Optimizing Content Dissemination for Real-Time Traffic Management in Large-Scale Internet of Vehicle Systems

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***Abstract*—As an application of "smart transport" for Internet of Things, Internet of Vehicle (IoV) has emerged as a new research field based on vehicular ad hoc networks (VANETs). With the development of smart vehicles and the integration of sensors, applications of traffic management and road safety in large-scale IoV systems have drawn great attentions. By sensing events occurred on roads, vehicles can broadcast messages to inform others about traffic jams or accidents. However, the store-carry-and-forward transmission pattern may cause a large transmission delay, making the implementation of large-scale traffic management difficult. In this paper, we put forward a feasible solution to minimize the response time for traffic management service, by enabling real-time content dissemination based on heterogeneous network access in IoV systems. We first design a crowdsensing-based system model for large-scale IoV systems. Then, a cluster-based optimization framework is investigated to provide timely responses for traffic management. Specifically, we estimate the message transmission delay by stochastic theory, which can provide a guideline for the next-hop relay selection in our delay-sensitive routing scheme. Furthermore, network performances are evaluated based on two city-road maps, and performance metrics, containing average delivery delay, average delivery ratio, average communication cost, and access ratio, demonstrate the superiority of our system. Finally, we conclude our work and discuss the further work.**

***Index Terms*—Large-scale Internet of Vehicle, traffic management, network optimization, crowdsensing.**

I. Introduction

INTERNET of Things (IoT) has drawn great attentions in both academic research fields and industry areas over the past few years. It is formed by ubiquitous things in our daily life, e.g., tablets, laptops, TVs, smartphones and vehicles, and is built on a heterogeneous network framework by integrating existing networks [1]. As a research field of IoT, Internet of Vehicle (IoV) has evolved as a new platform based on Vehicular Ad hoc NETworks (VANETs). With the rapid development of sensing, computing and networking technologies, mass data are generated daily in large-scale IoV networks, e.g., traffic information, socialized connections and human mobility information in urban areas [2], [3]. For the sake of effectively handling and utilizing real-time traffic information, applications, such as road safety and traffic management, require to be fulfilled based on IoV systems [4]. The establishment of IoV systems has been developed in many countries all over the world, e.g., ERTICO-ITS in Europe. In industry, worldwide automakers, such as BMW, Volvo and Toyota, have devoted to constructing testbed systems based on Vehicle-to-Vehicle (V2V) communication patterns.

Fig. 1 shows the typical network structure of IoV, including five types of communication patterns, i.e., V2V, Vehicle-to-Road Side Unit (RSU) (V2R), Vehicle-to-Infrastructure (V2I), Vehicle-to-Personal devices (V2P) and Vehicle-to-Sensors (V2S). V2V, V2P and V2S communication architectures enable vehicles to communicate with each other directly based on the communication mode of mobile ad-hoc network, i.e., without the support of any infrastructure [5]. RSUs, Base Stations (BSs) and other infrastructures can provide network access for vehicles. Specifically, the five communication patterns are always operated collaboratively, making IoV systems more

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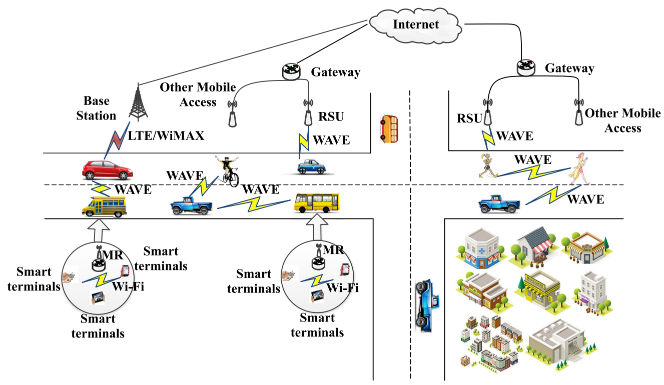


Fig. 1. The network structure of IoV.

complex compared with the traditional VANETs [6]. Intelligent applications of IoV can be generally classified into four types, i.e., traffic management, traffic safety, entertainment and service subscription. Particularly, large-scale IoV systems call for real-time traffic management to guarantee a good traffic environment [7]. Representative studies of traffic management in IoV systems include green and safety applications, congestion avoidance and content dissemination [8]. Although possible solutions have been provided, some researches heavily relay on the road side infrastructure, and others cannot make a dynamic and real-time routing planning according to current traffic conditions and driver preferences. Generally speaking, the challenges to design a real-time traffic management system in large-scale IoVs can be summarized as follows:

- In order to enable the traffic management server to take prompt actions for occurred events, vehicles need to upload accurate event reports based on their sensing abilities. However, how to improve the message accuracy and reduce the communication overhead between vehicles and infrastructures in heterogeneous IoV systems deserves to be investigated.
- How to reduce message transmission time by leveraging advantages of heterogeneous structures of IoV systems, and balancing the traffic among distinct network access schemes is challenging.
- How to encourage vehicles to participate in event reports to both satisfy users' personal utilities and improve the system performance needs to be comprehensively studied.
- Since the message forwarding in V2V communication pattern follows the store-carry-and-forward transmission mode, how to make intelligent routing decision based on the information of real-time traffic and encounter possibility is significant.

