DC = \frac{S \times T}{D_{avg}} \quad (1)$$

where S denotes the throughput achievable by multi-hop broadcast in the D-Zone, T denotes the broadcast cycle time, and D_{avg} denotes the average data size.

Equation 1 clearly shows two key factors that limit the dissemination capacity of the DP scheme. First, the DP scheme reduces the broadcast throughput since many control messages are used to improve the data delivery ratio. Second, in a given D-Zone, the location which requires the shortest broadcast cycle time determines the overall broadcast cycle for the entire dissemination zone. However, vehicles moving on other part of the road may not need such frequent broadcast, and vehicles moving along the A-Road indeed need much lower broadcast frequency. Thus, a large amount of bandwidth is wasted in the DP scheme. These drawbacks motivate our design of the following scheme.

C. Data Pouring with Intersection Buffering (DP-IB)

The DP-IB scheme follows the basic idea of the DP scheme, where the data are poured on the *A-Road*, and vehicles on the C-Roads get data when crossing the intersections. Instead of keeping the data on the A-Road, DP-IB only keeps the data at the intersections of the A-Road.

DP-IB relies on a simple device called *relay and broadcast station (IBer)* to improve the dissemination capacity. IBer can be the popular roadside units [21], [22] widely used in many VANETs, or a simple computing device with small amount of memory and a wireless card (e.g. 802.11b). These stand alone IBers can be easily installed at the intersection. Since they are not required to connect to the wired network, the deployment cost is low. The IBer is used to buffer data copies and rebroadcast them periodically. As a result, the data center does not need to ensure delivering data to the end user. Instead, it only transmits data to those IBers on the A-Road. In other words, the data center does not have to frequently broadcast data to guarantee that the vehicles from C-Roads receive the data. The IBers ensure that vehicles passing the intersection can still get the data, although the frequency required to pour

data from the data center is significantly reduced. Further, the IBers can adapt different broadcast cycle time at different intersection, i.e., longer cycle for slow moving traffic, while shorter cycle for fast moving traffic. Two issues still need further investigation:

- 1) How to reliably upload the data from the data center to the IBers and then deliver to the end users?
- 2) How to choose different broadcast cycle time for different parts of the road?

Next, we address the first problem and leave the second to Section III.

1) *Intersection data buffering and rebroadcasting*: The data center in DP-IB pours data on the A-Road using the reliable DP scheme. When data are forwarded through the intersections, the IBers overhear the data and update their own buffers accordingly, i.e., insert new data item, update existing data to a new version, or remove the invalid data. The IBER will broadcast the updated data in the next broadcast cycle. Since the IBER uses a single hop broadcast to deliver data to vehicles, the data broadcast throughput is high.

One problem may arise when a new data item from the data center is transmitted to the intersection, while the IBER is in the middle of broadcasting its buffered data. It is possible that the transmission of the new data item collides with the IBER broadcast, and the IBER cannot receive the new data. Our solution is to have the IBER and the forwarding nodes alternatively obtain the channel to broadcast. More specifically, the IBER broadcast cycle is divided into two periods: in the first period (called *busy period*), the IBER broadcasts its buffered data while the forwarding nodes temporarily hold their data. In the second period (the *idle period*), the forwarding nodes forward pending packets, while the IBER stops broadcasting and only listens to the channel for passing-by data packets. In this way, the IBER releases the channel for a period of time in every broadcast cycle so that new data items can be received. **Intersection contention avoidance protocol**: All vehicles switch between two modes: *active* and *inactive* forwarding mode. They stay in the active forwarding mode most of time, and only switch to inactive when they are inside an IBER broadcast range and the IBER is in the busy period at the same time. When the vehicle is in the active forwarding mode, it forwards data using the reliable DP scheme. It switches to inactive immediately after receiving a broadcast data packet from an IBER. In the inactive forwarding mode, the vehicle stops forwarding data until it goes back to active.

The IBER broadcasts an *IBer_Idle* message when its busy period ends. All vehicles receiving this message switch to active forwarding and start to forward any pending data. A vehicle in the inactive forwarding mode may fail to receive the *IBer_Idle* message due to message loss, or it may move out of the IBER broadcast range when the busy period ends. Thus, the inactive forwarding mode is set as a *soft state*, and the vehicle switches back to active if it does not receive any broadcast packet from the IBER for a time period.

Determining the busy/idle period: If an IBER does not buffer too much data, it can simply send an *IBer_Idle* message after broadcasting all its buffered data. However, if the amount of data buffered exceeds the data dissemination capacity, the IBER

should stop broadcasting before the end of the cycle, and leave some time for the idle period. Equation 2 is used to determine the length of the busy period.

$$L_{est} = \frac{n \times D_{avg}}{B_{IBer}} + \frac{\sum_{i=1}^m \frac{T}{T_i} \times D_{avg}}{B_{R-DP}} \quad (2)$$

In Equation 2, n is the number of buffered data items, D_{avg} is the average data size, m is the number of data centers which have stored data at the IBER, and the IBER receives the data packet from the i th data center every T_i time interval; B_{IBer} and B_{R-DP} represent the measured broadcast throughput of the IBER and the Reliable DP scheme respectively; T is the actual broadcast cycle of the IBER. The IBER can obtain all the above information locally. L_{est} estimates the time needed to finish broadcasting all the buffered data, and the time to overhear all the new data packet generated in a broadcast cycle. If L_{est} is smaller than T , the IBER can finish broadcasting all the buffered data, and then send the *IBer_Idle* message. The rest of the broadcast cycle still allows the IBER to overhear all the new data. When L_{est} is larger than T , the IBER is only given αT in a cycle to broadcast data before sending out the *IBer_Idle* message, where α is a system parameter, and it is much smaller than 1. In the rest of the broadcast cycle $(1 - \alpha)T$, the IBER enters the idle period.

