Data Uploading in Hybrid V2V/V2I Vehicular Networks: Modeling and Cooperative Strategy

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***Abstract*—Supporting data dissemination in vehicular networks is difficult due to high mobility of vehicle traffic, limited communication resources, and dynamic communication requirements. In this paper, we investigate data dissemination in hybrid vehicular networks, where messages generated at vehicles should be uploaded to the roadside unit (RSU) assisted by vehicle-to-vehicle (V2V) communications, using vehicles traveling in both directions as relays. The objective is to optimize the resource utilization and reduce the data delivery delay. We first analyze the data uploading capacity and delivery delay in hybrid vehicular networks with the store-carry-and-forward mechanism. Applying the analytical results and given the traffic and data information, a distributed multisource scheduling algorithm is proposed. Extensive simulations are conducted to verify the correctness of the analysis. It shows that the proposed algorithm significantly improves the data dissemination efficiency compared with the existing solutions.**

***Index Terms*—Capacity and delay analysis, strategy design, data dissemination, hybrid vehicular network.**

I. Introduction

WITH the development of vehicular communication technologies and the increasing penetration of vehicle-related services, future transportation systems will be more intelligent, secure and comfortable for riders. To enable these advanced services and applications, data dissemination plays a critical role in intelligent transportation systems [1]–[3]. Two key communication technologies, Vehicle-to-Vehicle (V2V) communications and Vehicle-to-Infrastructure (V2I) communications, have been proposed and developed for vehicular communication networks [4]–[7]. V2V communications help extend the communication range by utilizing the mobility of the vehicles and the multi-hop relays between vehicles. Vehicle-to-Infrastructure (V2I) communications make it possible to connect the vehicles in the coverage of the infrastructure (e.g., Roadside Unit (RSU), cellular base station, etc.) to the Internet. Relying on V2V or V2I only is insufficient for constructing a reliable, scalable and effective data dissemination system due to the uncertainty of the V2V communications and the high cost and limited coverage of V2I communications. Therefore, a hybrid vehicular communication system, incorporating both V2V and V2I communications, is indispensable for future Intelligent Transportation Systems (ITS).

In a hybrid V2V/V2I network, to improve the connectivity when the network is sparse, the store-carry-and-forward mechanism has attracted attention. Using this mechanism [8]–[10], a vehicle carrying a message will try to forward it to the next-hop relay in the data dissemination direction if possible. If not possible, the message will be stored and carried until it reaches a suitable relay. By utilizing the mobility and connectivity of the bidirectional vehicles, the reliability of message dissemination in vehicular networks is largely improved, at the cost of random delay.

In this paper, we consider a typical data dissemination scenario where the message is generated at the vehicle and meant to be uploaded to the infrastructure in the vehicular networks. e.g., RSU or base station. For road safety applications, vehicles traveling on the road periodically broadcast their driving status, current road conditions, etc. in beacons. At the same time, the V2V/V2I networks should handle the data uploading requests from one or more vehicles simultaneously, e.g., vehicles may report accidents happening on the road to the emergency center, upload the crowd-sensing data to the Internet, reserve the charging or re-fueling slots in the highway lounge area, etc.

To support the above services in a hybrid V2V/V2I network, scheduling the data transmission and optimizing the communication resource allocation is a challenging problem [11]–[14]. Specifically, it remains an open issue on how to optimize the decision of when and where to transfer the message (containing multiple packets) or a part of it to whom (the next-hop relay), till it reaches the infrastructure. Although many efforts have been devoted to studying the data dissemination in the highway scenario under the store-carry-and-forward mechanism, the previous solutions mainly focused on the performance of single-hop transmission or broadcast [15], [16], single-direction vehicle traffic [3], [17], or the downloading case [13], [15]. Thus, the existing solutions are insufficient to address the large-size message uploading cases using both V2I and multi-hop V2V transmissions.

To fill the gap, first of all, an analytical framework considering the random vehicle network topology is needed to gain essential insights of the data dissemination process, to design effective forwarding strategy, and to optimize network planning including

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the infrastructure deployment. Given the existing literature and our previous research, the challenges of obtaining an accurate modeling and analytical framework include the following two aspects. i) The randomness of the vehicle mobility makes a significant impact on the network connectivity and thereby on the performance, but the relationship between them is difficult to quantify. ii) It is sophisticated to measure the effects of the decisive factors including RSU spacing, V2V/V2I transmission rates and uploading location on the delivery performance. To accomplish the data dissemination modeling and analysis, based on the vehicle clustering and store-carry-and-forward mechanism, we take the randomness of the vehicle distribution into account and examine the impacts of the V2V/V2I transmission rate, the uploading initiated position, etc.

In this paper, based on the vehicle clustering and store-carry-and-forward mechanism, we develop a tractable yet accurate analytical framework to quantify the uploading capacity and delay performance in hybrid V2V/V2I system. Given the analytical model, a distributed cooperative strategy is designed. The main contributions of this paper are summarized as follows:

1) we develop the analytical framework to quantify the capacity and delay performance, considering the random vehicle distribution under the store-carry-and-forward mechanism. The analytical results reveal the relationship between the communication efficiency and the vehicular network parameters including vehicle/RSU density, V2V/V2I communication range, data rate and the vehicle speed in both directions;
2) based on the above analysis, we propose a distributed online cooperative strategy to maximize the average uploading throughput for all types of vehicles. The proposed strategy can efficiently utilize both V2V and V2I communication resources to enhance the network performance in terms of capacity and delay;
3) NS-3 simulations have been conducted to verify the correctness of the analysis and demonstrate that the proposed strategy reduces up-to half of the average delivery delay compared with the benchmark methods.

The rest of this paper is organized as follows. Section II introduces the related work. System model and problem formulation are presented in Section III. Section IV provides the framework of the capacity and delay analysis. Section V introduces the proposed scheduling strategy for the data dissemination followed by the performance evaluation in Section VI. Section VII discusses the multi-channel scenario and the co-existence with the existing technologies. Conclusion and open issues are presented in Section VIII.

II. Related Work

Message delivery in hybrid V2V/V2I vehicular networks has attracted extensive research. Broad researches have been done to analyze the data dissemination performance in vehicular networks, and many strategies and designs have been proposed to improve the effectiveness of the process. The existing works can be divided into the following three categories.

First, protocols and strategies have been proposed to use hybrid/cooperative transmission mechanisms to better fulfill the Quality of Service (QoS) requirements of message delivery [5], [18]–[23]. In [5], Mario *et al.* enhanced the real-time video dissemination in highway vehicular networks considering the Quality of Experience (QoE). [18] focused on the utility optimization problem based on a utility model considering the users' satisfaction level. [19] proposed a class of routing protocols based on the real-time city road vehicular traffic information using both reactive and proactive mechanisms. How to model and quantify the performance was not addressed.

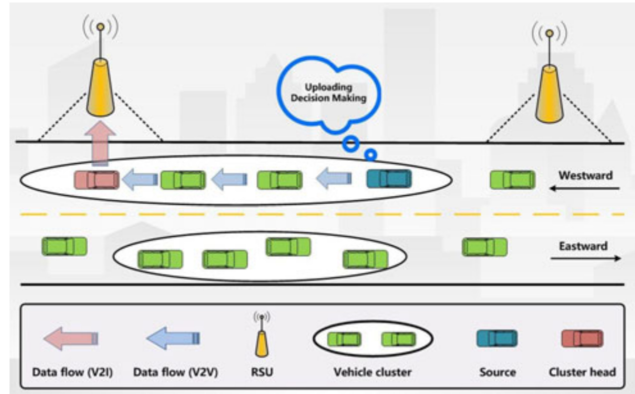


Fig. 1. Highway vehicular network scenario.

Second, there are several works focusing on modeling and analysis of the performance in vehicular networks [15], [24]–[26]. [15] analyzed the achievable throughput of message dissemination in cooperative vehicular networks. [24] studied the message delivery in bidirectional Vehicular Ad Hoc Network (VANET) and obtained a linear relationship between the delivery delay and distance.

Third, combining the performance study and protocol design, optimization solutions have been proposed based on the analysis [3], [27]–[30]. [3] introduced a store-and-forward framework, and proposed the optimal routing strategy based on the analysis of the expected path delay which has been validated by simulations. In [27], Bi *et al.* reduced the message redundancy and enhanced the message reliability in emergency message dissemination using an urban multi-hop broadcast protocol based on the analysis of message propagation speed. Wang *et al.* [28] analyzed the throughput capacity in VANETs by exploiting the vehicle mobility and developed a routing scheme maximizing the throughput from vehicles to RSU.

