Exploiting Opportunities in V2V Transmissions with RSU-Assisted Backward Delivery

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***Abstract*—The vehicle-to-vehicle (V2V) data transmissions in Vehicular Ad-hoc Networks (VANETs) have been applied in many areas including the Internet of Vehicles, mobile data offloading, and mobile crowdsensing. The V2V-based data delivery that is opposite to the direction of a vehicle is called a *backward delivery* against the traffic flow, and it is blocked by an existing problem: a traffic hole. Under the backward delivery with a traffic hole problem, there are no available vehicles that can move the data to its destination using the movement-assisted routing protocol; the data move in the direction opposite to that of the vehicle's motion. In this paper, we investigate backward data delivery under the traffic hole problem in order to provide more opportunities for V2V data transmissions. To mitigate the impact of the traffic hole on the backward data delivery, we propose an RSU-Assisted Backward Delivery scheme (RABD) which employs the road-side units (RSUs) as low-cost relays instead of traditional access points. RABD combines two methods of data delivery: one based on backward data forwarding among vehicles and another which is forwarded by the RSU. To reduce resource consumption, we investigate the single-copy scheme and consider the tradeoffs of both methods. Our extensional simulations verify the effectiveness of our proposed schemes.**

***Index Terms*—Road-side unit, traffic hole, V2V data transmission, VANETs**

I. INTRODUCTION

As a special sensor and cyber-physical system, Vehicular Ad-hoc Networks (VANETs) have been paid a lot of attention by both academic researchers and automotive industries, with the increasing demand of various applications on vehicles, such as road condition sensing, traffic management, location-based services, and so on [1], [2]. The vehicle-to-vehicle (V2V) data transmissions in VANETs have been applied in many areas including the Internet of Vehicles [3], mobile data offloading [4], and mobile crowdsensing [5]. Timely and lossless multi-hop data delivery among vehicles is essential for VANETs, and various routing protocols have been proposed for infrastructure-less vehicle-to-vehicle (V2V) communications [6], [7]. However, due to intermittent connectivity in VANETs [7], many studies have proposed movement-assisted routing protocols [8] which adopt the carry-and-forward mechanism by considering the delay-tolerant network (DTN) [9]. This type of routing protocol can increase the data delivery delay for a higher data delivery ratio. Specifically, a mobile node can carry the received packet on the move until it meets a node with a higher probability of transmitting the packet to the destination.

However, the V2V-based data delivery that is the opposite of the moving directions of vehicles, termed as *backward delivery* against the traffic flow, is blocked by the existing problem of a traffic hole [10]. In the case of V2V data transmissions, data delivery normally follows traffic flows that are determined by the roads. However, the distribution of vehicles can be affected by their mobilities or by external means, like traffic lights. A gap with a distance larger than the communication range of the vehicles could appear along the traffic flow, which is referred to as the traffic hole. The traffic hole can stop data delivery along a particular traffic flow, which can prevent the data from reaching its destination. Moreover, the influence of the traffic hole problem on the backward data delivery can be worse than that of the data delivery along the direction of the motion of the vehicle. The traffic holes can interrupt the end-to-end connective path for backward delivery through the connection-based protocols. Furthermore, no available vehicles can carry the data to the destination by the movement-assisted routing protocols, since the data are headed in the direction opposite of the direction of the motion of the vehicle.

In this paper, we investigate backward data delivery under the traffic hole problem, in order to provide more opportunities for V2V data transmissions. To mitigate the impact of the traffic hole on the backward data delivery, we propose an RSU-Assisted Backward Delivery scheme (RABD), which employs road-side units (RSUs) as low-cost relays rather than as traditional access points. RABD combines two methods of data delivery: one based on the backward data forwarding among vehicles and another which is forwarded by the RSU. To reduce the resource consumption, we investigate the single-copy scheme by combining the two methods. For different demands of data delivery, we extend two more schemes: the two-copies scheme and the multiple-copies scheme. Our extensional simulations verify the effectiveness of our proposed schemes.