2) *Data Update and Invalidation*: When new data items are added or old data items are updated at the data center, the data center immediately broadcasts the new data or the invalidation message using the reliable DP scheme. The data center may occasionally rebroadcast the data that have been disseminated, in case the IBER fails to obtain the data. Since all copies of the disseminated data are only buffered at the intersections along the A-Road, one invalidation message sent along the A-Road will be able to remove the invalid copies.

3) *Data Dissemination Capacity*: The dissemination capacity of DP-IB is limited by the broadcast cycles of the IBers. Compared with the DP scheme, the number of control messages in DP-IB is significantly reduced, and hence can speed up the data transmission. Although an idle period is added to the broadcast cycle, it only takes a small portion of the broadcast cycle time, while the majority of the broadcast cycle time is spent on data broadcast. Thus, it has better bandwidth utilization than DP, where each data packet transmission may involve many control messages and extra backoff times. As a result, the throughput of data broadcast in DP-IB is much higher than DP, and the dissemination capacity is higher.

III. ANALYZING AND DETERMINING THE BROADCAST CYCLE TIME

In this section, we use an analytical model to determine the broadcast cycle time at the intersection, denoted as T_i . T_i is used to determine the dissemination capacity and the delivery ratio of the DP scheme and the DP-IB scheme. T_i is also closely related to the time for a vehicle going through the intersection region, denoted as t_i . Intuitively, T_i should be less than the minimum t_i of all vehicles moving through the intersection region to guarantee that all vehicles passing the intersection can receive the broadcasted data. If disseminating

more data becomes the main objective, we can improve the dissemination capacity by increasing T_i . This is at the cost of reducing the data delivery ratio, since some vehicles moving across the intersection may miss part of the data. To derive T_i , we first model the intersection delay.

A. Modeling the Intersection Delay

Although there are many different intersection structures in reality, such as signalized, isolated, roundabout and etc., our intersection delay model only studies the vehicle delay at the signalized intersection with two crossing paths, because it can simplify the presentation and still show the relation between the network properties and the vehicle traffic properties. Our analysis can be easily extended to more complicated intersections, where the vehicle delay distribution is usually modeled by applying advanced transportation traffic theory or empirical traffic flow statistics, which is beyond the scope of this paper.

The delay t_i can be represented by two parts[23]: the first part, referred to as the moving delay (denoted as t_m), is the ideal travel time if this vehicle does not meet any traffic control signal. It is equal to the moving distance at the intersection divided by the normal moving speed of the vehicle. The second part, referred to as the queuing delay (denoted as t_q), is the extra delay caused by the traffic signal, including deceleration delay, stopped delay and acceleration delay. Their relations are given by:

$$t_i = t_m + t_q. \quad (3)$$

1) *Calculating t_m , t_q and t_i :* t_m is related to the vehicle moving distance and speed on the C-Road covered by the data broadcast. The broadcast node is always on the A-Road, and the broadcast can reach a fixed portion of the C-Road. Given the length of the C-Road covered by the broadcast as R , t_m can be easily computed as

$$t_m = R/v \quad (4)$$

where v is the normal speed of the vehicle moving across the intersection.

To get the minimum t_i , vehicles move through the intersection at its normal speed without deceleration and stop. Thus, $t_i^{min} = t_m$. In reality vehicles rarely keep the normal speed at the intersection because of traffic control signals. Most vehicles experience deceleration, acceleration, and often wait in line with full stop [24]. Not all the vehicles experience the same delay when traveling through an intersection. The delay depends on a number of factors such as the traffic flow density, signal time and the time when the vehicle arrives at the intersection. Based on an example about 11 vehicles shown in [24], the first eight vehicles reaching the intersection come to a complete stop. These vehicles need to stop either as a consequence of their arrival during the red interval or during the green interval when the queue of vehicles that had formed during the previous red interval has not yet fully dissipated. It is further observed that the following three vehicles only experience deceleration and acceleration delay, as these vehicles reach the intersection when all previously queued vehicles have already started to move and therefore

only need to slow down to maintain a safe distance with the vehicles ahead of them.

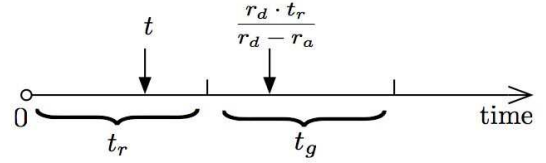


Fig. 2. Analytical model for t_q

We study the intersection delay with under-saturated traffic flow, which means the arrival rate r_a is less than the saturated departure rate r_d , and we assume that the queue of vehicles formed during the red signal cycle can always be cleared before the next red signal.