Previous analysis and design are based on the assumptions such as V2V/V2I transmission delay is negligible, each message is small enough to be transmitted by any V2V link, only one-direction vehicles can be used as relays, or the downloading scenario is considered. Different from the previous work, we consider the uploading scenario leveraging both the V2I and multi-hop V2V communications, and using the vehicles from both directions as relays, so the message can be uploaded to the infrastructure promptly.

III. System Model and Problem Formulation

A. System Model

In this paper, we focus on the data dissemination problem in hybrid V2V/V2I vehicular networks. As shown in Fig. 1, vehicles travel along the one-dimensional road (such as highway)

TABLE I
NOTATIONS

λ_1, λ_2	$\triangleq$	Vehicle density in forward/backward direction
d	$\triangleq$	RSUs spacing
d_0	$\triangleq$	Distance between the source and the previous RSU
r_i, r_v	$\triangleq$	V2I/V2V data rate
v_1, v_2	$\triangleq$	Vehicle speed in forward/backward direction
C_B	$\triangleq$	Backward capacity
C_F	$\triangleq$	Forward capacity
D_{Ab}	$\triangleq$	Uploading delay after backtrack
D_{Bt}	$\triangleq$	Backtrack delay
D_B	$\triangleq$	Backward delay
D_F	$\triangleq$	Forward delay
R_i, R_v	$\triangleq$	V2I/V2V communication range
V_T	$\triangleq$	Message size

in both directions. Data can be exchanged among vehicles and RSUs using V2V and V2I communications. Vehicles moving on the highway are potential data sources. Each vehicle periodically broadcasts beacons to its neighborhood, including its location, speed, service request, availability as a relay and etc. In addition to beacons, vehicles may generate data to be uploaded to the RSUs, e.g., when an accident occurs, the video of the incident is captured by the camera on a vehicle and it should be uploaded to the Internet through the nearby RSUs so that the emergency center can effectively deal with the accident. The information is disseminated by multi-hop V2V and V2I links during the contact time among RSUs and vehicles. For easy reference, the important notations used in this paper are summarized in Table I.

Network Architecture: To efficiently and effectively organize the vehicular network and implement the data dissemination, the following system architecture is used. As shown in Fig. 1, RSUs are placed along the road with specified spacing. In both directions, vehicles equipped with vehicular communication modules can exchange data packets with other vehicles or RSUs. It is assumed that the beacons and the uploading data packets use independent wireless resources for communication, such as different time-slot in single-channel systems or different channels in multi-channel systems. During the data delivery, the vehicles having data to upload should first notify the other vehicles by including the uploading request in their beacons. Then, the other vehicles in both directions respond the availability of the communication resources. After the vehicle successfully obtains the communication resource, it starts the data delivery by either uploading to the RSU directly or forwarding the data to the next-hop relay.

Assumption: We assume that a constant transmission data rate if the receiver is within the transmission range. The data rates of V2V and V2I may be different due to the different antenna gain and transmission power. Usually, the data rate and communication range of V2I is greater than that of V2V thanks to the higher transmission power and antenna gain. For time-varying channels, the data rate can be replaced by the time-averaged value and our analysis still applies. The difference between constant and time-varying data rate cases is marginal and verified by the simulation results in Section VI. In the highway scenario without traffic light control, vehicles move at a speed with a limited variance most of the time. Thus, for simplicity in the analysis, we assume that all vehicles move at a constant speed in each road segment and the inter-distances of them are i.i.d. exponential random variables, according to the analysis of the vehicle traces in [25]. These assumptions also have been widely used in the analytical framework studying the linear vehicular networks [3], [9], [15], [25].

Cluster: In the vehicular network, vehicles are organized into clusters in which the distances between two neighboring vehicles are smaller than or equal to the V2V communication range, R_v. In a vehicle cluster, a message can be forwarded to any vehicle by applying multi-hop V2V links. It is noted that the vehicles in the opposite direction are not included in the cluster considering the formation instability from the opposite moving directions.

According to [9], [31], given the inter-vehicle distance probability distribution function, assumed to be the exponential function, since the vehicles arrive at a certain rate λ, the probability distribution function of cluster size $f_c(x)$ can be approximated by

$$f_c(x) = \frac{x^{k-1} e^{-\frac{x}{\theta}}}{\theta^k \Gamma(k)}, x > 0, \tag{1}$$

where $k = \frac{E\{C_s\}^2}{E\{{C_s}^2\} - E\{C_s\}^2}$, $\theta = \frac{E\{{C_s}^2\} - E\{C_s\}^2}{E\{C_s\}}$, C_s denotes th e cluster size, $E\{C_s\}$ and $E\{C_s^2\}$ are obtained by using the Theorem 4.1 and Corollary 4.2 in [9]. In a cluster, the message can be propagated to each other and the Cluster Head (CH) is defined as the vehicle nearest to the chosen RSU. The CH changes when another vehicle moves closer to the chosen RSU than the current CH, or the chosen RSU for uploading changes. By utilizing the cluster-based data dissemination, the message can be delivered farther and faster.

Relay Selection and Mode Switch: Within a cluster, it is proposed that the farthest vehicle in the communication range of the previous message carrier should be selected as the next hop relay. Thus, not all vehicles are used as relays simultaneously and the distance between two relays more than one-hop away is always greater than R_v, which greatly reduces the number of the hops and the congestion in a dense environment. The relay selection will be ended until the message reaches the delivery destination or encounters the boundary of the vehicle cluster.

To improve the efficiency of the large-size message delivery, it is expected that the relays forward the packets to the next hop after receiving from the previous message carrier for a certain time period rather than after receiving the whole message. Thus, the relays should transmit and receive the data packets alternately as a pipeline as shown in Fig. 2. Channel resources for the beacon broadcast and the multi-hop data relaying are separated and independent to each other, while the multi-hop V2V relay transmissions all share the same channel resource. To mitigate the impact of interference, only one-third of the relays in the cluster will be switched to transmission mode at a time, e.g., in Fig. 2, the $(i + 3j,\ j \in \mathcal{Z})$-th vehicles are in the transmission mode at the k-th time slot. Since we assume that the wireless devices can operate in a half-duplex mode only, and we need to ensure that the signal strength is always larger than the interference, we let any neighboring transmitters be three-hop away from each other. By letting relays switch among the

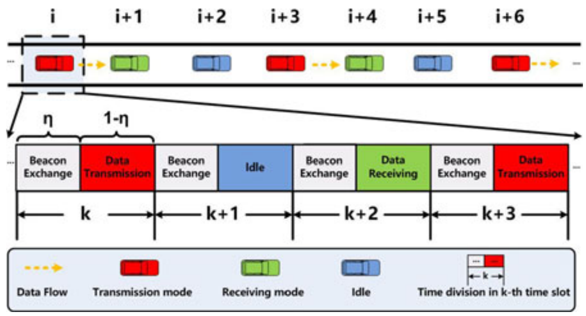


Fig. 2. A time-division based channel access method.

transmission, receiving and idle modes alternatively, any three continuing relays will stay in each of the above three statuses as shown in Fig. 2. Hence, under the proposed scheme, any pair of the transmitter and receiver can exchange data freely while the idle vehicles will not be involved in others' data exchange.

The V2V data rate r_v over the multi-hop relay path is obtained by $r_v = \frac{(1-\eta)}{3} \times r'_v, \eta \in [0, 1]$, where η is the portion of wireless channel resource allocated to the beacon exchange in the time slot, and r'_v is the total V2V transmission rate. Under the proposed mechanism, the communication interference and collisions are reduced and the vehicles may continuously push the message from the source to the destination.

B. Problem Formulation

The vehicle with the original copy of the data is named as the source. Here, we study the multi-source uploading problem in a road segment with two RSUs deployed at both ends. The problem can be formulated as follows

$$s^* = \arg\max_{s \in S} \sum_{i=1}^{2} W_i(s), \tag{P1}$$

where s^* and S are the optimal strategy and the strategy set, respectively, and $W_i(s)$ is the expected uploading throughput corresponding to the i-th RSU under the strategy s. The strategy tells which sources should upload the data in the coming time period and which RSU is chosen as the sink for each active source.