Our technical contributions are multi-fold, and include the following:

- We investigate the backward data delivery under the traffic hole problem, and we propose an RSU-Assisted Backward Delivery (RABD) scheme.
- We analyze the performance of RABD with a single-copy by combining the V2V-based forwarding and the V2R-based forwarding. For the different demands of data delivery, we extend two more schemes: the two-copies

scheme and the multiple-copies scheme.

- We conduct intensive simulations for evaluating the performance of RABD in VANETs.

This paper is organized as follows: Section II presents the backward delivery under the traffic hole problem and the RSU-Assisted Backward Delivery. In the next section, we analyze our proposed backward delivery scheme with a single-copy. In Section IV, we describe the results from our simulations. In Section V, we discuss related work. Finally, in the last section, we conclude the paper.

II. BACKWARD DATA DELIVERY

In this section, we give the assumptions and discuss the backward delivery under the traffic hole problem in VANETs. Then, we propose a backward delivery scheme with road-side units, called RABD.

A. Assumption

Vehicles communicate with each other through short-range wireless channels. Let R denote the communication range of each vehicle node. For a vehicle, its neighbors refer to the vehicles that are in its communication range. Vehicles can find their neighbors through beacon messages, which have been discussed in [6]. The well-known car-following model [11] states that a vehicle moves at the same or a similar speed as the vehicle in front of it, as long as there is a vehicle within range of the current vehicle. Thus, due to the speed limitation, we assume that the speed of the vehicles (v) on a road are all the same. It is well-known that the distances between cars if free-flow traffic are uncorrelated, and the spacing distribution follows the Poisson distribution [12].

B. Applications of Backward Data Delivery

Many applications in VANETs require delivering data packets backwards. In sensing applications, vehicles need to obtain the conditions about the roads that lie ahead of them. Figure 1 shows an accident alert application. As soon as a collision occurs, the cars that crashed and possibly other cars in the vicinity immediately generate an alert message. This alert message needs to be delivered to the vehicles on the road approaching the accident area, and it must tell them to slow down. As an example in Figure 1, an alert message needs to be delivered from the first vehicle, V_1, to the 5^{th} vehicle, V_5. The total data delivery delay is calculated from the interval time between when the first vehicle generates the alert message and when V_5 receives the message, which is denoted by $\sigma_{1\to 5}$. Jeong *et al.* in [13] introduce an application of Wi-Fi sensing. The vehicles need to obtain the distribution of the Wi-Fi APs ahead for mobile data offloading. Thus, the data is backwardly delivered from the probing vehicles ahead of the receivers.

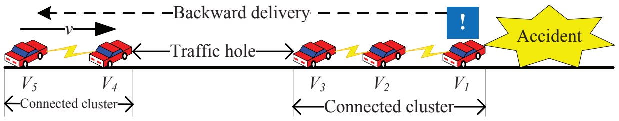


Fig. 1. The traffic hole problem affects the backward data delivery

Under a traffic flow with a high density, the backward data delivery can be based on the multi-hop among the vehicles moving on the road. While any two adjacent vehicles are in their communication ranges, there is a connected routing path from V_1 to V_m. Thus, the alert message can be immediately forwarded to the destination, V_m, by the wireless communications. The data delivery delay can be calculated as follows:

$$\sigma_{1\to m} = \lceil \frac{d_{1,m}}{R} \rceil \cdot t_{hop} \tag{1}$$

where $d_{1,m}$ denotes the distance between V_1 and V_m.

C. Traffic Hole Problem

Data delivery with V2V communications in VANETs is based on the vehicles on the roads, but the distribution of the vehicles could be affected by their mobilities or by external means, such as traffic lights. A gap with a distance larger than the communication range of the vehicles could appear along the traffic flow; this is considered a *traffic hole* [10]. It could block the data delivery along the traffic flow.

Unlike our previous work, this paper investigates backward data delivery under the traffic hole problem. As shown in Figure 1, when the distance between the vehicles V_3 and V_4 is larger than their communication range R, a traffic hole appears in the road traffic flow and partitions the road traffic flow into two connected clusters. On a one-way road, the message is backwardly delivered from the vehicle V_3 to V_4, and is blocked by the traffic hole. Because the data are headed in the direction opposite to that of the motion of the vehicle, no available vehicles can carry the data to the destination using the movement-assisted routing protocol.