Let t_r and t_g denote the red and green signal duration respectively. Suppose a vehicle arrives at the intersection t seconds after the red signal turns on, as shown in Figure 2, t_q of this vehicle is given by:

$$t_q = \begin{cases} t_r - t + \frac{r_a \cdot t}{r_d}, & t \in [0, \frac{r_d \cdot t_r}{r_d - r_a}] \\ 0, & \text{else} \end{cases} \quad (5)$$

In Equation 5, $\frac{r_d \cdot t_r}{r_d - r_a}$ shows the time it takes to clear the queue accumulated at the intersection after the red signal starts. When the vehicle arrives at the intersection after that time, it will go through the intersection without delay; if the vehicle arrives before that time, it waits for the vehicles that queued at the intersection to depart, and the delay can be calculated by Equation 5.

We assume the vehicle arrival follows uniform distribution, which is widely used in traffic flow modeling [24]. The probability distribution function (PDF) of t_q is given by:

$$f_{t_q}(x) = Prob\{t_q = x\} = \begin{cases} 0, & x < 0 \\ 1 - \frac{r_d \cdot t_r}{(r_d - r_a)(t_r + t_g)}, & x = 0 \\ \frac{r_d}{(r_d - r_a)(t_r + t_g)}, & 0 < x \leq t_r \\ 0, & x > t_r \end{cases} \quad (6)$$

Since t_m can be computed as a constant from Equation 4, the PDF of t_i ($f_{t_i}(t)$) can be easily computed by combining Equation 3, 4 and 6:

$$f_{t_i}(x) = Prob\{t_i = x\} = Prob\{t_q = x - t_m\} = f_{t_q}(x - t_m) \quad (7)$$

B. Determining the Broadcast Cycle Time

Only when the data broadcast cycle time T_i at the intersection is smaller than the minimum vehicle delay t_i , it is possible to deliver all data in D-Set to every moving vehicles on the C-Road. We define this broadcast cycle time which allows all vehicles to receive all data in D-Set as *full delivery broadcast cycle time*, denoted by \bar{T}_i , and it is given by:

$$\bar{T}_i \leq t_m = R/v \quad (8)$$

Suppose the transmission range of the broadcast is 100 meters, and the C-Road perpendicularly intersects with the A-Road. Then, the length of the C-Road covered by the broadcast $R = 200m$. Assume the normal vehicle speed at the intersection is 45 miles/hour (20.1 meter/sec). Then, \bar{T}_i is less than 9.95sec, i.e. the broadcast node at the intersection has to finish broadcasting all data in the D-Set in 9.95 seconds.

In Simple DP and Reliable DP, all intersections on the A-Road and the data center use the same same broadcast cycle time, which is computed by

$$T_{DC} = \min_{i \in A-Road} \{\bar{T}_i\}. \quad (9)$$

Thus, the intersection which requires minimum broadcast cycle time among all the intersections determines the broadcast cycle time. However, in DP-IB, different intersections use different broadcast cycle time. It is controlled by the local broadcast node IBer, and can be adaptively adjusted based on the local vehicle traffic condition.

C. Relations between Delivery Ratio, Broadcast Cycle Time and Dissemination Capacity

Equation 1 shows that the dissemination capacity is linear to the broadcast cycle time. From the previous section, \bar{T}_i sets the upper bound for the broadcast cycle time to ensure the best delivery ratio, which also bounds the maximum dissemination capacity. By sacrificing some data delivery ratio, we can increase T_i and broadcast more data. Next, we study the effects of T_i on the data delivery ratio, and explore the trade-off between dissemination capacity and data delivery ratio.

Given that the PDF of t_i , $f_{t_i}(x)$, can be computed by Equation 7, the data delivery ratio at the intersection (denoted as DR) can be computed as:

$$DR = \int_{T_i}^{\infty} f_{t_i}(x) dx + \int_0^{T_i} f_{t_i}(x) \cdot \frac{x}{T_i} dx \quad (10)$$

Equation 10 shows that vehicles staying longer than T_i at the intersection (i.e., $t_i > T_i$) can receive all the broadcasted data, while those staying shorter than T_i (i.e., $t_i < T_i$) only receive $\frac{t_i}{T_i}$ portion of the broadcasted data.

By combining Equation 6, 7 and 10, the relation between DR and T_i can be derived as:

$$DR = \begin{cases} 1, & T_i \leq t_m \\ \frac{t_m((r_d - r_a)(t_r + t_g) - r_d t_r - \frac{1}{2} r_d t_m)}{(r_d - r_a)(t_r + t_g)T_i} + \frac{r_d(t_m + t_r) - \frac{1}{2} r_d T_i}{(r_d - r_a)(t_r + t_g)}, & t_m < T_i \leq t_m + t_r \\ \frac{2t_m(t_r + t_g)(r_d - r_a) + r_d t_r^2}{2T_i(r_d - r_a)(t_r + t_g)}, & T_i > t_m + t_r \end{cases} \quad (11)$$

In the above equation, the signal length t_g and t_r can be seen as fixed road properties. Parameter r_d represents the capability of the intersection to disperse vehicle traffic, which is usually fixed after the road has been constructed. Parameter r_a indicates the dynamic vehicle traffic load at the intersection. Therefore, with $t_g = 30s$, $t_r = 30s$, $t_m = 10s$, $r_d = 30$, the relations among T_i , DR and the local vehicle traffic load are shown in Figure 3.