By optimizing the strategy including the source and relay selection in each time slot, the network throughput of data uploading can be maximized. A few open issues need to be addressed:

1) vehicles in the both directions are used to assist the data delivery, we should quantify the transmitted data amount and delivery delay in the complicated scenario;
2) since the size of the file is large, multiple separated pieces of the file would be carried by different vehicles which may lead to a more complex situation compared with one-piece message delivery;
3) the multi-transmitter case is considered in this paper so vehicles not only help relay for each other, but also the data source vehicles should cooperate with each other to mitigate collisions in wireless communications.

To solve this problem, there are two critical steps. First is the vehicle uploading capacity analysis. The data delivery is limited by various factors including wireless communication, vehicle mobility, and ubiquitous uploading request. Quantifying the capacity of data delivery initiated under different conditions is critical to optimize the network performance. Second is the delivery delay analysis. Choosing a direction with a shorter delay is not only beneficial to the source but also saves the network resources for others. Thus, given the data delivery conditions, the corresponding delay estimation is necessary for the decision making. In the data delivery, the strategy not only selects which RSU for uploading, but also decides when and where the delivery should be initiated.

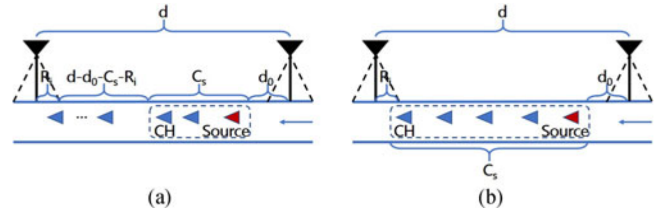


Fig. 3. Message forward phase. (a) Carry and upload. (b) Upload directly.

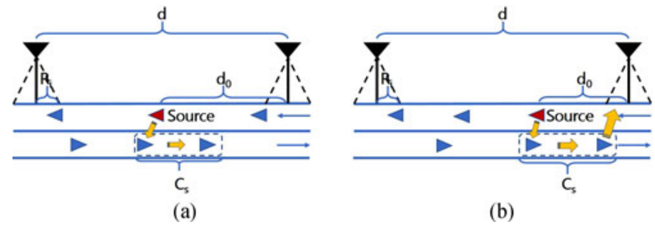


Fig. 4. Message backward phase. (a) Backtrack and upload later. (b) Backtrack and upload simultaneously.

IV. Capacity and Delay Analysis

In this section, the uploading capacity and delivery delay analysis are provided for the message uploading to the RSU in front of or behind the vehicle carrying the message. The capacity and delay of either choice is a random variable given the random inter-vehicle distance. Here, we focus on the expected capacity and delay.

A. Capacity Analysis

We define *uploading capacity* as the data amount a moving source can upload to the target RSU during certain time period. As a starting point, we assume that there is one source only and the other vehicles can be used as relays if needed. To develop an accurate model, we consider different message delivery phases and the associated capacities and delays. First, a message may be carried by a vehicle or a vehicle cluster (traveling at a speed of v_1) till it is transmitted to an RSU. This phase is called the message forward phase as shown in Fig. 3. Second, a message may be carried and forwarded to the vehicles in the opposite direction (traveling at a speed of v_2). This phase is called the message backward phase as shown in Fig. 4. Thus, the analytical work is divided into two parts for the two delivery directions, i.e., the forward uploading capacity and the backward uploading capacity.

Given the V2V and V2I transmission rate and transmission range are fixed, we first focus on the impacts of the location of the source d_0, the vehicle arrival rate λ in both directions and the time duration T on the uploading capacity C. C is a function of d_0, λ, and T, i.e., $C = f(d_0, \lambda, T)$.

Capacity of the message forward phase: C_F measures the data amount one source can upload to the next RSU in the following time duration T while traveling from location d_0 of a road segment with vehicle arrival rate λ_1. Considering that the uploading processes between different road segments are similar, without loss of the generality, we focus on one cycle where the vehicle moves between two neighboring RSUs.

In the message forward phase under the store-carry-and-forward mechanism, the source first tries to forward the message to the CH using V2V links. With the vehicle movement, after the CH enters the RSU radio range, the uploading begins using V2I link. Let t_1 and t_2 be the time when the CH and source enter the RSU radio range starting from d_0, respectively. Since the vehicles move at the constant speed, C_s does not change with time. Therefore, $t_1 = \max(\frac{d-R_i-d_0-C_s}{v_1}, 0)$ and $t_2 = \frac{d-R_i-d_0}{v_1}$, respectively.

Theorem 1 (Forward capacity): Given the cluster size probability distribution function $f_c(C_s)$, the vehicle density λ_1, and $C_F(d_0, \lambda_1, T, C_s)$ which is the corresponding data uploading capacity of the source moving from d_0 for duration T, $\overline{C_F}(d_0, \lambda_1, T)$ is obtained by

$$\overline{C_F}(d_0, \lambda_1, T) = \int_0^\infty C_F(d_0, \lambda_1, T, C_s) f_c(C_s) dC_s, \tag{2}$$

where $C_F(d_0, \lambda_1, T, C_s)$ is determined by (3).

$$C_F(C_s, t) = \begin{cases} C_{F_1}(t), & C_s > C_{f_1}, \\ C_{F_2}(t), & C_{f_1}\frac{r_v}{r_i} < C_s \le C_{f_1}, \\ C_{F_3}(t), & 0 \le C_s \le C_{f_1}\frac{r_v}{r_i}, \end{cases} \tag{3}$$

where $C_{f_1} = d - R_i - d_0$ and $C_{F_1}(t)$, $C_{F_2}(t)$ and $C_{F_3}(t)$ are given in (4a)–(4c).

$$C_{F_1}(t) = r_v t,\ 0 \le t \le t_2, \tag{4a}$$

$$C_{F_2}(t) = \begin{cases} 0, & 0 \le t \le t_1, \\ r_i(t - t_1), & t_1 < t \le t_1\frac{r_i}{r_i - r_v}, \\ r_v t, & t_1\frac{r_i}{r_i - r_v} < t \le t_2, \end{cases} \tag{4b}$$

$$C_{F_3}(t) = \begin{cases} 0, & 0 \le t \le t_1, \\ r_i(t - t_1), & t_1 < t \le t_2. \end{cases} \tag{4c}$$

Proof: See Appendix A. ■

Capacity of the message backward phase: C_B measures the data amount one source can upload to the previous RSU in the following time duration T while traveling from location d_0, and the vehicle arrival rate in the opposite direction is λ_2. In the backward uploading process, the previous RSU will gradually receive the message relayed by the opposite vehicles which are grouped into vehicle clusters. When the CH enters the coverage of the RSU, it can keep uploading until finishing all the data in this cluster. As the distance between any two neighboring vehicles is always less than the V2V communication range R_v in a cluster, during the contact period, the source can keep transmitting data to the cluster without stops at the V2V data rate r_v. Furthermore, even if the inter-distance between two clusters is greater than R_v but still less than $2R_v$, the source can still find a vehicle within its radio range to relay the message at the rate of r_v. If the relaying vehicle can connect to the RSU when receiving the data from the source through its cluster or by itself, and the uploading rate is $r_1 = r_v$. Otherwise, if the relaying vehicle or its cluster needs to move into the coverage of the RSU for the uploading opportunity after receiving the message, the average uploading data rate would be $r_2 = r_v \frac{v_2}{v_1 + v_2}$ considering the relative motion.

Theorem 2 (Backward capacity): Given the opposite vehicle density λ_2, the expectation of the data uploading capacity $\overline{C_B}(d_0, \lambda_2, T)$ of the source moving from d_0 for duration T is obtained by

$$\begin{aligned} \overline{C_B}(d_0, \lambda_2, T) &= \int_0^T \overline{W}(d_0, \lambda_2, t) dt \\ &= \int_0^T (r_1 P_1(d_0, \lambda_2, t) + r_2 P_2(d_0, \lambda_2, t)) dt, \end{aligned} \tag{5}$$

where $\overline{W}(d_0, \lambda_2, t)$ is the expectation of the uploading throughout from the source to the previous RSU at time t. $P_1(d_0, \lambda_2, t)$ and $P_2(d_0, \lambda_2, t)$ are given in (6a) and (6b), respectively.

$$P_1(d_0, \lambda_2, t) = \int_0^{\frac{2R_v}{v_2}} \lambda_2 e^{-\lambda_2 u} du \int_{C_{b_1}}^\infty f_c(C_s) dC_s, \tag{6a}$$

$$\begin{aligned} P_2(d_0, \lambda_2, t) = &\left(\int_0^{\frac{R_v}{v_2}} \lambda_2 e^{-\lambda_2 u} du \int_{C_{b_2}}^\infty f_c(x) dx \right. \\ &\left. + e^{\frac{-\lambda_2 R_v}{v_2}} - e^{\frac{-\lambda_2 (R_i + R_v - d_0 + v_2 t)}{v_2}} \right) \\ &\times \int_0^{\frac{2R_v}{v_2}} \lambda_2 e^{-\lambda_2 u} du \int_0^{C_{b_1}} f_c(C_s) dC_s, \end{aligned} \tag{6b}$$

where $C_{b_1} = d_0 + v_1 t - R_v - R_i + v_2 u$ and $C_{b_2} = d_0 - R_v - R_i + v_2 u - v_2 t$.