In order to cope with the challenges mentioned above, we construct a Content Dissemination framework for Real-time trAffic Management, called CDRAM, in large-scale IoV systems. The traffic management server can take prompt actions according to vehicles' timely feedback of the occurred event on the road, e.g., a traffic jam or an accident. Our main contributions can be summarized as follows:

- We design a crowdsensing-based system model for traffic management in IoVs, and specify the components and interactions among different participants to sense and report occurred events.
- We propose a cluster-based traffic management scheme to collect event reports and upload messages cooperatively, which largely shortens the response time of traffic management server and reduces the communication overhead.
- We formulate an optimization problem by considering the expected response time and message receiving time of the traffic management server. In order to both satisfy user's personal utility and reach the global objective, we provide an analysis model and make a trade-off between two different message uploading strategies, i.e., uploading by RSUs and BSs, respectively.
- We present a delay-sensitive routing algorithm for event propagation based on the store-carry-and-forward transmission mode in IoV systems. We first investigate a message transmission delay estimation method. Then, a routing decision for the next-relay cluster selection based on the information of multi-dimension road intersection is put forward.

Routing analyses based on two city-road maps are provided to demonstrate the effectiveness of the designed framework. The rest of this paper is structured as follows: we review the related work in Section II; we construct the system model in Section III, followed by illustrating the crowdsourcing-based traffic management method in Section IV; a delay-sensitive routing scheme is specified in Section V, and performance evaluation is discussed in Section VI; finally, we conclude this work in Section VII.

II. Related Work

In this section, we review the state-of-art for traffic management and crowdsensing to solve the content dissemination problem in large-scale IoV systems.

A. Traffic Management

With the development of vehicles and unprecedented traffic flows, traffic management has become a hot topic to effectively alleviate traffic problems in IoV systems. The technologies and challenges for developing a sustainable intelligent transportation system are discussed in [9]. The integration of clouding computing, connected vehicles and IoT systems is also studied to improve the safety and efficiency of transportation in urban areas [10]. A road information sharing architecture, named RISA, is designed in [11]. To our best knowledge, it is the first scheme to detect the road condition and disseminate the information of vehicular networks in a distributed manner. RISA aggregates and timely disseminates event information detected by vehicles to improve bandwidth efficiency and information reliability. However, it does not consider the different traffic directions in the road network.

Another research area for traffic management is to reduce the deployment cost and improve the resource utilization. In order to improve the efficiency of the intelligent vehicle grid and guarantee road safety, an RSU-cloud framework is established based on software-defined networking, including not only traditional RSUs but also specialized microscale datacenters [12].

A delay-optimal resource-scheduling scheme for virtualized radio resources in vehicular networks is proposed in [13]. Radio resource visualization and software defined networking are integrated into the LTE system to reduce the huge capital expenditure and operating expense. All the above schemes aim to reduce the network delay while considering the resource utilization. However, they do not fully utilize the advantages of difference access networks to balance the network traffic loads.

In addition, real-time traffic scheduling is also a hot research topic. In order to reduce the travel cost, a real-time path planning algorithm is proposed in [14]. An optimization technique based on Stochastic Lyapunov is employed with the purpose of both avoiding vehicles from traffic congestion, and improving network spatial utilization. An emerging vehicular communication system for real-time traffic monitoring is constructed in [15]. It is a cluster-based V2X data collection scheme, with the purpose of enabling reliable and accurate traffic monitors. Traffic density estimation under various kinds of Byzantine attacks in vehicular networks is conducted in [16]. The historical prior probability can be exploited based on theoretical analyses to obtain the spacing estimation. A cooperative traffic control framework is constructed to relieve traffic congestion in urban areas [17]. The authors take consideration of adjacent intersections to analyze the joint passing rates, with the purpose of maximizing the number of passing-by vehicles in a road network. Though distinct optimization mechanisms, including resource management, cluster-based data collection and cooperative traffic monitoring, are designed to improve the network performance, the trade-off between individual utilities and the global network optimization objective is not taken into consideration.

B. Crowdsensing in IoV Systems

Crowdsensing has natural connections with IoV systems by stimulating large-scale individuals to participate in task execution, aiming at making an improvement on network effectiveness and feasibility [18]. With the ubiquitous deployment of Wi-Fi Access Points (APs), roadside Wi-Fi can provide successive bandwidth connectivity in IoV systems [19]. A scheme named CrowdWiFi enables offline crowdsensing and online compressive sensing [20]. Crowdsensing is leveraged to deploy roadside APs in vehicular networks. Three crowdsensing parts, i.e., crowd-vehicle, crowd-server and user-vehicle, are designed respectively. Crowdsensed on-board cameras of vehicles are utilized in a collaborative traffic system for image sharing [21]. In that system, a route planning algorithm based on vehicular cloud service is designed by utilizing the traffic information of vehicles in proximity. As a result, crowdsensing is promising for vehicular networks.

In order to realize real-time navigation, spatial crowdsensing in fog-based VANETs can be integrated into a secure navigation algorithm [22]. Crowdsensing tasks are managed by fog nodes, and available routes are selected according to real-time traffic information. Opportunistic crowdsensing applications are developed based on battery-constrained and low-cost IoT sensors, enabling vehicles receive timely updates [23]. In particular, emerging narrowband IoT radio technology is deployed

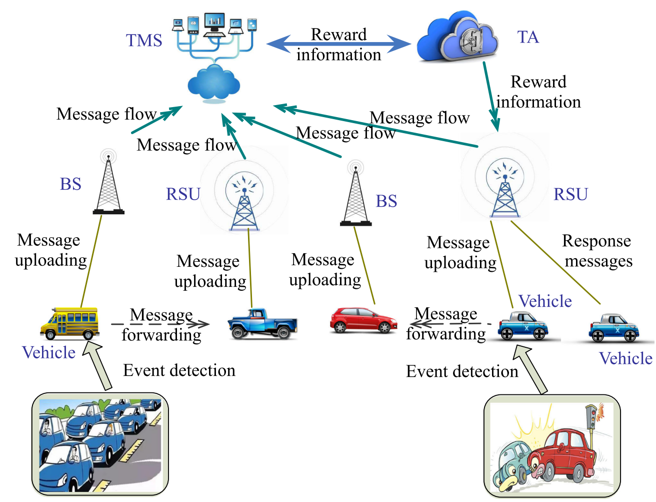


Fig. 2. System model of crowdsensing-based IoVs.

in this system. However, the communication overhead may be increased with the frequent communications among vehicles. In this paper, we integrate clustering-based data collection and reporting system with crowdsensing to avoid the unnecessary communication among vehicles and reduce the communication overhead.