Figure 3 clearly shows that the dissemination capacity and the data delivery ratio are conflict design goals. If we are given

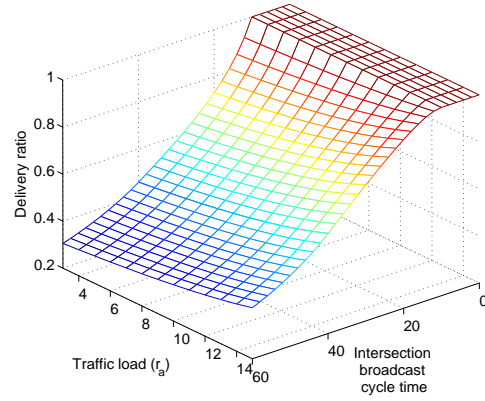


Fig. 3. Analyze the relation between the broadcast cycle time and the data delivery ratio

the delivery ratio requirement, for example $DR > 90\%$, we can compute the largest T_i based on Equation 11. This T_i value provides the maximum dissemination capacity while keeps the delivery ratio equal to 90%. Using the above relations, we can tradeoff these two metrics for the best broadcast strategy based on the requirement of the applications. This figure also addresses the second question raised in Sec II-C.1. The figure shows the relations among the broadcast cycle time, the data delivery ratio and the vehicle traffic load. Generally speaking, when T_i increase, the data delivery ratio drops. As the vehicle traffic density increases, vehicles stay longer at the intersection because they move slower and stop longer. Thus, more data can be delivered to drive-through vehicles by extending the broadcast cycle time at the intersection without reducing the data delivery ratio. Also, if the passing through vehicles only receive part of the D-Set, without changing the broadcast cycle time, the dissemination ratio will be higher as the vehicle traffic density increases. This provides guidelines for DP-IB to dynamically adapt its broadcast cycle time based on the local vehicle traffic load at different intersections.

IV. PERFORMANCE EVALUATIONS

In this section, we evaluate the performance of the Simple DP scheme (without using techniques presented in Section II-B.2), the reliable DP scheme, and the DP-IB scheme. We also compare these schemes to the opportunistic dissemination (OD) scheme presented in [11], and the MAC-layer based reliable multi-hop broadcast scheme (UMB) proposed in [16].

A. The Simulation Model

We developed an ns-2 [25] based simulator to evaluate the proposed schemes. The simulation is based on a $4500m \times 600m$ rectangle area extracted from a real street map of State College, Pennsylvania. The position of the data center and the D-Zone are shown in Figure 4, represented by the star and the crossing rectangle respectively. We choose East College Avenue, one of the most crowded streets in State College, as the A-Road. It runs through the downtown with 25 miles/hour speed limit. The C-Roads are selected from three major streets

that intersect with the East College Avenue. All the three C-Roads have the same speed limit (45 miles/hour). The street layout and speed limit information are translated into a text format map which meets the specification of Topologically Integrated Geographic Encoding and Referencing (TIGER) database [26] from U.S. Census Bureau. These text-based map data are then transformed into the data format that can be used by ns-2, based on techniques presented in [27]. In order

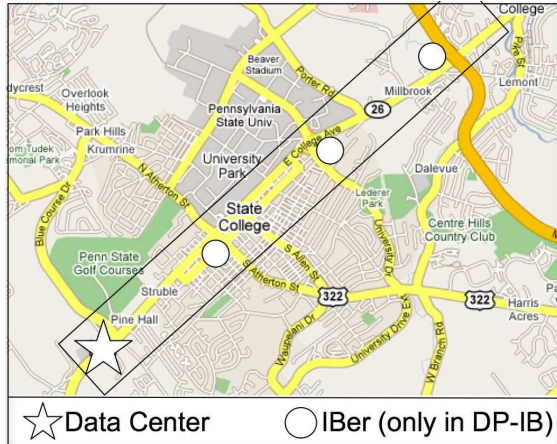


Fig. 4. A snapshot of the simulation setup area

to simulate the vehicle traffic on the A-Road, we initially randomly deploy 150 vehicles on the A-Road and let them move towards either end of the road. Those vehicles move back and forth with 25 miles/hour during the simulation to mimic continuous traffic flow along the A-Road. We assume the vehicle density on the A-Road is large enough to maintain network connection, which is possible in urban areas where our data dissemination scheme is designed for.