Proof: See Appendix B. ■

B. Delay Analysis

Similar to the capacity analysis, the delay analysis is also categorized into forward delay (the delay of a message transmitted to the RSU in the message forward phase), and backward delay (the delay of a message uploaded to the RSU behind the source, using opposite direction vehicles in the message backward phase). Different from the capacity analysis, the delivered data size is predetermined rather than infinite in the previous subsection. In the following, we analyze the expected delay in different phases.

Delay of the message forward phase: D_F measures the delay one source needed to upload the message to the RSU in front of it given V_T, d_0, v_1 and λ_1. Before t_1, the message is accumulated at the CH and cannot be uploaded. Between t_1 and t_2, the message can be delivered to the CH at the V2V data rate r_v and be uploaded to the RSU at the V2I data rate r_i simultaneously. After t_2, the source can directly upload the message to the RSU at the rate of r_i.

Theorem 3 (Forward delay). Let V_T be the message size, given $f_c(C_s)$, the expectation of the forward delivery delay

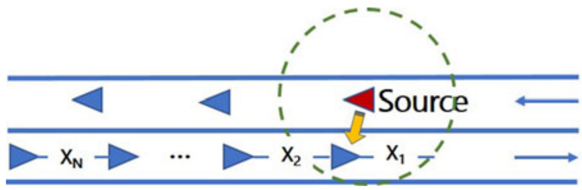


Fig. 5. Message backtrack.

to the next RSU D_F is obtained by

$$\overline{D_F}(d_0, \lambda_1, V_T) = \int_0^\infty D_F(d_0, \lambda_1, V_T, C_s) f_c(C_s) dC_s, \quad (7)$$

where $D_F(d_0, \lambda_1, V_T, C_s)$ is determined by (8).

$$D_F(V_T) = \begin{cases} D_{F_1}(V_T), & d_0 < d - R_i - \frac{v_1 V_T}{r_v}, \\ D_{F_2}(V_T), & d_0 \geq d - R_i - \frac{v_1 V_T}{r_v}, \end{cases} \quad (8)$$

and $D_{F_1}(V_T)$ and $D_{F_2}(V_T)$ are given in (9a)–(9b).

$$D_{F_1}(V_T) = \begin{cases} \frac{d - R_i - d_0 - C_s}{v_1} + \frac{V_T}{r_i}, & 0 \leq C_s \leq a, \\ \frac{V_T}{r_v}, & a < C_s, \end{cases} \quad (9a)$$

$$D_{F_2}(V_T) = \begin{cases} \frac{V_T}{r_i} + \frac{d - R_i - d_0 - C_s}{v_1}, & 0 \leq C_s \leq b, \\ \frac{V_T}{r_i} + \frac{(r_i - r_v)(d - R_i - d_0)}{r_i v_1}, & b < C_s, \end{cases} \quad (9b)$$

where $a = d - R_i - d_0 - v_1 V_T (\frac{1}{r_v} - \frac{1}{r_i})$ and $b = \frac{r_v}{r_i}(d - R_i - d_0)$.

Proof: See Appendix C. ■

Delay of the message backward phase: D_B measures the delay one source needed to upload the message to the RSU behind it given V_T, d_0, v_1, v_2 and λ_2. The backward phase includes two steps. First, the source vehicle needs to transmit the message to the opposite direction vehicles, named the *backtrack step* as shown in Fig. 5. Second, the opposite direction vehicles upload the message to the RSU. Here, we further define *backtrack delay* D_{bt} as the delay in the backtrack step of the backward phase. Clearly, the backward delay equals the backtrack delay plus the uploading time after the backtrack step. The upload may start during or after the backtrack step, depending on whether the opposite vehicle cluster is directly connected to the target RSU and uploads message during the backtrack step or not.

1) Backtrack: The delivered messages may be too large for a single vehicle to receive the whole message during the short contact time of two vehicles moving in the opposite directions. The source needs to divide the message into packets and transmit different parts of the message (called message segments) to several vehicles in the opposite direction. We thus investigate how long it takes to transmit all the message segments to the vehicles in the opposite direction, i.e., the backtrack delay D_{bt}.

Theorem 4 (Backtrack delay): Given the message size V_T, the backtrack delay D_{Bt} is obtained by

$$D_{Bt} = \frac{V_T}{r_v(1 - e^{-\lambda_r \frac{2R_v}{v_r}})} - \frac{e^{-\lambda_r \frac{2R_v}{v_r}}}{\lambda_r}, \quad (10)$$

where the relative speed $v_r = v_1 + v_2$ and the arrival rate $\lambda_r = \lambda_2 \frac{v_r}{v_2}$, respectively.

Proof: See Appendix D. ■

During the backtrack, the contact time of the last opposite-direction vehicle may not be fully utilized. Considering the scalability of the message delivery, in addition to the basic requirements, the source can keep transmitting data to improve the reliability and quality of the message until the contact ends.

2) Post-backtrack: The message forwarded to the opposite vehicles may be directly uploaded to the RSU through multi-hop relaying or should be stored in the CH until it enters the V2I communication range.

Proposition 1 (Uploading sequence): Under the assumption that $r_i \geq r_v$, $R_i \geq R_v$, all the packets being delivered to the opposite-direction vehicles are uploaded to the RSU sequentially.

Proof: See Appendix E. ■

According to Proposition 1, we can use at most $\lceil 2R_i/R_v \rceil$ RSU channels to guarantee the opposite-direction vehicle clusters can directly upload messages once they arrive in the communication coverage of RSU and the message in these clusters can be uploaded to RSU before they move out of the RSU's coverage. The total delay is determined by the moment when the last packet in the message is uploaded to RSU. Hence, we only need to consider the cluster with the vehicle carrying the last packets of the message. When a vehicle is receiving packets from the source, it can also forward the packets to the vehicle in front of it based on the mode switch mechanism in Section III.

Let t_3 denote the time instant that the last cluster starts upload data to the RSU, and t_c the contact duration to the last cluster, respectively. Similar to the message forward phase, the forward process of the message backward phase is divided into three cases corresponding to t_3. First, if the cluster connects to RSU after the backtrack process, there is no overlapping time for the backtrack and upload, so these two parts can be calculated separately. Second, if the cluster connects to RSU at the beginning of the backtrack process, this connection will not be ended during the backtrack, thus the upload can be finished simultaneously. Thirdly, the uploading starts at the backtrack step, the message is accumulated in the cluster for t_3 time at the rate of r_v, and then it can be uploaded at the rate of r_i until all the accumulated data is uploaded to the RSU. Afterward, if the backtrack process is still continuing, the backtrack and upload can be pipelined.

Theorem 5 (Backward delay): Let V_T be the message size, given $f_c(C_s)$, the expectation of the backward delivery delay to the next RSU D_B is obtained by

$$\overline{D_B}(d_0, \lambda_2, V_T) = \int_0^\infty D_B(d_0, \lambda_2, V_T, C_s) f_c(C_s) dC_s, \quad (11)$$

where $D_B(d_0, \lambda_2, V_T, C_s)$ is determined by (12).

$$\overline{D_B}(\cdot) = \begin{cases} D_{Bt} + t_3 + \frac{V_c}{r_i} - t_c, & t_c \frac{r_i - r_v}{r_i} < t_3, \\ D_{Bt}, & 0 \leq t_3 \leq t_c \frac{r_i - r_v}{r_i}, \end{cases} \quad (12)$$

where $t_3 = \frac{\max(0, d_1 - R_i - R_v - C_s + t_c v_2)}{v_2}$, $t_c = \frac{V_c}{r_v}$ and $V_c = \min(V_T, \frac{C_s}{v_r} r_v + \frac{r_v}{\lambda_r}(1 - e^{-\lambda_r \frac{R_v}{v_r}}) + \frac{R_v r_v}{v_r})$.