Specifically, we construct a large-scale real-time traffic management system based on crowdsensing. The innovations compared with existing traffic management schemes include: a) we comprehensively consider characteristics of heterogeneous networks in IoV systems, and analyze suitable choices for message uploading; b) we establish a cluster-based traffic management system, which is efficient for data collection and message uploading; c) we propose a delay estimation algorithm for the RSU-based routing scheme, which is effective for vehicles to make real-time intelligent decisions for the next-hop relay selection.

III. System Model

In this section, we first introduce the components in the designed traffic management system, and then illustrate the considered network scenario.

A. System Components

Fig. 2 illustrates the system model of crowdsensing-based IoVs. Five major components are contained, i.e., the vehicle, RSU, BS, Traffic Management Server (TMS) and Trust Authority (TA). Detailed descriptions of these components are as follows:

1) Vehicle: Vehicles have equipped On Board Units (OBUs) for wireless communications. Wi-Fi, bluetooth and other short distance wireless transmission technologies can be leveraged for V2V communications in our system. Vehicles in proximity can directly exchange data and even multimedia via wireless communications.

2) RSU: In order to connect with vehicles on roads, RSUs with the ability of wireless communications are installed along urban roads, acting as routers to upload messages generated by vehicles to TMS. It is costly to employ a great number of RSUs to cover the communications for all the vehicles. Therefore, we only consider the situation that only limited RSUs exist in the network. In addition, we consider that an RSU can acquire locations of neighboring RSUs by the process of information synchronization.

3) BS: Mobile operators regulate BSs in the system, and can almost provide full coverage of wireless communications for vehicles in urban areas. Wireless access services for vehicles are provided by LTE cellular networks. However, uploading messages to TMS through cellular networks is costly. In addition, network traffic congestion can be caused by seas of messages and the saturated bandwidth.

4) TMS: When TMS receives a message from a vehicle, message truthfulness will be validated. Then, TMS will inform officers in the traffic management department to solve problems mentioned in the validated message, e.g., maintaining the traffic by policemen in congested roads.

5) TA: It is a fully trusted server in crowdsensing-based IoV systems. When a vehicle enters into the network, it can get its initial credit by registering to TA. Besides, TA is considered to have a powerful ability to keep the security and privacy of users' information.

B. Network Scenario

The objective of the designed framework is to enable TMS to take prompt actions by receiving timely feedback of traffic events reported by vehicles. We consider that the driver or passengers can utilize a specific preinstalled software inside a vehicle to record an occurred event, e.g., traffic jam, car accident, or damage on the road surface, in terms of pictures, texts and short videos, when the vehicle comes across or detects the event on its travel route. Then, the vehicle packages the record into messages, and prepares to upload them to TMS. Actions will be taken right away when TMS obtains the detailed information of the uploaded messages. A notice message will be broadcasted to passing-by vehicles via RSUs.

The main obstacle for designing such a system is to enable timely response by TMS. There are two main factors affecting the system performance, i.e., the delay for message uploading and message accuracy. In order to reduce impacts brought by the two mentioned factors, a crowdsensing-based method is utilized for message collection to improve the accuracy of reported messages. With the purpose of reducing the communication cost, a cluster-based method is integrated in the message collection process. In each geographical cluster, Cluster Head (CH) collects messages sensed by Cluster Members (CMs), and extracts features from the collected messages to form an accurate message for the occurred event. In order to maximize personal benefits, CH chooses the upload policy for the generated message, i.e., whether to upload it via BSs or RSUs. If a BS is chosen, the message transmission delay is almost negligible while the transmission cost is high. Otherwise, a geographical routing needs to be planned for message forwarding to the nearest RSU without additional transmission cost, while a transmission delay will be caused. We propose a delay-sensitive routing scheme to find an optimal path for message transmission, with the purpose of minimizing the transmission delay.

TABLE I
MAIN NOTATIONS

Notation	Description
V_N	Node group in the network
C_M	Cluster group in the network
c_i	A cluster i in the network
m_i	A message generated by node i
m^a	A message generated by a CH
T_s	Expected response time for TMS
T_g	Time for the last message received by TMS
T_e	Occurrence time of event e
v_k^h	CH of cluster k
N_c	Total number of vehicles in cluster c_k
t_γ	Message receiving time of the message by TMS
t^e	Event occurrence time
U_l	Utility of cluster l
$y_i(t,s)$	Payment to cluster i by TMS
x_m	Size of the uploaded message m
c_m	Unit upload cost of message m
Δt	Transmission delay by RSU-based policy
l_{pq}	Road segment $p \rightarrow q$
λ_{pq}	Average arrival rate of traffic flows on road segment l_{pq}
$E\left(t_{v_j^{CH} \rightarrow RSU}\right)$	Expected delay from CH j to an RSU
$E(t_{i,i+1})$	Expected delay for a road segment $l_{i,i+1}$
$P^c(c_k)$	Cluster turning possibility of a cluster c_k
$P^e(c_k)$	Encounter turning possibility of a cluster c_k

IV. Cluster-Based Traffic Management

In this section, we specify the design of cluster-based traffic management scheme. First, we present the global objective of the designed system, followed by providing the local objective. At last, the cluster-based data collection scheme is provided. Main notations are listed in Table I.