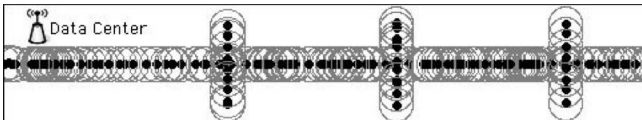


Fig. 5. A snapshot of the simulation setup area

Since vehicles move along the A-Road can always receive the disseminated data, we are more interested in vehicles on C-Roads. Among vehicles on the C-Roads, only those close to the intersections are relevant to data dissemination. Since simulating the movement of vehicles across the intersection is more important than the traffic beyond the intersection, we only consider the vehicle traffic on a 600-meter long section of C-Roads, whose middle point intersects with the A-Road. We initially deploy 20 nodes at the upper end of each C-Road, and let them move back and forth between the two ends of the C-Roads. When the node arrives at the intersection, it stops for a random amount of time with the distribution given by Equation 6 before moving again. When the node arrives at the other end of the road section, it pauses for a time period, and moves back. Each vehicle on C-Roads randomly picks a value between 15 to 45 (miles/hour) as its moving speed. Figure 5 shows a snapshot of the simulation area. The data center is

located at the left end of the A-Road, and disseminates data along the A-Road towards the right.

Simple DP and Reliable DP use the same broadcast cycle time throughout the A-Road. DP-IB can adapt the IBER broadcast cycle time based on the local vehicle traffic at the intersection. In our simulation model, the same traffic pattern is used in all the C-Roads, and hence we use the same intersection broadcast cycle time for all intersections.

At the data center, all data in the D-Set are repeatedly injected to the A-Road. The data items are sent by the data center one after another with a given time interval. In Simple DP and Reliable DP, this time interval is equal to the broadcast cycle time divided by the number of data items to be disseminated. In DP-IB, since the frequency required to pour data from the data center can be greatly reduced, it takes much longer time to broad the whole data set at the data center. Thus, the time interval is set as 250 *ms*. We only consider data items with fixed size of 2500 bits. Each vehicle sends a beacon message every 0.5 second to report its own location and speed.

TABLE I
SIMULATION SETUP

Parameter	Value
Simulation time	500 seconds
Simulation area	4500m × 600m
Communication range	100m
Number of nodes on the A-Road	150
Number of nodes on the C-Roads	60
Vehicle velocity	15 - 45 miles per hour
Data packet size	2500 bit
Dissemination data set size	10 - 600 data items
Bandwidth	10Mbps
Intersection broadcast cycle time	5 - 40 s
Beacon interval	2 beacon/second
Beacon packet size	512 bit
Control packet size	512 bit
DP-IB cache replacement policy	FIFO

Most experiment parameters are listed in Table I. The performance of the protocols is measured by the following two metrics:

- *Data delivery ratio*: For each vehicle, the data delivery ratio is the total number of nonidentical data items received divided by the total number of data items disseminated.
- *Network traffic overhead*: The number of bits generated per second, which is a summation of individual packet-hops. For instance, if a packet of 1000 bits is forwarded 10 hops, the network traffic overhead is counted as 10K bit-hops.

For each measurement, 30 simulation runs are used and a different seed value is used for each simulation run. For the data delivery ratio, the mean value of the measured data is obtained by collecting a large number of samples such that the confidence interval is reasonably small. In most cases, the 95 percent confidence interval for the measured data is less than 10 percent of the sample mean.

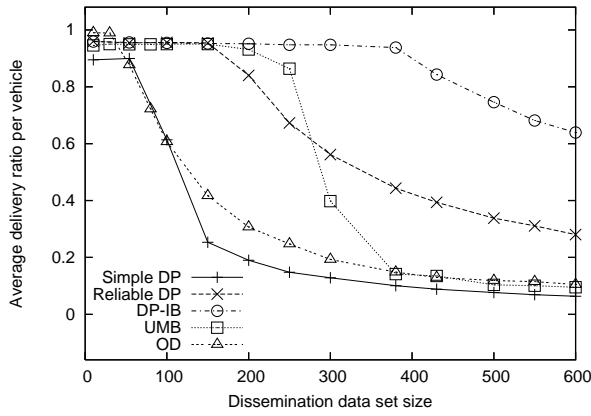


Fig. 6. Comparison of the data delivery ratio (with the broadcast cycle of 10s)

B. Simulation Results

1) *The relation between delivery ratio and dissemination capacity:* Figure 6 shows the relation between delivery ratio and the amount of data to be disseminated (dissemination capacity) for the five schemes. When only a small amount of data items are disseminated (e.g. 10 data items in Figure 6), there are plenty of bandwidth available and the data delivery ratio of all schemes are close to 100%. Among them, the OD scheme has slightly higher delivery ratio than others, because OD explores every possible path to propagate the data. However, the delivery ratio of OD becomes much lower than DP and DP-IB when more data items (above 50) are disseminated. As discussed in the introduction, the OD scheme generates too much redundant network traffic, which may lead to severe congestion and significantly reduce the data delivery ratio. When the D-Set size is above 50, there is a significant increase of data losses in the Simple DP scheme, and its data delivery ratio drops dramatically. Therefore, the dissemination capacity of the Simple DP scheme will be very low to maintain a good data delivery ratio.