Proof: See Appendix F. ■

V. Online Cooperative Uploading Strategy

In this section, the proposed multi-source online cooperative uploading strategy is introduced in detail. The cooperative

Algorithm 1: Uploading algorithm for source.

Input: $\lambda_1, \lambda_2, v_1, v_2$
$s^* = \emptyset$;
Exchange relaying requests;
Obtain relaying request set $\mathcal{R}$;
Wait for possible relay replies;
Obtain uploading strategy set $\mathcal{S}$;
while $\mathcal{S} \cup \mathcal{R} \neq \emptyset$ **do**
  if $\mathcal{S} \neq \emptyset$ **then**
    $s^* = \arg\min_{s \in \mathcal{S}} \{D(s), \forall s \in \mathcal{S}\}$;
  end if
  if $\mathcal{R} \neq \emptyset$ **then**
    $s^* = \arg\max_{s \in \{s^*, \mathcal{R}\}} \{C(s^*), C(r), \forall r \in \mathcal{R}\}$;
  end if
  Send s^* and wait for replies;
  if s^* is confirmed **then**
    $\mathcal{S} = \emptyset$, $\mathcal{R} = \emptyset$;
  else
    Update $\mathcal{S}$ and $\mathcal{R}$, $s^* = \emptyset$;
  end if
end while
Output: s^*

Algorithm 2: Cooperative algorithm for non-source.

Input: $\lambda_1, \lambda_2, v_1, v_2$
$s^* = \emptyset$;
Wait for relaying requests;
Obtain relaying request set $\mathcal{R}$;
while $\mathcal{R} \neq \emptyset$ **do**
  $s^* = \arg\max_{s \in \mathcal{R}} \{C(s), \forall s \in \mathcal{R}\}$;
  Send s^* and wait for replies;
  if s^* is confirmed **then**
    $\mathcal{R} = \emptyset$;
  else
    Update $\mathcal{R}$, $s^* = \emptyset$;
  end if
end while
Output: s^*

algorithms for the source and non-source vehicles are provided, respectively. In practice, the algorithms are executed every time period T to adjust the strategy according to the updated information including delivery status, new uploading requests and traffic statistics. A larger value of T helps the current delivery to be less disturbed by the decision-making process while the new request has to wait longer. Thus, the duration of T should consider the trade-off between the efficiency of existing data delivery and the initiation delay for the new request.

The main ideas of the algorithm are twofold. For a non-source, serving the source with the largest average throughput has the highest priority. For a source, choosing the available relays which lead to a smaller delay is preferred for the data uploading. If the source is also applied to be a relay by other sources at the same time, it needs to make the decision by comparing the throughput. It is natural that these two aspects are coupled with each other since the decisions are made independently and the agreement among vehicles is not guaranteed. Thus, several rounds of cooperation and interactions among vehicles are needed to converge to the optimal strategy. Apart from those exchanged between vehicles, the information needed for Algorithm 1 and 2 are non-real-time, estimated traffic statistics rather than the accurate, real-time global information. This information can be obtained from historical statistics and preloaded into the communication devices on vehicles.

A. Uploading Algorithm for Source

The objective of Algorithm 1 is to select the proper solution for a source such that the usage of this source leads to the highest benefit to the multi-source data delivery. As shown in Algorithm 1, the source needs to apply for the permission of relays before initiating the data delivery. First, the relay requests and the relay availability included in the beacons are exchanged among vehicles. Based on the information received, the source obtains the strategy set $\mathcal{S}$ indicating the possible uploading RSUs and the corresponding relays, and the relaying request set $\mathcal{R}$ indicating the requests from other sources. Then, the source decides whether it should choose the optimal solution in $\mathcal{S}$ or become a relay of other sources among $\mathcal{R}$. If the proposed solution s^* is confirmed by the corresponding relays or another source, then the source will execute it in the following time period T. Otherwise, the source should update $\mathcal{S}$ and $\mathcal{R}$ according to the replies, and obtain the new s^* again until reaching an agreement with the corresponding vehicles till both $\mathcal{S}$ and $\mathcal{R}$ become empty sets.

Using Algorithm 1, the source needs to make a decision based on the limited information and the theoretical analysis. The delay analysis is used for solving the optimal strategy among $\mathcal{S}$ for a specific source while the capacity analysis is used for comparing the uploading efficiency among different sources. It is noted that the expected uploading capacity in the following time duration T for a source who has been uploading for a time period t is $C(t+T) - C(t)$ rather than $C(T)$. After finishing the data uploading, the source becomes a non-source and conducts the Algorithm 2 as introduced below in the following time period.

B. Cooperative Algorithm for Non-Source

The objective of Algorithm 2 is to let a non-source vehicle select the proper source such that the multi-source data delivery has the most benefit. As shown in Algorithm 2, after receiving the relaying request set $\mathcal{R}$, the non-source vehicle should first decide which request brings the highest uploading capacity in the following time period T based on the estimated traffic information including the vehicle densities and speeds in both directions. Then, if the proposed solution is also confirmed by the corresponding source, the non-source will execute the solution in the following time period. Otherwise, the non-source should update $\mathcal{R}$ and obtain new s^* again until reaching an agreement with the corresponding source or $\mathcal{R}$ becomes an empty set.

It is noted that the source with the highest uploading capacity in $\mathcal{R}$ might not select this non-source as a relay considering the possible existence of a higher uploading capacity in the other direction. In addition, the algorithm is guaranteed to converge since there is always a group of source and non-sources making the same decision under the highest uploading capacity, which

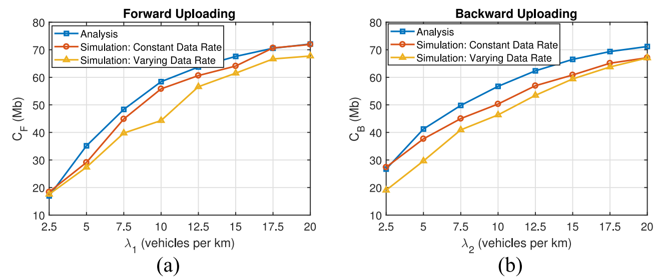


Fig. 6. Capacity analysis verification.

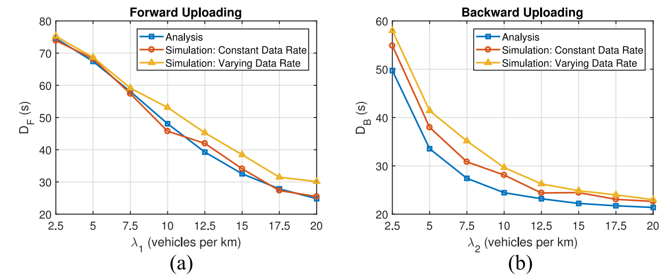


Fig. 7. Delay analysis verification.

reduces the dimension of R for other vehicles in the following iteration. Thus, the non-source will either be chosen as a relay or left with no relaying request. Similarly, if there is any data generated at a non-source, it becomes a source and conducts the Algorithm 1 starting from the next cycle.

VI. Performance Evaluation

In this section, the proposed analytical framework is verified and the performance of the proposed strategy is compared with the existing methods using the open-source simulator NS-3. The single source uploading experiments are conducted to examine the correctness of the capacity and delay analysis. The multi-source experiments with various locations and file sizes are conducted to compare the delivery delays between the proposed strategy and other benchmark strategies.

A. Simulation Setting

In the simulation, the protocols used in the current NS-3 model are modified to implement the store-carry-and-forward mechanism. For example, for the long-term data storage in the relaying vehicles, the maximum packet number and the maximum delay of the MAC layer queue should be enlarged based on the simulation parameter setting.

The density of the vehicles in the simulation is predetermined based on the transportation system statistics, varying from 2.5 to 20 vehicles per km, and the location of each vehicle is randomly generated based on the density estimation and the exponential inter-arrival distribution in both directions, respectively. The distance between two neighboring RSUs is 2 km. All vehicles travel at the speed of 20 m/s and the sources are randomly chosen in the multi-source experiments. r_v and r_i are 1 Mbps and 4.5 Mbps, respectively, and the message data size is 20 Mb for single-source experiments and varying for multi-source cases. The duration of each data transmission mode is 50 ms and the relay selection cycle T is 2 seconds. The source forwards data to the next hop relay in the transmission period and holds the transmission in the other modes.