A. Global Objective

We consider that there are N vehicles in the network, denoted by $V_N = \{v_1, v_2, \ldots, v_N\}$. These vehicles can be classified into M clusters at time t, represented by $C_M = \{c_1, c_i, ..., c_M\}$.

When a vehicle v_i detects an event on the road, it generates message m_i to record the detailed information of the event. Then, vehicle v_i delivers message m_i to CH. After collecting all the messages from CMs, CH creates a message m^a according to the collected messages. Then, it makes a choice between message uploading policies based on RSUs and BSs. At first, the local objective for the two different policies is compared. Then, the vehicle will immediately upload the message if the uploading policy based on BSs is selected. Otherwise, a delay-sensitive routing scheme is leveraged to forward messages through V2V communications. After receiving and abstracting the accurate information of messages, TMS will take actions immediately. In order to minimize the expected response time T_s of TMS, we model the message transmission process as an optimization problem, illustrated as:

$$\min T_s = \min_{g \leq M} E\left\{t_g - t^e\right\}. \tag{1}$$

The variable t_g is message receiving time by TMS, and t^e is the occurrence time of event e. The variable g represents the last received message for event e, where $g \in \{1, \ldots, M\}$, and M is the maximum number of clusters in the network at time t.

B. Local Objective

In order to stimulate vehicles to participate in message forwarding, a local objective is formed for vehicles. From the perspective of social networks, all the vehicles in the cluster desire to maximize their own profit by reporting events to TMS. When CM v_i in a cluster detects an event e_i on the road, v_i generates a message m_i to record e_i. Then, v_i forwards m_i to CH. After CH gathers all the messages from active vehicles within its cluster, it can create an accurate message. As a result, the local objective can be formulated as:

$$\max U_l = \max \sum_{i=1}^{N_c} u_i^v, \tag{2}$$

where U_l is the utility of cluster c_l, and equals to the total utilities of vehicles in the cluster. The symbol N_c is the total number of vehicles in cluster c_l, and u_i^v is the utility of vehicle v_i. The larger U_l is, the more profit vehicles in the cluster can obtain. Therefore, when CH generates a message m^a according to the collected messages, it chooses a larger value between the utilities gained by BSs and RSUs.

C. Biased Credit-Based Incentive Scheme

In order to encourage vehicles to cooperate in message forwarding, a biased credit-based incentive scheme is designed. Virtual money is employed as rewards, which is determined by vehicles' contribution to the decision of TMS [24].

If a CH uploads a useful message before TMS takes actions, all vehicles in the cluster will be rewarded. The utility of cluster U_l is related to the server reward for its uploaded message, the size and cost of the message, and the delay for uploading the message to the server. This is because they determine the timeliness of server responses and the benefits of vehicles. The server reward is the major factor affecting U_l, while the other three elements have impacts on the cluster's uploading decision. All the four network metrics have positive correlations with U_l. Similar to the definition in [25], the utility of cluster U_l is computed according to the server reward and the uploading cost, i.e.,

$$U_l = y_i\,(t, s) \cdot \left(1 - e^{-x_m\, c_m\, \Delta t} \cdot \theta\right), \tag{3}$$

where $y_i(t, s)$ is the payment of TMS, and is a function of time t and report quality s. We use x_m to denote the size of an uploaded message, and employ c_m to represent the cost for uploading a message unit through BSs. We define Δt as the gap of transmission delay caused by the uploading between RSU-based and BS-based policies. It also equals to the time when a message is transmitted from CH to the nearest RSU. If RSUs are utilized to upload message m^a, θ is 0. Otherwise, θ equals to 1. The proportion of reward for each CM is determined by CH. Vehicles in a cluster will participate in event detection and make accurate reports, because they are stimulated to maximize their own utilities.

Proposition 1: If $y_i(t, s)$ is a decreasing function with time t, the local objective is compatible with the global objective. With the local objective, vehicles can maximize their profit, and the global objective can also be achieved simultaneously.

Proof: See Appendix A. ■

D. Clustering-Based Data Collection

In order to improve routing efficiency and reduce the communication overhead by the crowdsensing method, we aggregate vehicles into several clusters. Our designed system is compatible with many position-based clustering algorithms, such as the position-based clustering algorithm for V2V communications in [26]. The geographic positions and the traffic information of vehicles determine the cluster structure. Each cluster elects a vehicle as its CH, and a maximum distance between the CH and its members is predefined to control the cluster size. Furthermore, the cluster is independently controlled and dynamically reconfigured as the movement of vehicles.

1) Message Collection: When a cluster c_l passes by an event scene, CMs can record this event in form of a message. For instance, a vehicle v_i in c_l creates a message in form of $m_i = \{location, time, description\}$, indicating the occurrence location, time and detailed information of the event. Then, v_i sends m_i to CH. After collecting all the messages from CMs, CH adopts certain data aggregation mechanisms (e.g., cluster-based accurate syntactic compression method in [27]) to form an accurate message m^a. The aggregated location and time are computed by the average values of the location and time of CMs. The aggregated description is the detailed information based on the collected ones. Besides, a pre-defined time threshold t_β is available for the message collection process. If t_β is reached after receiving the first message from a CM, CH can conduct the data aggregation algorithm immediately no matter whether all CMs have finished submitting their sensed data. Furthermore, if some fields are missed in the collected messages, these fields will not be used in the data aggregation algorithm.