UMB, Reliable DP and DP-IB have very high data delivery ratio when the data set size is below 150. When more data are to be disseminated, the delivery ratio of the UMB scheme and the reliable DP scheme drops quickly, while the DP-IB scheme keeps the same data delivery ratio. The data delivery ratio of UMB drops sharply because the packets in a dissemination data flow interfere with each other. As the channel usage increases, the interference problem becomes worse, leading to severe packet loss. Although UMB can effectively improve the reliability of multi-hop broadcast, this MAC layer approach cannot address network congestion. The low delivery ratio of Reliable DP is not because of packet loss, since the packet can still be reliably transmitted. Thus, the delivery ratio of Reliable DP drops gracefully compared to UMB. However, the reliable DP scheme reaches the saturate status when the D-Set size reaches 150. When more data need to be disseminated, reliable DP cannot finish broadcasting the whole data set within one cycle. As a result, some vehicles move across the intersection, without receiving all the data. DP-IB can broadcast data with higher throughput, and will not reach the saturate state until 360 data items are broadcasted. Thus, it

has more dissemination capacity than the reliable DP scheme. When the D-Set size is more than 360, the Iber in the DP-IB scheme may not be able to finish broadcasting the whole data set within its broadcast cycle time, and the data delivery ratio decreases.

2) *Revisiting the relations between delivery ratio, broadcast cycle time and dissemination capacity:* Figure 6 only shows the results under a fixed broadcast cycle time (10 seconds). To further examine the relations among the broadcast cycle time T_i , the data delivery ratio and the dissemination capacity, we present more results in Figure 7 when the D-Set size and the broadcast cycle time change. Figure 7 shows additional relations not shown in Figure 3 which does not consider the network bandwidth limit. In Figure 3, we assume the whole D-Set can be transmitted. If vehicles fail to receive the data, it is because the broadcast cycle time is too long and the vehicles pass the intersection before one cycle finishes (short intersection stay). However, data may not be delivered because the D-Set set is too large. That is, the network is saturated and cannot accommodate all the disseminated data.

Figure 7 studies the packet loss caused by both factors: short intersection stay and network saturation, under the same vehicle traffic load. In Figure 7, the 3D surface in each figure can be divided into four regions, based on the factors causing the packet loss. As shown in Figure 7(a), in Region 1, there is no packet loss because of the above factors, and the delivery ratio is close to 100%. In this region, the broadcast cycle time is smaller than 10 seconds. Then, there is no packet loss due to short intersection stay since even the fastest vehicle takes 10 seconds to move across the intersection. Also, the D-Set size is small, and the network is not saturated. In Region 2, the only factor for packet loss is network saturation, since the D-Set cannot be delivered within 10 seconds. There is no packet loss due to short intersection stay as the broadcast cycle time is still less than 10 seconds. In Region 3, the packet loss is due to short intersection stay, since the broadcast cycle time is longer than 10 seconds, and some vehicles may pass the intersection without getting the data. There is no packet loss due to network saturation, because the D-Set can be sent within the given broadcast cycle time. Thus, within this region, the D-Set size can be increased without affecting the data delivery ratio. In Region 4, the D-Set size exceeds the network capacity and the broadcast cycle time is longer than 10 seconds, so packets are lost for both factors.

Figure 7 (b) and (c) can also be divided to four regions using the same criteria, but the areas of the same region are different in these three schemes. The areas of Region 1 and Region 3 in DP-IB are much larger and flatter than the other schemes. It means that DP-IB can always disseminate the largest amount of data without reaching network saturation. In Simple DP, there is no mechanism to reduce the collision, so the bandwidth utilization is very low. Therefore, the areas of its Region 2 and Region 4 are very large while the areas of its Region 1 and Region 3 are quite small. In most cases, the network is saturated and less data can be successfully transmitted without collision or being dropped.

Overall, given any required data delivery ratio, DP-IB can always disseminate the largest amount of data when a proper

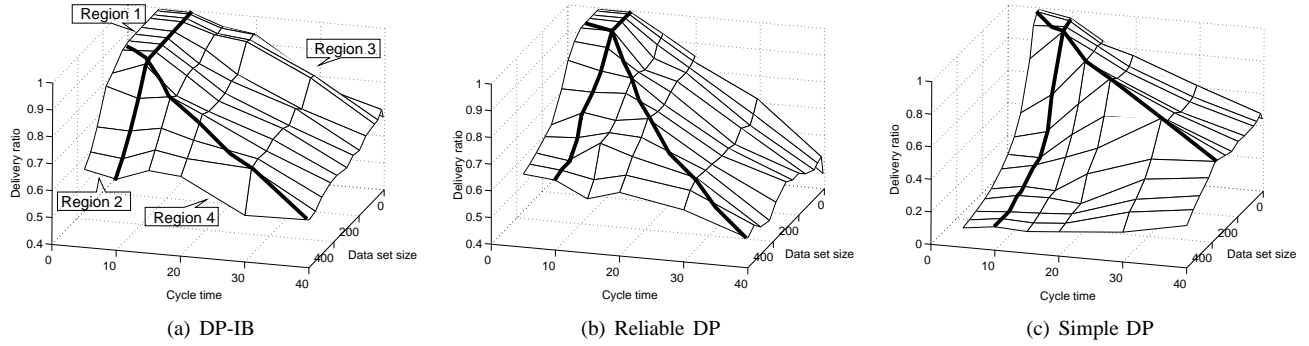


Fig. 7. Relations among cycle time, data set size and delivery ratio

broadcast cycle time is chosen. Reliable DP can disseminate less data than DP-IB, but still far more than the Simple DP scheme under any data delivery ratio requirement.