D. RSU-Assisted Backward Delivery

An intuitive approach is to employ some inter-nodes in the traffic hole to help forward data packets across the traffic hole. However, due to the existence of the traffic hole, it is hard to find the inter-nodes along the traffic flow. Out of the traffic flow, we can utilize some static road-side units (RSUs) to help forwarding the packets to reduce the data delivery delay. An RSU can be a wireless access point, a parked vehicle, vehicles waiting at an intersection, or the static node presented in [14]. The RSU only acts as a relay, so it incurs a lower cost than a traditional access point. We term this type of data delivery as RSU-Assisted Backward Delivery (RABD). Each road can be regarded as a river. The vehicles are regarded as boats, and they can move from upstream to downstream. Thus, each RSU can be seen as a dock for delivering the data packets.

The packet delivery ratio (PDR) of vehicles for uploading the data packets to the road-side unit follows a specified distribution, as many studies have discussed [15], [16]. We assume that the quality of the upload-link from the vehicle to an RSU is unreliable. The probabilities of upload-links between the i^{th} vehicle and the road-side unit are denoted by P_i, which are independent and identically distributed (i.i.d.).

Algorithm 1 Single-copy

```
1: Forward the packet to the $j^{th}$ vehicle
2: The $j^{th}$ vehicle uploads the packet to an RSU
3: The $1^{st}$ vehicle of the next cluster downloads the packet
4: Repeat step 1
```

Let Q_i be equal to $1 - P_i$. We define the expected value of the probabilities as $E[P_i] = p$, and $E[Q_i] = q$. Due to the powerful communication capability of the RSU, we assume that the download-link from the RSU to the vehicle is reliable and that its PDR is equal to 1.

By considering the resource consumption, we propose a single-copy scheme which adopts the following steps: (1) *Intra-cluster forwarding*: the data packet is forwarded to the specified vehicle in the connected cluster, such as the j^{th} vehicle; (2) *Uploading*: the j^{th} vehicle tries to upload the data packet to the RSU with an unreliable upload-link. If the vehicle fails to upload the data packet, it will carry the packet until the next upload-link to the next downstream RSU; (3) *Downloading*: the RSU sends the data packet to the first vehicle in the next connected-cluster; (4) *Receiving*: repeat step 1 until the target vehicle receives the data packet. The details of the algorithm are given in Algorithm 1.

In this scheme, the vehicle which carries the data packet has two choices for data delivery, i.e. it directly uploads the data packet to the RSU, or it backwardly forwards the packet to the j^{th} vehicle in the connected cluster. The reasons for forwarding the data packet to the backward vehicles include the following: (1) a potential opportunity to deliver the data packet to the destination vehicle by a connected path; (2) a potential opportunity to deliver the data packet to an upstream RSU by a connected path. The qualities of the upload-links for the vehicles, which are affected by many factors like the position of the vehicle in the connected cluster and the time of the upload-link, are different.

III. ANALYSIS OF BACKWARD DELIVERY

In this section, we analyze our proposed backward delivery scheme with single-copy. We investigate the data delivery delay from the first vehicle in the first connected cluster along the road, to the last vehicle in the n^{th} connected cluster, as shown in Figure 2. Because the speed of wireless communication is much faster than that of the vehicle, the data delivery delay by way of forwarding among the vehicles is much slower than that of carrying. Therefore, we ignore the data delivery delay among the vehicles in the same connected cluster by way of forwarding.

A. Conditional Expected Delay

We assume the vehicle can communicate each RSU only in a small vehicle-to-RSU (V2R) area, which is the nearest one to the RSU on the road. The length of the V2R area is equal to the length of the vehicle. As shown in Figure 2, when the time, t, is equal to 0, the 1^{st} vehicle of the 1^{st} connected cluster receives the data packet, and the destination of this packet is the last vehicle in the n^{th} connected cluster. Let σ_n denote the data delivery delay from the 1^{st} vehicle of the 1^{st} cluster to the last vehicle of the n^{th} cluster.