2) Message Uploading: Two choices are available for a vehicle to upload messages toward TMS: one is uploading messages through RSUs directly; the other is utilizing cellular networks through BSs. If the first choice is selected, a geographical message forwarding algorithm needs to be planned for message routing from CH to the nearest RSU, since there is a long distance from the location of a cluster to that of the nearest RSU. The advantage of the first choice is that uploading messages to TMS is free. For the second choice, a vehicle can transmit messages through BSs almost without any delay. The disadvantage is that cellular data transmission causes additional some costs.

We consider that an event occurs at time t_0, and a vehicle v_i records this event and creates a message m_i at time t_1. Then, v_i sends message m_i to CH at time $t_1^{'}$. Thus, CH needs to upload the message at time $t_1^{'} + t_\beta$ at latest. After generating message m^a, CH requires to make a decision about how to upload m^a toward TMS, since the reward function is a decreasing function with time t. Because CH and its members are only one hop away, the transmission time for a message from node v_i to CH is much shorter than the waiting time t_β. Therefore, we can regard that $t_1 \approx t_1^{'}$, and the time $t_1^{'} + t_\beta \approx t_1 + t_\beta$. We set $t^c = t_1 + t_\beta$, and $U_l^B = U_l(t^c)$ holds when BSs are utilized to upload message m^a. Otherwise, $U_l^R = U_l(t^c + \Delta t)$. Generally, Δt contains two parts, i.e., the transmission time for a message from its current location to the nearest RSU, and the uploading time for the message from an RSU to TMS. We compute Δt by merely taking the transmission time into consideration, because the uploading time is short and can be ignored compared with the transmission time. Therefore, if $U_l^B > U_l^R$, BSs are selected to upload message m^a; otherwise, RSUs are chosen. It is noticed that the estimation of Δt is important when a vehicle makes decisions on the choice of message uploading policies. As illustrated in Section V, we estimate Δt by presenting a delay estimation algorithm.

3) Server Response: When TMS receives message m^a, its accuracy will be validated, e.g., the time, location and detailed description of the recorded event. A data trustworthiness assurance method in [28] can be integrated with our scheme for message accuracy judgment. If TMS deduces an accurate information of the event, a notification message can be formed and sent to passing-by vehicles via RSUs. Thus, vehicle v_i will receive the notification message when it enters the wireless communication range of an RSU. The vehicle can broadcast the received notification message in its cluster locally to reduce the communication overhead between an RSU and vehicles. If TMS cannot parse the received message, it will wait for other messages.

Vehicles contributing to event reports will be rewarded by TMS based on the accuracy of event description s and report time t. Therefore, we formulate the function of reward $y_i(t,s)$ as:

$$y_i(t,s) = \lambda s \cdot e^{-\gamma t}, \tag{4}$$

where λ and γ are two adjust coefficients. If the message is of low accuracy, the reward will decrease.

Theoerm 1: Based on the reward function in Equation (4), the theoretical maximum transmission delay is $T = \frac{\ln(e^{x_m c_m} + e^{\gamma})}{\gamma + x_m c_m - 1}$.

Proof: See Appendix B. ■

The neighboring vehicles, transmitting the reported messages as relay nodes, can be rewarded by TMS. Their rewards are parts of final values of $y_i(t,s)$. The reward strategy has been fully investigated in many existing studies, thus how to reward the neighboring vehicles is not specified in our work and it is not our main focus.

V. Delay-Sensitive Routing Scheme

In this section, we elaborate the delay-sensitive routing scheme. When a CH prepares to utilize RSUs to upload messages, a V2V-based routing scheme is designed to forward them to the nearest RSU.

A. Traffic and Mobility Model

We transfer the real map of a city into a directed graph $G = (O, L)$, where O is the set of nodes representing road intersections, and L is the set of links standing for road segments between each pair of intersections. Meanwhile, the flow entering a road segment is considered to follow a Poisson process as demonstrated in [29], and its average arrival rate is λ_{pq}, where $p, q \in O$ and $l_{pq} \in L$. Since the average arrival rate can be estimated based on history statistical records, we assume that the speed of a vehicle is within the range of $[R_{\min}, R_{\max}]$ similar to [30], and the vehicle maintains its speed constant during the entire period on its route. Therefore, the traffic density ρ_{pq} of road segment l_{pq} in the direction of $\overrightarrow{pq}$ is $\rho_{pq} = \lambda_{pq}/E(R)$, where $E(R)$ is the average speed of vehicles on l_{pq}.

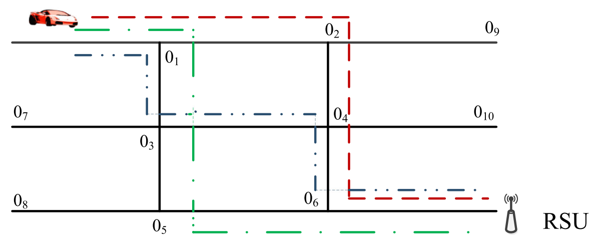


Fig. 3. Three shortest paths from a CH to the nearest RSU.