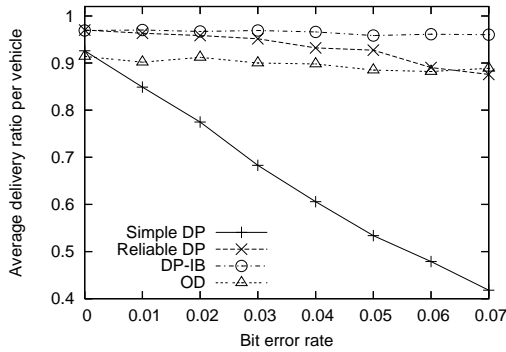


Fig. 8. Impact of the transmission bit error rate

3) *The effects of bit error rate:* Figure 8 compares the four schemes with different transmission bit error rate when 50 data items are disseminated. The simple DP scheme is based on simple broadcast, so the data delivery ratio quickly drops when the error rate increases. The data delivery ratio of the reliable DP scheme only drops slightly when the error rate increases, which verifies the effectiveness of the reliable multi-hop broadcast. The OD scheme can also keep a good delivery ratio due to its opportunistic nature. Among the four, DP-IB is the most resilient to bit errors. Since the data are buffered at the intersection, the impact of bit error on multi-hop transmission is minimized.

4) *Dissemination distance:* Figure 9 shows the data delivery ratio of the three DP schemes when the data are delivered to vehicles far away from the data center. The D-Set size is 100. As can be seen, the delivery ratios of both Reliable DP and DP-IB are not affected by the dissemination distance. This also verifies the effectiveness of the reliable multi-hop broadcast scheme in handling transmission errors. On the other hand, the delivery ratio of the Simple DP scheme drops quickly as the distance increases, because packet loss occurs at every hop and not much data left after a long-distance pouring.

5) *Dissemination delay:* Figure 10 shows the delay of delivering a new data item to vehicles at three intersections using the UMB scheme and the three DP schemes. The D-Set size is set to 50. The delay is computed from a new

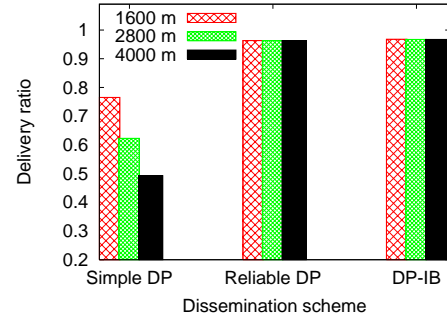


Fig. 9. Delivery ratio at different distances from the data center

version of a data item generated at the data center to the time when the first vehicle receives it at the specific intersection. As shown in the figure, UMB has the lowest delay since it does not block the data flow, and does not use any timers. The simple DP scheme does not use any reliable transmission mechanism, but the delay is still longer than UMB, because some new data items fails to reach the intersection in the first cycle after being generated. When it is delivered in the second cycle, the delay is increased by one cycle time (10 seconds). The reliable DP scheme has higher delay since it blocks the flow until the ACK is received for the previous packet, and this increases the packet forwarding latency. DP-IB has the highest delay due to the following reason. After a new data item has been generated, it needs to be uploaded to the IBER, and the upload only starts after the IBER finishes its broadcast cycle. Hence, the new data item needs to wait for half of the broadcast cycle time on average before transmitting the data to the IBER. However, the delay is at the level of seconds and only happen when the accessed data item is updated. Most of time, this delay does not exist. Thus, this dissemination delay should not be a big issue compared to other factors such as dissemination capacity and data delivery ratio.

6) *Network traffic overhead:* Figure 11 compares the overall network traffic overhead generated by the five schemes when the D-Set size increases. The simple DP scheme generates the least amount of traffic, since it simply broadcasts the data, without adding any control message. Further, many data packets are dropped before going too far on the A-Road. This can be reflected by the low data delivery ratio shown in

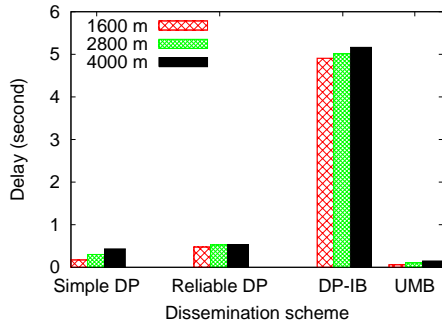


Fig. 10. Delivery delay at different distance from the data center

Figure 6.

The OD scheme has the highest traffic overhead since vehicles keep sending data to each other. The traffic overhead of the reliable DP scheme is also pretty high, because many control messages are generated for each data packet transmission and it introduces many retransmissions to improve the reliability. DP-IB generates much less traffic compared to Reliable DP, since DP-IB delivers data to end nodes by single hop broadcast from the IBers, instead of reliable multi-hop broadcast from the data center. As a result, the data center broadcasts data at a much lower rate, which greatly reduces the network traffic overhead.