B. Analytical Framework Verification

In the single-source experiment, the source travels starting from the boundary of the previous RSU ($d_0 = R_i$) and ends after traveling for a distance of d. 200 runs of experiments are conducted for statistic collection. Figs. 6 and 7 compare the simulation results and the theoretical results in terms of the uploading capacity and the message delivery delay, where the accuracy of the proposed analytical framework is verified.

As shown in Fig. 6(a) and (b), with the increase in vehicle density, the message delivery capacity grows. This is because the higher density leads to a higher connectivity which is critical for multi-hop message delivery. Specifically, thanks to the higher density, the inter-distances between vehicles are smaller which is beneficial to constructing a larger vehicle cluster. According to the experiment results, when the density is higher than 17.5 vehicles per km, almost all the vehicles in a road segment are connected thus the data delivery is effective and convenient. However, when the vehicle density becomes even higher, the improvement is no longer noticeable since it is close to the performance upper bound, i.e., 1.0 Mbps $\times$ 100 s $=$ 100 Mb.

Similar to the capacity results, Fig. 7(a) and (b) reveal that the data delivery delay decreases with the increment of the vehicle density. The lower bound of the delivery delay is 20 Mb/1 Mbps $=$ 20 s.

The reasons for the gap between the analytical results and simulation results are twofold. First, in the NS-3 simulation, even the energy of the received signal is larger than the energy detection threshold, there still exists a probability that the packet is received with an error [32]. Consequently, the simulated performance is slightly worse than the theoretical one which did not consider transmission errors. Second, the real-time relay selection is operated in a discrete rather than continuous manner. The chosen relays may not always be effective in the data delivery due to topology change which makes some packets cannot be delivered as scheduled. Also, since the backward case experienced more topology change, the gap between the analytical and simulation results in Figs. 6(b) and 7(b) is larger than that in Figs. 6(a) and 7(a).

Since the data rate may be varying in practice, comparative simulations are conducted to estimate the impact of the varying data rate. In each time period of the simulation, i.e., 1 second, r_v takes the value of 0.5 Mbps, 1 Mbps and 1.5 Mbps randomly with equal probability and the corresponding capacity and delay are given in Figs. 6 and 7, respectively. As shown in the comparison, the performance is slightly degraded in terms of lower capacity and higher delivery delay. This is because the varying data rate leads to unbalanced data forwarding among different transmission links, which means some good-state links may not have sufficient packets to forward in a period while some packets are congested in the bad-state links.

C. Multi-Source Strategy Comparison

Table II shows the multi-source cases where there are four sources requesting to upload data to the RSU simultaneously. The comparison between the proposed strategy and benchmark

TABLE II
COMPARISON OF DIFFERENT SCHEMES

Source		1	2	3	4
Data size (Mb)		40	30	20	10
Initial location (m)		275.14	1614.72	1036.33	1903.67
Request time (s)		1	6	11	16
Driving direction		W	W	E	E
Finish time	Proposed	43.9	26.0	36.2	33.7
	AODV	80.2	26.4	45.7	84.2
	DSDV	82.6	26.0	49.7	84.9
	OLSR	82.0	26.0	61.8	84.9

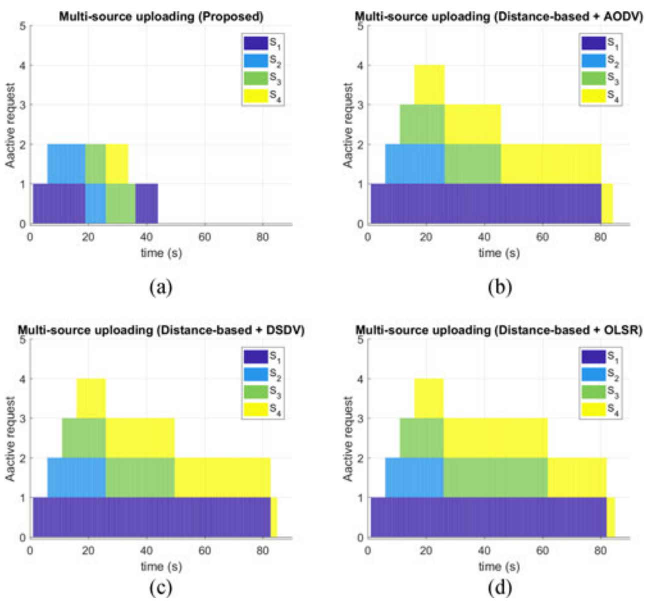


Fig. 8. The comparison of multi-source resource usage. (a) Proposed method. (b) Distance-based + AODV. (c) Distance-based + DSDV. (d) Distance-based + OLSR.

strategies is provided. In the existing strategy, the sources choose the RSU closer to themselves when the uploading requests are initiated. As shown in the comparison, the proposed strategy achieves lower delivery delays than the benchmark methods. This is because the proposed strategy always chooses the sources with the higher uploading data rates, while the other benchmark strategies need to search for the possible relays and paths in an unguided manner. For the proposed strategy, it also maintains a better fairness performance since each source will arrive the "optimal" location among the sources during a certain time period.

Fig. 8 demonstrates the communication usage condition during the multi-source uploading. As shown in the simulation results, the proposed method can significantly reduce the resource occupancy and delivery delay compared with distance-based Ad hoc routing methods. This is because the proposed method provides a competition-free scheduling which means no more than one source would use the same relays or the sink RSU to conduct the data uploading. Thus, the communication efficiency is guaranteed. Furthermore, thanks to the modeling and analysis, by comprehensively taking the data size, position and vehicle traffic into consideration, the source at the most suitable position would be enabled to transmit data during the movement rather than simply determined by distance.

VII. Further Discussion

A. Multi-Channel Scenario

In the multi-channel scenario, vehicles can accept more data transmission requests simultaneously so long as the transmitters and receivers can use the same channel(s) and there is no resource usage collision between the vehicles. This requires the vehicles to specify the available channel number when they exchange beacons. The requests will be accepted once both source and non-source have the same available channels which will surely increase the system performance.

Our results can be extended to the multi-channel scenario by allocating the data transmission to different channels simultaneously. This will help increase the system capacity and resource utilization if the devices support the multi-channel operations. For example, in the current system, to avoid the interferences between vehicle communications, only a part of the relays are activated to transmit data at a time. After applying multi-channel transmission, one relay can transmit at different channels for one or multiple delivery requests simultaneously. Therefore, more data can be exchanged between vehicles without increasing the interferences. For the system performance, the capacity is increased w.r.t the total bandwidth of the channels, and the delivery delay is also decreased accordingly.

B. Co-Existence With the Existing Technologies

The mechanism can be implemented using the existing communication technologies, e.g., WiFi Direct, Dedicated Short Range Communications (DSRC) and IEEE 802.11p. For example, WiFi Direct can help with the device discovery, role negotiation, service discovery and etc. [33], with which the vehicles can discover the potential relays and form necessary Peer-to-Peer (P2P) groups. Since one vehicle can play different roles in different groups simultaneously as specified in [34], data can be forwarded across groups within a linear topology by using the communication links established between vehicles [35]. Also, DSRC along with IEEE 802.11p can provide reliable real-time communication links with moving vehicles in the 5.850-5.925 GHz band [36], [37], which is critical for realizing the V2V and V2I communications in the data delivery strategy. Overall, the proposed solution in this paper can leverage the existing technologies and help improve the data delivery efficiency.

VIII. Conclusion

This paper has investigated the message delivery problem considering bidirectional dissemination in hybrid V2I/V2V networks. We have modeled the capacity and delay during the message forward phase and message backward phase, respectively, so that the expected capacity and delay are accurately obtained based on the limited information shared among vehicles. Based on our analysis, a multi-source message delivery strategy is proposed to reduce the expected delay, and the results also provide an important guideline on the RSU deployment density and coverage, etc. The analysis has been validated by simulation.

The results show that the proposed solution substantially improves the message delivery performance. There are many issues requiring further investigation. For instance, how to extend the work considering two-dimensional vehicle networks, how to model and manage the delivery process in the extra-high density networks are challenging issues beckoning further research.

Appendix A
Proof of the Theorem 1

Proof: Let $U_R(T)$ and $U_B(T)$ denote the achievable receiving amount of RSU and the available uploading data buffered in the CH within time period T, respectively. $U_R(T)$ is defined as

$$U_R(T) = \int_0^T r_u(t)dt, \tag{13}$$

where $r_u(t)$ is the achievable uploading rate at time t.

Considering there is always a path connecting the source and the CH in a cluster, $U_B(T) = r_v T$, where r_v is the V2V transmission rate assumed as a constant.