A CH is responsible for forwarding the generated message m^a to the nearest RSU. We consider that each RSU is aware of the locations of nearby RSUs, and it can send the local map of RSUs, specifying their locations and the latest updated time, to the passing-by vehicles. Therefore, CH can also be aware of the location of the nearest RSU. Then, k shortest paths from the location of a CH to the nearest RSU can be computed by the algorithm proposed in [31]. The city map can be obtained by a map or navigation application preinstalled in the car or a mobile phone. As illustrated in Fig. 3 , three predefined shortest paths can be obtained from CH to the nearest RSU, i.e., $CH \rightarrow o_1 \rightarrow o_2 \rightarrow o_4 \rightarrow o_6 \rightarrow RSU$, $CH \rightarrow o_1 \rightarrow o_3 \rightarrow o_4 \rightarrow o_6 \rightarrow RSU$, and $CH \rightarrow o_1 \rightarrow o_3 \rightarrow o_5 \rightarrow o_6 \rightarrow RSU$. The message m^a will be transmitted along one of the predefined shortest paths.

For each road segment, if cluster c_j carrying the message m^a encounters another cluster c_k, it requests c_k to send both its possibility for traveling along a predefined path and its estimated time to the nearest RSU. A cluster with a large probability and short estimated time is suitable to be the next-hop cluster. When a cluster is approaching to a road intersection, CH computes the cluster turning possibility, encounter turning possibility, and estimates transmission time along with one of the predefined k shortest paths according to travel plans of its CMs. Then, it can compare these values with other encounter clusters preparing to travel along the predefined paths. Message m^a will be taken into a new road segment along a predefined path by a cluster, which is suitable for message forwarding. If no suitable cluster exists, the CH will forward message m^a to a cluster behind, aiming to wait for a proper vehicle that can take message m^a to the proper direction at the road intersection.

B. Delay Estimation

From Theoerm 1, we know that if the estimated transmission delay from the cluster generating message m^a to the nearest RSU is lower than theoretical maximum transmission delay

T, an RSU-based delay-sensitive routing scheme will be conducted. CH estimates the transmission delays of all the k shortest paths according to the current traffic flows.

Theoerm 2: The expected path delay, caused by message m^a delivered from CH to the nearest RSU along with the intersections $o_1 \rightarrow o_2 \cdots \rightarrow o_k$, can be calculated by:

$$E\left(t_{v_j^{CH} \rightarrow RSU}\right) = \sum_{i=1}^{k-1} Y - \sum_{i=1}^{k-1} (t+Y)\, p_{i,i+1}(t), \quad (5)$$

where $Y = \frac{1}{\lambda_{i,i+1}} + t^R_{i,i+1}$, and $t^R_{i,i+1} = \frac{d_{i,i+1}}{E(R)}$.

Proof: See Appendix C. ■

The expected delivery delay of the k shortest paths can be obtained by Theorem 2. We compare it with Δt, and compute the ratio $P(E(t_{v_j^{CH} \rightarrow RSU}) \leq \Delta t) = \frac{s}{k}$. Herein, s is the number of paths that their expected delivery delays are lower than Δt. Then, we compare $P(E(t_{v_j^{CH} \rightarrow RSU}) \leq \Delta t)$ with a predefined threshold μ. If it is larger than the threshold, we conduct the RSU-based routing scheme.

C. Routing Decision

After making a decision to upload messages by RSUs, a routing scheme deserves to be investigated. In Section V-B, we can obtain the paths out of the k shortest paths, such that their expected delays are lower than Δt. Hence, we record these paths as $PH_s = \{ph_1, ph_2, ..., ph_s\}$. Message m^a can be transmitted along one of the paths in PH_s. The main challenges for transmitting along such paths are as follows:

- How to select the next-hop relay cluster to ensure that message m^a can be transmitted to the right direction at the road intersection.
- How to shorten the propagation time in each road segment and reduce the waiting time for message m^a at the road intersection.

We define *cluster turning possibility* as the probability of a cluster to turn into the right direction towards a road segment, which is contained in the paths of PH_s at a road intersection. It should be noted that the cluster is also moving on a road segment contained in the paths of PH_s. For example, there are two directions towards road segments in the path of PH_s at road intersection o_3 in Fig. 3, i.e., $o_3 \rightarrow o_4$ and $o_3 \rightarrow o_5$. If cluster c_i is moving on road segment $l_{1,3}$, the cluster turning possibility of c_i is the total possibility that vehicles in c_i turn into the directions of $o_3 \rightarrow o_4$ and $o_3 \rightarrow o_5$ at road intersection o_3. *Encounter turning possibility* is defined as the probability of clusters encountered by c_i in another road segment to turn into the right direction towards a road segment in the paths of PH_s. Note that those encounter clusters are moving on a road segment not embraced in the path of PH_s, and they are going to pass through the same road intersection with c_i. For example, when a cluster c_i on the road segment $l_{1,3}$ is going to cross the road intersection o_3, if it encounters a cluster moving on the road segment $l_{7,3}$ before passing by o_3, the possibility of the cluster to turn to the directions of $o_3 \rightarrow o_4$ and $o_3 \rightarrow o_5$ is called *encounter turning possibility*.