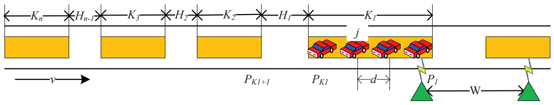


Fig. 2. Backward delivery among multiple clusters

Let K_i denote the number of vehicles in the i^{th} connected cluster, and let the expected number of vehicles in a connected cluster be denoted by $E[K_i] = \beta$. The distance between two adjacent vehicles in a connected cluster is denoted by D, which should be less than the communication range (R). The expected value of these distances is denoted by $E[D] = d$. Thus, the expected length of the i^{th} connected cluster is equal to $(K_1 - 1)d$. Let H_i denote the length of the i^{th} traffic hole. For simplicity, we assume the expected distance of the traffic hole can be calculated as: $E[H_i] = \gamma d$. The distance of two adjacent road-side units is denoted by $W = wd$. Here, γ and w are both positive integers.

We define $\mathbb{1}_{j \to \Delta}$ as an indicator function for the data delivery from the j^{th} vehicle to the road-side unit. Let $\mathbb{1}_{j \xrightarrow{s} \Delta}$ denote a successful data delivery from the j^{th} vehicle to the road-side unit, and let $\mathbb{1}_{j \xrightarrow{f} \Delta}$ denote a failed data delivery from the j^{th} vehicle to the road-side unit.

Let $E[\sigma_n \mid K_1 = k_1]$ denote the expected data delivery delay from the first vehicle in the first connected cluster to the last vehicle in the n^{th} connected cluster, when the number of the vehicles in the first connected cluster (K_1) is equal to k_1. The data packet is forwarded to the j^{th} vehicle ($1 \leq j \leq k_1$) in the first connected cluster by the wireless communications among the vehicles, and it is then uploaded to a road-side unit by the j^{th} vehicle with a probability of P_j. If the j^{th} vehicle fails to upload to the road-side unit, it will carry the packet until it reaches another upload-link to the next road-side unit. The road-side unit will keep the data packet until the destination vehicle moves into its communication range. Therefore, the conditional expected data delivery delay can be calculated as follows:

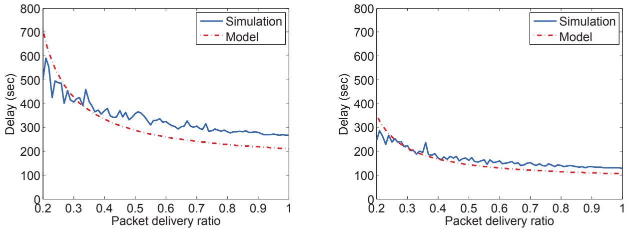
When K_1 is equal to 1, the conditional expected delivery delay can be calculated as follows:

$$E[\sigma_n \mid K_1 = 1] = \frac{d}{v}[(n-1)(\beta + \gamma - 1) + \frac{q}{p}w] \tag{2}$$

Thus, with the help of Equation 2, we can iteratively calculate the conditional expected delivery delay as follows:

$$E[\sigma_n \mid K_1 = 0] = 0, \tag{3}$$

$$\begin{aligned} &E[\sigma_n \mid K_1 = k_1] \\ &= \frac{d}{v}[\frac{p+1}{p}k_1 - \frac{1}{p} + \frac{q}{p}w + (n-1)(\beta + \gamma) - n] \\ &+ \frac{1}{p}E[\sigma_n \mid K_1 = k_1 - 1] \; (k_1 \geq 1) \end{aligned} \tag{4}$$



(a) $v = 10$ m/s (b) $v = 20$ m/s

Fig. 3. Impact of PDR on data delivery delay

Equations 4 and 5 calculate the conditional expected delay under any distributions with the fixed values of β, γ, and p.