Since the actual uploaded data amount will not exceed neither U_R nor U_B, given C_s, d_0 and T, the corresponding $C_F(C_s, d_0, T)$ is given by

$$C_F(C_s, d_0, T) = \min\left(U_R(C_s, d_0, T), U_B(C_s, d_0, T)\right). \tag{14}$$

There are two cases in the data uploading using CH. First, if the cluster size is big enough, the data is uploaded to RSU directly when it is received by the CH. Second, the data is accumulated at the CH until it enters the coverage of the RSU.

On the one hand, r_u equals 0 before t_1 and increases to r_i after t_1, Therefore, $U_R(t)$ is obtained by

$$U_R(t) = \begin{cases} 0, & 0 \le t \le t_1, \\ r_i(t - t_1), & t_1 < t \le t_2. \end{cases} \tag{15}$$

On the other hand, U_B increases at the constant rate r_v when assuming the data is infinite, i.e.,

$$U_B(t) = r_v t,\ 0 \le t \le t_2. \tag{16}$$

Combining (14) to (16), C_F is categorized into the following cases accordingly.

i) If $C_s > d - R_i - d_0$ which means $t_1 = 0$,

$$C_{F_1}(t) = \min(U_R, U_B) = \min(r_i t, r_v t) = r_v t. \tag{17}$$

ii) If $C_s \le d - R_i - d_0$ which means the $t_1 > 0$ and we further divided it into two cases. First, $(d - R_i - d_0)\frac{r_v}{r_i} < C_s \le d - R_i - d_0$ which means the accumulated data in the CH would be uploaded to the RSU before t_2, then

$$C_{F_2}(t) = \begin{cases} 0, & 0 \le t \le t_1, \\ r_i(t - t_1), & t_1 < t \le t_1 \frac{r_i}{r_i - r_v}, \\ r_v t, & t_1 \frac{r_i}{r_i - r_v} < t \le t_2. \end{cases} \tag{18}$$

Second, $0 \le C_s \le (d - R_i - d_0)\frac{r_v}{r_i}$ which means the accumulated data in the CH is too much to be completely uploaded before t_2, then the RSU receiving rate keeps at the maximum value v_i, thus

$$C_{F_3}(t) = \begin{cases} 0, & 0 \le t \le t_1, \\ r_i(t - t_1), & t_1 < t \le t_2. \end{cases} \tag{19}$$

Since C_s is a random variable following the PDF $f_c(x)$, the expected uploading capacity $\overline{C_F}(T)$ is obtained by

$$\begin{aligned} \overline{C_F}(T) = & \int_0^{C_{f_1}\frac{r_v}{r_i}} C_{F_1}(T) f_c(C_s) dC_s \\ & + \int_{C_{f_1}\frac{r_v}{r_i}}^{C_{f_1}} C_{F_2}(T) f_c(C_s) dC_s \\ & + \int_{C_{f_1}}^{\infty} C_{F_3}(T) f_c(C_s) dC_s \end{aligned} \tag{20}$$

where $C_{f_1} = d - R_i - d_0$. ■

Appendix B
Proof of the Theorem 2

Proof: In the backward uploading, the expected uploading throughput $W(t)$ is obtained by

$$W(t) = r_1 P_{r_1}(t) + r_2 P_{r_2}(t), \tag{21}$$

where $P_{r_1}(t)$ and $P_{r_2}(t)$ indicate the probabilities of the two cases introduced below with the uploading rate r_1 and r_2, respectively.

i) Data is uploaded to the RSU directly using opposite vehicle cluster. Thus $r_1 = r_v$, and the corresponding $P_{r_1}(t)$ is calculated as

$$P_{r_1}(t) = \int_0^{\frac{2R_v}{v_2}} \lambda_2 e^{-\lambda_2 u} du \int_{C_{b_1}}^{\infty} f_c(C_s) dC_s, \tag{22}$$

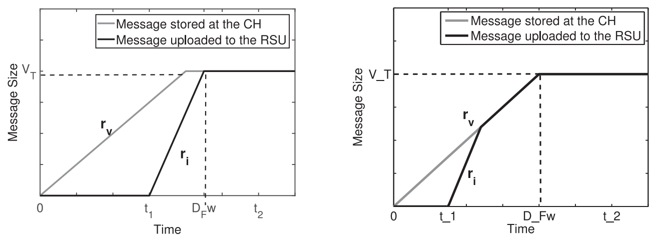
where $C_{b_1} = d_0 + v_1 t - R_v - R_i + v_2 u$. The first integration represents the probability of the source can found a relay within its communication range, and the second integration represents the probability of the cluster size of the chosen relay is larger enough to connect to the RSU.

ii) If the data is not directly uploaded, the expected uploading rate estimation needs to take the vehicle relative motion into account. Thus, $r_2 = r_v \frac{v_2}{v_1 + v_2}$, and the corresponding $P_{r_2}(t)$ is calculated as

$$P_{r_2}(t) = P(t_s < t) \int_0^{\frac{2R_v}{v_2}} \lambda_2 e^{-\lambda_2 u} du \int_0^{C_{b_1}} f_c(C_s) dC_s, \tag{23}$$

where t_s the time when the RSU actually starts to receive data. The latter two integrations represent the probability of finding a relay within communication range and the cluster of the relay cannot connect to the RSU immediately, respectively. Since t_s is determined by when the first relay can forward the data to the RSU through its CH or move into the RSU's coverage by itself, $P(t_s < t)$ is given by

$$\begin{aligned} P(t_s < t) = & \int_0^{\frac{R_v}{v_2}} \lambda_2 e^{-\lambda_2 u} du \int_{C_{b_2}}^{\infty} f_c(C_s) dC_s \\ & + e^{\frac{-\lambda_2 R_v}{v_2}} - e^{\frac{-\lambda_2 (R_i + R_v - d_0 + v_2 t)}{v_2}}, \end{aligned} \tag{24}$$



(a) (b)

Fig. 9. Case 1 in the message forward phase.

where $C_{b_2} = d_0 - R_v - R_i + v_2 u - v_2 t$.

Based on the above results, the expectation of the backward capacity $\overline{C_B}(T)$ is

$$\overline{C_B}(T) = \int_0^T \overline{W}(t, d_0, \lambda_2) dt. \tag{25}$$

By substituting (21) to (24) into (25), the expected backward capacity are obtained. ■

Appendix C
Proof of the Theorem 3

Proof: In the message forward phase, before t_1, the message is accumulated at the CH and cannot be uploaded. Between t_1 and t_2, the message can be delivered to the CH with V2V data rate r_v and be uploaded to the RSU with V2I data rate r_i simultaneously. After t_2, the source can directly upload the message to the RSU with the rate of r_i. Whether the message can be delivered to the CH before t_2 is determined given the maximum data volume to reach the CH is $r_v t_2$. Hence, we consider these two cases separately.

Case 1: If $d_0 < d - R_i - \frac{v_1 V_T}{r_v}$, the whole message can be delivered to the CH before t_2. Fig. 9 shows that the forward delay depends on whether the message stored at the CH can be uploaded to RSU before the whole message is delivered to the CH.

1) If $C_s < d - R_i - d_0 - v_1 V_T(\frac{1}{r_v} - \frac{1}{r_i})$ as shown in Fig. 9(a), the message stored at the CH cannot be completely uploaded to the RSU before the whole message is delivered to the CH. Thus, the uploading data rate is always r_i, and the forward delay is given by

$$D_F(C_s) = (d - R_i - d_0 - C_s)/v_1 + V_T/r_i. \tag{26}$$

2) If $C_s \geq d - R_i - d_0 - v_1 V_T(\frac{1}{r_v} - \frac{1}{r_i})$ as shown in Fig. 9(b), the message stored at the CH can be uploaded to the RSU before the whole message is delivered to the CH. Then the message can be uploaded to RSU once it is delivered from the source to the CH, and there is no data accumulated at the CH. Therefore, the data rates of the message being delivered from the source to the CH and from the CH to RSU are both r_v. Thus, the forward delay equals the delay of the message transmitted to the CH, and can be calculated by

$$D_F(C_s) = V_T/r_v. \tag{27}$$

Combining (26) and (27), we have

$$\overline{D_{F_1}} = \int_0^a \left(\frac{d - R_i - d_0 - C_s}{v_1} + \frac{V_T}{r_i} \right) f_c(C_s) dC_s + \int_a^\infty \left(\frac{V_T}{r_v} \right) f_c(C_s) dC_s, \tag{28}$$

where $a = d - R_i - d_0 - v_1 V_T(\frac{1}{r_v} - \frac{1}{r_i})$.