Similar to [32], we consider three types of road intersections, i.e., Cross-intersection, T-intersection and L-intersection. We then provide unified expressions to describe the *cluster turning possibility* and *encounter turning possibility* of a cluster. We can draw the following theorem:

Theoerm 3: Consider that there are δ directions at a road intersection o_i, i.e., $o_i \rightarrow o_j$, $o_i \rightarrow o_{j+1}$, $o_i \rightarrow o_{j+2}, \ldots, o_i \rightarrow o_{j-1+\delta}$, then:

- The cluster turning possibility of cluster c_k at an intersection o_i can be calculated by:

$$P^c(c_k) = 1 - \prod_{j=1}^{\delta} \prod_{m=1}^{N_c} \left(1 - p_m^{i \rightarrow j} \cdot \beta_{ij}\right); \quad (6)$$

- The encounter turning possibility of cluster c_k at an intersection o_i can be computed by:

$$P^e(c_k) = 1 - e^{-\frac{\left(\sum_{r=1}^{\delta}\sum_{j=1}^{\delta} \lambda_{rj}\cdot(1-\beta_{ri})\cdot\beta_{ij}\right)\left(L_{c_k}+R'\right)}{E(v_c)}}. \quad (7)$$

Proof: See Appendix D. ■

When cluster c_k moves on a road segment, it selects the next-hop cluster based on the following two scenes: a) if $p^c(c_k)$ is a large value, the cluster turning possibility satisfies $p^c(c_j) > p^c(c_k)$, and the expected transmission time meets $d_{j,o_2}/E(R_j) > d_{k,o_2}/E(R_k)$, cluster c_j will be selected; b) if $p^c(c_k)$ is a small value, satisfying $p^c(c_j) > p^c(c_k)$, cluster v_k will be selected. If the cluster turning possibility satisfies $|p^c(c_k) - p^c(c_j)| < \epsilon$, where ϵ is a threshold with a small value, the encounter turning possibilities of the two clusters will be compared. Cluster c_k will be selected if $P^e(c_j) > P^e(c_k)$. The pseudo-code of the routing decision algorithm for node v_i is illustrated in Algorithm 1.

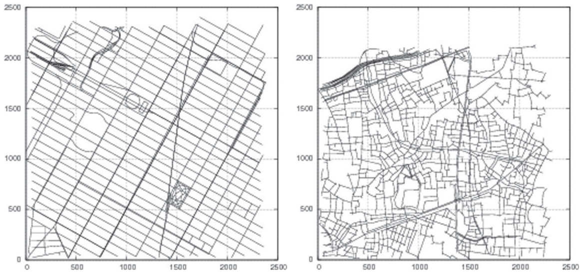
For Algorithm 1, its time complexity mainly contains two parts, i.e., the time complexity of computing all the k shortest paths and that of finding the suitable relay cluster. We can obtain that the former is $O(log(k) + log(R))$ according to the analysis in [31], where R is the total number of nodes in the road network. The latter can be computed with the computational complexity of $O((M-1)(\delta N_c + \delta^2))$, because there are at most $M-1$ neighboring clusters for cluster c_k to compute the next-hop relay cluster. In addition, since variables R, k and δ are far less than M, the time complexity of Algorithm 1 can be simplified as $O(MN_c)$.

VI. Performance Evaluation

We evaluate the performance of CDRAM by using a Java-custom simulator. We first illustrate the simulation setup, and then provide the simulation results and analysis.

A. Simulation Setup

As illustrated in Fig. 4 , we use two city maps, i.e., Manhattan and Tokyo, to validate the system performance. These two maps are obtained from *OpenStreetMap* [33]. The tool *OSM2WKT* [34] is leveraged to convert files in OpenStreetMap XML language to WKT. The movement of vehicles follows *Shortest Path Map based Movement* [35], and the average arrival rate of the traffic flow on each road segment is estimated according to the history records of vehicle movements. The simulation time is 168 hours and the wireless communica-



(a) Manhattan (b) Tokyo

Fig. 4. Two city maps. The units of the horizontal and vertical coordinates are meters.

tion range of a vehicle is 40 meters. Message size is between 200 MB and 500 MB [36], and message Time-To-Live (TTL) is 30 minutes. The speed of a vehicle is between 20 km and 60 km per hour, and the unit cost of a message is \$0.007 per MB [37]. We run each simulation setting 100 times to compute the average value of each performance metric. The following four performance metrics are evaluated:

- Average delivery ratio: the result of messages that can be parsed by TMS divided by the total number of generated messages.
- Average delivery delay: the average time from the time when a message is generated to that when it is received by TMS.
- Average communication cost: the total number of uploaded messages divided by the number of messages responded by TMS.
- Access ratio: the ratio of messages uploaded by RSUs compared with those uploaded by BSs.

The following algorithms are utilized for comparison, for the sake of demonstrating the effectiveness of our proposed CDRAM:

- Epidemic Routing [38]: a flood routing scheme, enabling vehicles to replicate and transmit messages to others within their wireless communication ranges. The sensed messages by vehicles are transmitted to the nearest RSU based on the V2V communication pattern.
- Greedy forwarding position based routing with available relays (GFAVR) [39]: a crowdsensing-based routing scheme, which can reduce the transmission delay by avoiding packets blocking in certain areas. It leverages both BSs and RSUs to upload messages toward TMS.

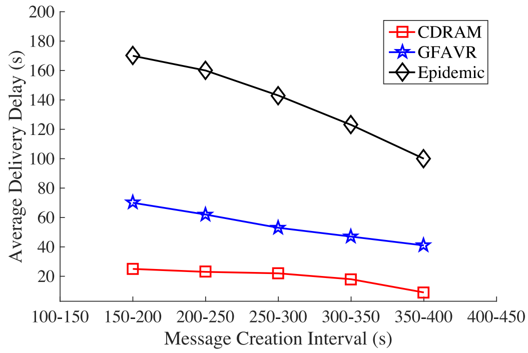
Algorithm 1: Pseudo-code of the Routing Decision Algorithm for Node v_i.