B. Expected Delay

For illustrating the estimation of the expected data delivery delay, we assume that the number of vehicles in a connected cluster follows a geometric distribution as follows: $P(K_i = k) = (1-\lambda)^{k-1} \cdot \lambda$, and its expected value is: $E[K_i] = \frac{1}{\lambda} = \beta$. Let $f_k = E[\sigma \mid K_1 = k]$, $(k = 1, 2, \cdots)$. Let $u(z) = \sum_{k=1}^{\infty} f_k \cdot z^k$. Let $ak_1 + b = \frac{p+1}{p} k_1 - \frac{1}{p} + \frac{q}{p} w + (n-1)(\beta+\gamma) - n$, where $a = \frac{p+1}{p}$, and $b = -\frac{1}{p} + \frac{q}{p} w + (n-1)(\beta+\gamma) - n$. Thus, the expected data delivery delay can be calculated as follows:

$$E[\sigma_n] = \frac{\lambda}{1-\lambda} u(1-\lambda), \tag{5}$$

where

$$u(z) = \frac{f_1 z - \phi(z)}{1 - \frac{z}{p}},$$

and

$$\begin{aligned} \phi(z) &= \sum_{k=2}^{\infty} (ak+b) z^k \\ &= a \cdot z\left(\frac{1}{(1-z)^2} - 1\right) + b \cdot \left(\frac{1}{1-z} - 1 - z\right) \end{aligned}$$

Figure 3 shows a comparison between the calculation results of our model and the results of our simulations. The details of the simulation setup will be introduced in Section IV. We notice that while increasing the packet delivery ratio (PDR) of the upload-link, the data delivery delay decreases. The quality of the upload-link can affect the data delivery delay, which means that there is a high probability that the upload-link can reduce the data delivery delay. The results of our proposed equations are approximated to those of the simulations, which verify our proposed model for the data delivery.

C. Delay from the j^{th} Vehicle

With the help of Equations 4 and 5, we can calculate the data delivery from the j^{th} vehicle in the first connected cluster.

$$\begin{aligned} &E[\sigma_n \cdot \mathbb{1}_{j \to \Delta} \mid K_1 = k_1],\ k_1 \geq 1,\ 1 \leq j \leq k_1 \\ &= p\frac{d}{v}\{k_1 + [(n-1)\beta - n] + (n-1)\gamma\} \\ &+ q\{E[\sigma \mid K_1 = k_1 - j + 1] + \frac{(j-1)d + wd}{v}\} \end{aligned} \tag{6}$$

Algorithm 2 Two-copies

```
1: The first vehicle uploads the packet to an RSU
2: Forward the packet to the the tail of the cluster
3: The tail of the cluster uploads the packet to an RSU
4: Repeat step 1
```