Case 2: If $d_0 \geq d - R_i - \frac{v_1 V_T}{r_v}$, the message cannot be totally delivered to CH before t_2. Similar to Case 1, the delivery delay is examined based on the whether the stored data can be uploaded to the RSU before t_2.

1) If $C_s < \frac{r_v}{r_i}(d - R_i - d_0)$, the stored data cannot completely be uploaded before the source arrives in the coverage of the RSU. The upload rate is always r_i. The forward delay is obtained from

$$D_F(C_s) = V_T/r_i + (d - R_i - d_0 - C_s)/v_1. \tag{29}$$

2) If $C_s > \frac{r_v}{r_i}(d - R_i - d_0)$, the stored data can be uploaded to the RSU before t_2, the process contains two parts, where the upload rate is r_v or r_i before or after t_2, respectively. The forward delay is

$$D_F(C_s) = V_T/r_i + (r_i - r_v)(d - R_i - d_0)/(r_i v_1). \tag{30}$$

Combining (29) and (30), we can obtain the expected forward delay, which is given by

$$\overline{D_{F_2}} = \int_0^b \left(\frac{V_T}{r_i} + \frac{d - R_i - d_0 - C_s}{v_1} \right) f_c(C_s) dC_s + \int_b^\infty \left(\frac{V_T}{r_i} + \frac{(r_i - r_v)(d - R_i - d_0)}{r_i v_1} \right) f_c(C_s) dC_s, \tag{31}$$

where $b = \frac{r_v}{r_i}(d - R_i - d_0)$.

Combining (28) and (31), the expected forward delay is obtained. ■

Appendix D
Proof of the Theorem 4

Proof: Let $X_i, i = 2, 3, \ldots$ denote the distance between the $(i-1)$-th vehicle and the i-th vehicle in the opposite direction. Consider the source as a static point, and thus the opposite vehicles arrive with the relative speed of $v_r = v_1 + v_2$ and the arrival rate of $\lambda_r = \lambda_2(v_r/v_2)$. If $X_i \geqslant 2R_v$, the contact duration with the i-th vehicle is $\frac{2Rv}{v_r}$, so the transmission data volume is $V(X_i \geqslant 2R_v) = r_v(2R_v/v_r)$. If $X_i \in (0, 2R_v)$, the connection duration is X_i/v_r while the transmission data volume is $V(X_i \in (0, 2R_v)) = r_v(X_i/v_r)$.

We can obtain the expected exchanged data size during the contact time with one vehicle by

$$\overline{V_X} = \int_0^{\frac{2R_v}{v_r}} r_v t \lambda_r e^{-\lambda_r t} dt + \int_{\frac{2R_v}{v_r}}^\infty r_v \frac{2R_v}{v_r} \lambda_r e^{-\lambda_r t} dt = r_v \left(1 - e^{-\lambda_r \frac{2R_v}{v_r}}\right) / \lambda_r. \tag{32}$$

To deliver a message with the size of V_T, the expected number of transmissions $T = V_T/\overline{V_X}$. The backtrack delay D_{Bt} can be calculated as:

$$D_{Bt} = \left(E\left(\sum_{i=1}^{T} X_i\right)\right)/v_r = (T-1)/\lambda_r + t_0, \quad (33)$$

where t_0 is the expected transmission time for the first vehicle. Because the backtrack process does not begin until the first vehicle reaches the communication range of the source, t_0 is calculated as follows:

$$\begin{aligned} t_0 &= e^{-\lambda_r \frac{2R_v}{v_r}} \frac{2R_v}{v_r} + \int_0^{\frac{2R_v}{v_r}} t\lambda_r e^{-\lambda_r t} dt \\ &= \left(1 - e^{-\lambda_r \frac{2R_v}{v_r}}\right)/\lambda_r. \end{aligned} \quad (34)$$

Plugging (34) in (33), the backtrack delay is given by

$$D_{Bt} = V_T/\left(r_v\left(1 - e^{-\lambda_r \frac{2R_v}{v_r}}\right)\right) - e^{-\lambda_r \frac{2R_v}{v_r}}/\lambda_r. \quad (35)$$

■

APPENDIX E
PROOF OF THE PROPOSITION 1

Proof: For the packets transmitted to the i-th opposite direction vehicles, $V_{X_i} = \min\left(\frac{r_v X_i}{v_r}, \frac{2r_v R_v}{v_r}\right)$. The worst situation for uploading is $X_i > 2R_v$, so that no packet can be forwarded to the CH. The message can only be uploaded when the vehicles enter the coverage of the RSU. If the channel resource of the RSU is always fully utilized, the (i)-th vehicle can connect to the RSU no later than the moment the previous vehicle leaves the coverage of the RSU. Hence the minimum available connection duration for the (i)-th vehicle is $\min(\frac{X_i}{v_2}, \frac{2R_i}{v_2})$, and the corresponding data amount is $\min(\frac{r_i X_i}{v_2}, \frac{2r_i R_i}{v_2})$. Based on the assumptions that $r_i \geq r_v, R_i \geq R_v$ and $v_2 < v_r$,

$$r_i \cdot \min(X_i, 2R_i)/v_2 > V_{X_i}. \quad (36)$$

Thus the proof is completed. ■

APPENDIX F
PROOF OF THE THEOREM 5

Proof: In the message backward phase, the expected data volume received by the first vehicle of a cluster in the backtrack process V_{ch} is obtained using

$$V_{ch} = \frac{r_v}{\lambda_r}(1 - e^{-\lambda_r \frac{R_v}{v_r}}) + \frac{R_v r_v}{v_r}. \quad (37)$$

Specifically, the location of the source has moved to $d_1 = d_0 + v_1 D_{Bt}$, and the last cluster size is C_s. The total data volume in the cluster $V_c = \min(V_T, \frac{C_s}{v_r} r_v + V_{ch})$. The contact duration to this cluster $t_c = \frac{V_c}{r_v}$. Define $t_3 = \max(0, d_1 - R_i - R_v - C_s + t_c v_2)/v_2$ the time instant that this cluster can upload data to RSU. Three cases corresponding to t_3 are considered for the message backward phase.

Case 1: If $t_3 > t_c$, the CH is still out of the coverage of the RSU when backtrack procedure is finished. It needs to carry the message and upload at the rate of r_i afterward.

Case 2: If $t_c \frac{r_i - r_v}{r_i} < t_3 < t_c$, the backtrack finishes after the CH connects to the RSU but earlier than the stored data all being uploaded to the RSU. Hence, the CH uploading data rate is r_i.

In Case 1 and Case 2, the upload data rates are both r_i when $t_3 > t_c \frac{r_i - r_v}{r_i}$, so the uploading delay after backtrack step D_{Ab} can be calculated as

$$D_{Ab} = t_3 + V_c/r_i - t_c. \quad (38)$$

Case 3: If $0 \leq t_3 \leq t_c \frac{r_i - r_v}{r_i}$, the stored data is uploaded to the RSU before the backtrack process finishes. Hence, the backtrack and upload procedure is synchronous afterward, and there is no delay in addition to D_{Bt}, $D_{Ab} = 0$.

The backward delay is obtained by $D_B = D_{Bt} + D_{Ab}$ and $\overline{D_B}(V_T)$ is obtained by

$$\overline{D_B}(d_0, \lambda_2, V_T) = \int_0^{\infty} D_B(d_0, \lambda_2, V_T, C_s) f_c(C_s) dC_s, \quad (39)$$

and

$$D_B(\cdot) = \begin{cases} D_{Bt} + t_3 + \frac{V_c}{r_i} - t_c, & t_c \frac{r_i - r_v}{r_i} < t_3, \\ D_{Bt}, & 0 \leq t_3 \leq t_c \frac{r_i - r_v}{r_i}, \end{cases} \quad (40)$$

where $t_3 = \frac{\max(0, d_1 - R_i - R_v - C_s + t_c v_2)}{v_2}$, $t_c = \frac{V_c}{r_v}$ and $V_c = \min(V_T, \frac{C_s}{v_r} r_v + \frac{r_v}{\lambda_r}(1 - e^{-\lambda_r \frac{R_v}{v_r}}) + \frac{R_v r_v}{v_r})$. ■

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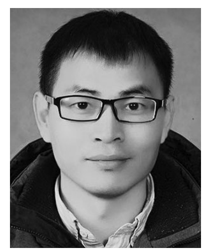

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