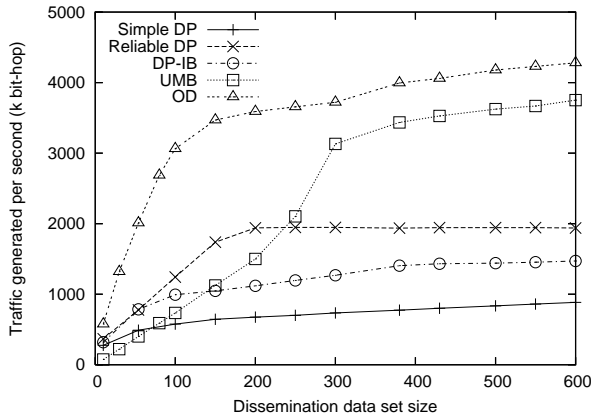


Fig. 11. Comparison of the network traffic

These five schemes generate more network traffic when the D-Set size increases at the beginning. After the channel saturates, the disseminated data may be dropped and the traffic only slightly grows or even keeps constant when the number of the dissemination data increases. Figure 11 shows that the network traffic of the Reliable DP scheme keeps almost constant and DP-IB only slightly grows when they disseminate more data than their dissemination capacity, which is 150 and 360 data items respectively. Figure 11 also shows that when the channel saturates, DP-IB disseminates more data than Reliable DP but still generates less traffic, which verifies that DP-IB can improve the bandwidth utilization.

Figure 12 shows the distribution of the network traffic. The control packet includes the beacon packets used by all schemes except UMB, RTS/CTS handshake used by reliable DP and DP-IB, and the control packets for the intersection contention

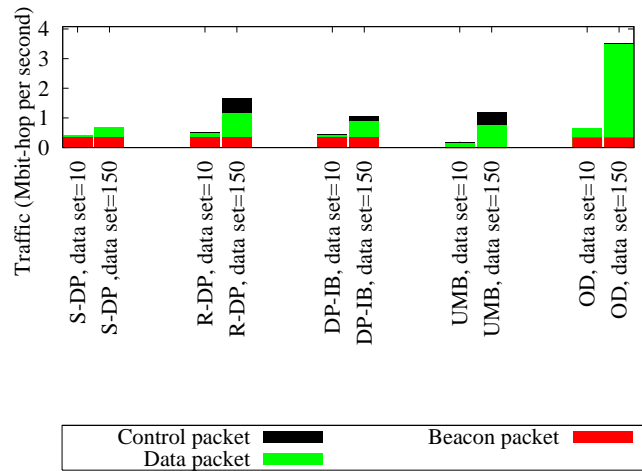


Fig. 12. Detailed comparison of the network traffic

avoidance used by DP-IB. In the figure, all schemes generate the same amount of beacon messages except UMB. As can be seen, all schemes have very small amount of control packets when the network traffic load is low (e.g. to disseminate 10 data items). When the network traffic load increases (e.g. to disseminate 100 data items), the portion of control packets becomes significant for the reliable DP (R-DP) scheme. On the other hand, the control traffic of the DP-IB scheme is not very high, because the data center can slow down the rate of pushing data to the intersections. For the OD scheme, although it does not have control traffic overhead, its data packet overhead is much higher. As explained earlier, the simple DP scheme drops many packets, and hence the traffic overhead is lower than others.

V. CONCLUSIONS AND FUTURE WORK

Vehicular ad hoc networks (VANET) have been envisioned to provide increased convenience and efficiency to drivers on the road. To realize this vision, we proposed a data pouring and buffering paradigm to address the data dissemination problem in VANET. In Data Pouring (DP), data are periodically broadcasted to vehicles on the road. In DP-IB, data poured from the data center are buffered and rebroadcasted at the intersections. Simulation results show that the proposed DP-IB scheme can significantly improve the data delivery ratio and reduce the network traffic. Further, we provide analytical models to explore the dissemination capacity of the proposed schemes. The analytical models also provide guidelines on choosing the system parameters to maximize the dissemination capacity under different data delivery ratio requirements.

To the best of our knowledge, this is the first paper to study dissemination capacity in VANET. The DP-IB scheme is proposed as a general solution for maximizing the dissemination capacity, where different broadcast cycle time is used at the data center and different intersections. As stated in our system model, the DP scheme is designed for environments where the vehicle density is reasonably high to maintain connection. Since the DP scheme is only used to deliver the data from the data center to the intersection, it can be

replaced by other schemes without significantly affecting the dissemination capacity. Thus, in sparse environment, store and forward solutions [28] and caching techniques [29] can be added to the DP scheme to deal with disconnections.

In this paper, we focused on push-based data dissemination, where the data can be efficiently delivered from moving vehicles or fixed stations to other vehicles. In our previous work [28], we studied the *pull-based* data dissemination/access, where a vehicle is enabled to query information about specific targets. Generally speaking, push-based approach is used for disseminating data that are useful for many people, whereas pull-based approach is used for querying data specific for some user. In practice, a hybrid of push/pull can be used to improve the system performance, and will be studied in our future work.

VI. ACKNOWLEDGMENTS

We would like to thank the anonymous referees whose insightful comments helped us to improve the presentation of the paper. This work was supported in part by National Science Foundation (CNS-0092770, CNS-0519460, CNS-0721479).

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