Algorithm 3 Multiple-copies

```
1: Duplicate the packet to all the vehicles of the cluster
2: The vehicles duplicate and upload the packet to an RSU
3: The first vehicle of the next cluster downloads it
4: Repeat step 1
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With the help of Equation 7, the vehicles can estimate the expected delivery delay under the single-copy scheme by the j^{th} vehicle in the first connected cluster. Moreover, the first cluster can select the the j^{th} vehicle as the forwarding node to the road-side unit, which has a minimal expected delay.

D. Extensional Schemes

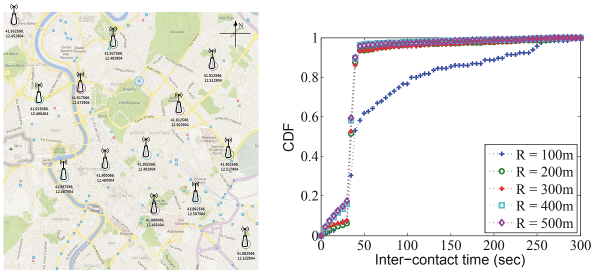
In order to improve the performance of the backward delivery, we propose the two-copies scheme shown in Algorithm 2. The two-copies scheme has two ways for backward delivery: V2R backward delivery and V2V backward delivery. Each method of backward delivery only has one copy of the data packet. We further propose a multiple-copies scheme to improve the performance of backward delivery without considering resource consumption. The multiple-copies scheme also has two ways for backward delivery: V2R backward delivery and V2V backward delivery. During backward delivery, all the contacted vehicles and RSUs will have a copy of each data packet. The details of the algorithm are given in Algorithm 3.

IV. SIMULATION RESULTS

In this section, we evaluate the performance of our proposed backward scheme with a single-copy. For the different demands of data delivery, we evaluate two extensional schemes: the two-copies scheme and the multiple-copies scheme. We compare the three schemes under different scenarios. When comparing the protocols, we choose *data delivery delay* to evaluate them.

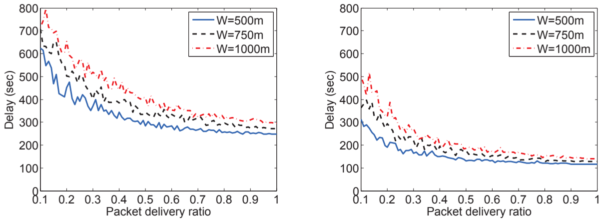
A. ICT with RSU

To evaluate connectivity among the vehicles and RSUs by inter-contact time (ICT) [17], we experiment on the Taxi-ROMA dataset [18]. This dataset contains real mobility traces of taxi cabs in Rome, Italy. It contains the GPS coordinates of approximately 320 taxis collected over 30 days. We select the dataset of traces collected on Feb. 14, 2014. The traces cover an area with a range of 66Km $\times$ 59Km. As shown in Figure 4(a), our experiment scenario consists of 13 RSUs at different places. We collect the ICT between the vehicles and the RSUs. The results of CDF under different communication ranges (R) are shown in Figure 4(b). We notice that the smaller communication range has a longer ICT, and that 82% of the ICTs under the largest range, 600m, are longer than 35



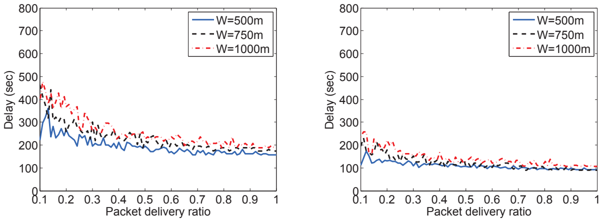
(a) Map of Roma (b) CDF of ICT

Fig. 4. Inter-contact time with RSUs



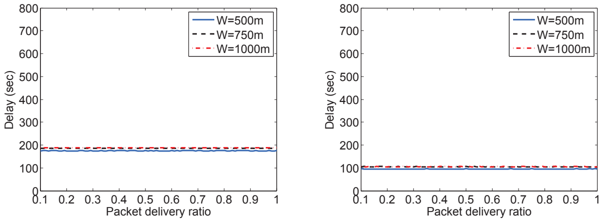
(a) $v = 10$ m/s (b) $v = 20$ m/s

Fig. 5. Impact of PDR on data delivery delay with the single-copy scheme



(a) $v = 10$ m/s (b) $v = 20$ m/s

Fig. 6. Impact of PDR on data delivery delay with the two-copies scheme



(a) $v = 10$ m/s (b) $v = 20$ m/s

Fig. 7. Impact of PDR on data delivery delay with the multiple-copies scheme

seconds. The reason for this is that there are a fewer number of vehicles in the sparse area while the traffic hole problem is in the denser area. This implies that although RSUs can help to forward under the sparse area or the traffic hole problem, they will increase data delivery delays. Therefore, we propose combining the two kinds of methods: V2V and V2R.

B. Performances of Delivery Schemes

We use the combination of NS-2 [19] and SUMO [20] for the simulations. SUMO (Simulation of Urban Mobility) is an open-source traffic simulator that models realistic vehicle behavior. NS-2 is an open-source discrete event network simulator that supports both wired and wireless networks, including most MANET routing protocols and an implementation of the IEEE 802.11 MAC layer. In our simulations, the average velocity of the vehicles is 10 m/s, and the average distance between two adjacent vehicles is 100m. The wireless communication range for each node is 100m, and the buffer size of each node is 50 packets. The data packet size is 200B. The distance between two adjacent RSUs (denoted by W) is 500m, 750m, or 1000m. The average PDR (packet delivery ratio) of the upload-link from a vehicle to an RSU is 0.6. The number of vehicles is 20. The simulation time is 1000s.

We evaluate the data delivery delay under different average PDRs of the upload-links by the single-copy scheme. The simulation results are shown in Figure 5. Figure 5(a) shows the data delivery delay with a speed of 10m/s, and Figure 5(b) shows the data delivery delay with a speed of 20m/s. We notice that the delay decreases while the PDR increases. While the distance between each of the two adjacent road-side units increases, the data delivery increases. Due to the failure of upload-links, the larger distance between the adjacent road-side units can increase the data delivery delay.

We evaluate the data delivery delay under different average PDRs of the upload-links with the two-copies scheme. The simulation results are shown in Figure 6. Figure 6(a) shows the data delivery delay with a speed of 10m/s, and Figure 6(b) shows the data delivery delay with a speed of 20m/s. We notice that the delay decreases while the PDR increases. While the distance between each of the two adjacent road-side units increases, the data delivery increases. Due to the failure of the upload-links, the larger distance between the adjacent road-side units can increase the data delivery delay. Compared with the single-copy scheme, the two-copies scheme has a lower data delivery delay under the lower PDR of the upload-link, because of the increasing number of copies.

We evaluate the data delivery delay under different average PDRs of the upload-links with the multiple-copies scheme. The simulation results are shown in Figure 7. Figure 7(a) shows the data delivery delay with a speed of 10m/s, and Figure 7(b) shows the data delivery delay with a speed of 20m/s. We notice that the delay decreases while the PDR increases. While the distance between each of the two adjacent road-side units increases, the data delivery increases as well. Due to the failure of the upload-links, the larger distance between the adjacent road-side units can increase the data delivery delay. Compared with the single-copy scheme and the two-copies scheme, the multiple-copies scheme has a lower data delivery delay. However, it also consumes the most resources, such as bandwidth and the buffers of the vehicles or the RSUs.

V. RELATED WORK

The Internet of Vehicles (IoV) can be seen as a superset of VANET, which extends VANET's scale, structure, and applications [3]. Li *et al.* in [4] investigate DTN to offload traffic from cellular networks to high capacity and free device-to-device networks. The mobile users are either vehicles or humans carrying wireless devices, e.g. mobile phones. Karaliopoulo *et al.* in [5] discuss mobile crowdsensing with the opportunistic networking paradigm, as practised in DTNs. DTNs are designed to overcome limitations in connectivity due to conditions such as mobility, poor infrastructure, and short range radios. However, missed contact opportunities decrease throughput and increase delay in the network. Jeong *et al.* in [21] propose to effectively utilize vehicles trajectory information for the data forwarding in light-traffic vehicular ad hoc networks. For the accurate end-to-end delay computation, they also propose a link delay model to estimate the packet forwarding delay on a road segment. Zhao *et al.* [22] propose the use of throwboxes in mobile DTNs to create a greater number of contact opportunities, consequently improving the performance of the network. Shahbazi *et al.* in [23] study a passive approach in DTN where messages are delivered from a source by being deposited at one or more locations that are later visited by the destination.

VI. CONCLUSION

Many applications in VANETs, such as accident alerts and traffic monitoring, require backward delivery. However, the traffic hole problem in VANETs affects the performance of the backward delivery. In this paper, we investigate backward delivery with the traffic hole problem. We propose utilizing road-side units (RSUs) to overcome the problem. For the different demands of data delivery, we propose three different backward delivery schemes. Our extensional simulations verify the effectiveness of our proposed schemes. Our future work will consider scenarios in which the download-link is unreliable and has a probability of successfully downloading packets. We will also investigate a scenario in which the RSU has a larger communication range that can simultaneously communicate with multiple vehicles.

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REFERENCES

[1] A. Fox, B. V. K. V. Kumar, and B. Fan, "Multi-source variable-rate sampled signal reconstructions in vehicular cps," in *Proc. of IEEE INFOCOM*, 2016.

[2] A. E. Oualkadi and J. Zbitou, *Handbook of Research on Advanced Trends in Microwave and Communication Engineering*. IGI Global, 2017.

[3] J. Cheng, J. Cheng, M. Zhou, F. Liu, S. Gao, and C. Liu, "Routing in internet of vehicles: A review," *IEEE Transactions on Intelligent Transportation Systems*, vol. 16, no. 5, pp. 1–14, 2015.

[4] Y. Li, M. Qian, D. Jin, P. Hui, Z. Wang, and S. Chen, "Multiple mobile data offloading through disruption tolerant networks," *IEEE Transactions on Mobile Computing*, vol. 13, no. 7, pp. 1579–1596, 2014.

[5] M. Karaliopoulos, O. Telelis, and I. Koutsopoulos, "User recruitment for mobile crowdsensing over opportunistic networks," in *Computer Communications*, 2015.

[6] V. Naumov and T. R. Gross, "Connectivity-aware routing (car) in vehicular ad-hoc networks," in *Proc. of IEEE INFOCOM*, 2007.

[7] J. Zhao and G. Cao, "Vadd: Vehicle-assisted data delivery in vehicular ad hoc networks," *IEEE Transactions on Vehicular Technology*, vol. 57, no. 3, pp. 1910–1922, 2008.

[8] J. Wu, S. Yang, and F. Dai, "Logarithmic store-carry-forward routing in mobile ad hoc networks," *IEEE Transactions on Parallel and Distributed Systems*, vol. 18, no. 6, pp. 735–748, 2007.

[9] K. Fall, "A delay-tolerant network architecture for challenged internets," in *Proc. of ACM SIGCOMM*, 2003, pp. 27–34.

[10] C. Song, J. Wu, and M. Liu, "On characterization of the traffic hole problem in vehicular ad-hoc networks," in *Proc. of IEEE GlobeCom*, 2013.

[11] R. W. Rothery, "Car following models," *Traffic Flow Theory*, 1992.

[12] A. Abul-Magd, "Modeling highway-traffic headway distributions using superstatistics," *Physical Review E*, vol. 76, no. 5, 2007.

[13] J. Jaeseong, Y. Yung, C. Jeong-woo, E. Do Young, and C. Song, "Wi-fi sensing: Should mobiles sleep longer as they age?" in *Proc. of IEEE INFOCOM*, 2013.

[14] Y. Ding, C. Wang, and L. Xiao, "A static-node assisted adaptive routing protocol in vehicular networks," in *Proc. of ACM VANET*, 2007.

[15] J. Ott and D. Kutscher, "Drive-thru internet: Ieee 802.11 b for automobile users," in *Proc.of IEEE INFOCOM*, 2004.

[16] T. H. Luan, X. Ling, and X. Shen, "Mac in motion: impact of mobility on the mac of drive-thru internet," *IEEE Transactions on Mobile Computing*, vol. 11, no. 2, pp. 305–319, 2012.

[17] H. Zhu, M. Li, L. Fu, G. Xue, Y. Zhu, and L. M. Ni, "Impact of traffic influxes: Revealing exponential intercontact time in urban vanets," *IEEE Transactions on Parallel and Distributed Systems*, vol. 22, no. 8, pp. 1258–1266, 2010.

[18] L. Bracciale, M. Bonola, P. Loreti, G. Bianchi, R. Amici, and A. Rabuffi, "CRAWDAD data set roma/taxi (v. 2014-07-17)," Downloaded from http://crawdad.org/roma/taxi/, Jul. 2014.

[19] "The network simulator - ns-2." [Online]. Available: http://isi.edu/nsnam/ns/

[20] "Sumo - simulation of urban mobility." [Online]. Available: http://sumo.sourceforge.net/

[21] J. Jeong, S. Guo, Y. Gu, T. He, and D. H. C. Du, "Trajectory-based data forwarding for light-traffic vehicular ad hoc networks," *IEEE Transactions on Parallel and Distributed Systems*, vol. 22, no. 5, pp. 743–757, 2010.

[22] W. Zhao, Y. Chen, M. Ammar, M. Corner, B. Levine, and E. Zegura, "Capacity enhancement using throwboxes in dtns," in *Proc. of IEEE MASS*, 2006.

[23] S. Shahbazi, S. Karunasekera, and A. Harwood, "Improving performance in delay/disruption tolerant networks through passive relay points," *Wireless Networks*, vol. 18, no. 1, pp. 9–31, 2012.