Input: v_i
Output: The input messages for node v_j
if $this.Host.IsClusterHead \neq TRUE$ **then return** SENDMESTOCLUSTERHEAD($this.Messages$)
end if
$locOfRSU \leftarrow$ GETLOCOFNEARESTRSU($this.loc$)
$shortestPaths \leftarrow$ GETSHORTESTPATHSBASEDMAP ($this.loc, locOfRSU$)
$estDelaysforPaths \leftarrow$ COMPUTEDELAYSFORPATHS (shortestPaths)
$isUpBS \leftarrow$ GETISUPLOADBYBS(estDelaysforPaths)
if $isUpBS$ **then return**
UPLOADMESSAGESBYBS($this.Messages$)
end if
$neighbors \leftarrow$ GETALLNEIGHBOURS(this.loc)
for $i \leftarrow 0$ **To** $Length[neighbors]$ **do**
  $isMoving \leftarrow$ ISMOVINGONTHESHORTESTPATHS ($neighbors[i].loc$)
  if $isMoving == TRUE$ **then**
    $ncTurningPos \leftarrow$ COMPUTETURNINGPOS ($neighbors[i]$)
    $neTurningPos \leftarrow$ COMPUTEENTURNINGPOS $neighbors[i]$
    if $this.cTurningPos > threthold$ **And**
$ncTurningPos > this.cTurningPos$ **And**
$neighbors[i].estimatedDelay <$ $this.estimatedDelay$
then
      SENDMESTONEIGHBOR ($this.Messages$)
    end if
    if $this.cTurningPos < threthold$ **then**
      if $ncTurningPos - this.cTurningPos > \epsilon$ **then**
        SENDMESTONEIGHBOR ($this.Messages$)
      else $ncTurningPos - this.cTurningPos < \epsilon$ **And** $neTurningPos > this.eTurningPos$
        SENDMESTONEIGHBOR ($this.Messages$)
      end if
    end if
  end if
end for

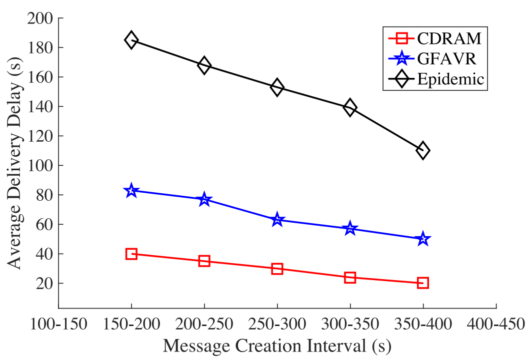
B. Simulation Results

In this section, we provide a comparison among different schemes according to various kinds of network metrics.

1) Average Delivery Ratio: Fig. 6(a) and Fig. 6(b) demonstrate average delivery ratios of the three algorithms (CDRAM, GFAVR and Epidemic routing) based on city maps of Manhattan and Tokyo, respectively. It is obvious that the performance of CDRAM is better than those of GFAVR and Epidemic routing. For example, in Fig. 6(a), when the message creation interval is between 200 s and 250 s, the average delivery ratio of CDRAM is 0.9, and the counterparts of the other two algorithms are 0.8 and 0.55 respectively. The reason is that, CDRAM utilizes the clustering-based traffic management scheme and collects messages from CMs to form an accurate message, which is likely to receive a response from TMS. However, vehicles in GFAVR and Epidemic routing do not collect sensed messages in a cooperative manner, which may result in uploading redundant and inaccurate information to TMS. Therefore, the average delivery ratios of these two algorithms are lower than that of CDRAM.

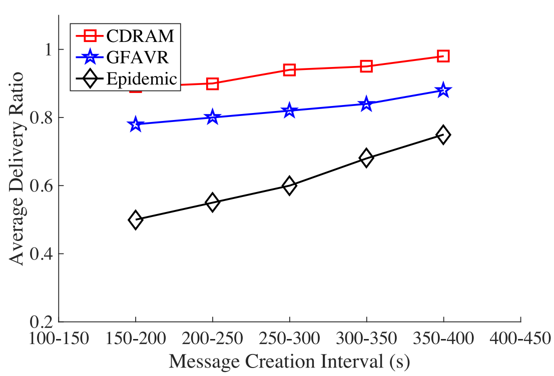


(a) Manhattan

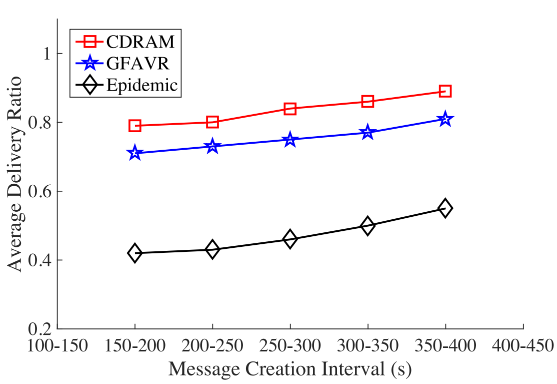


(b) Tokyo

Fig. 5. Average delivery delay vs. different message interval.

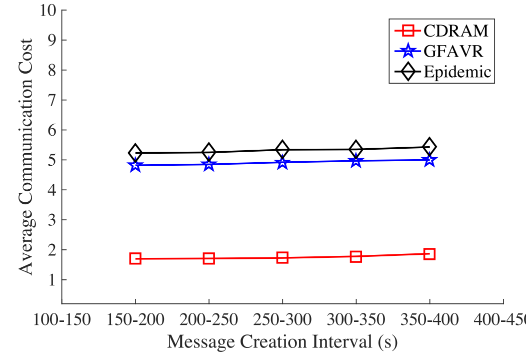


(a) Manhattan

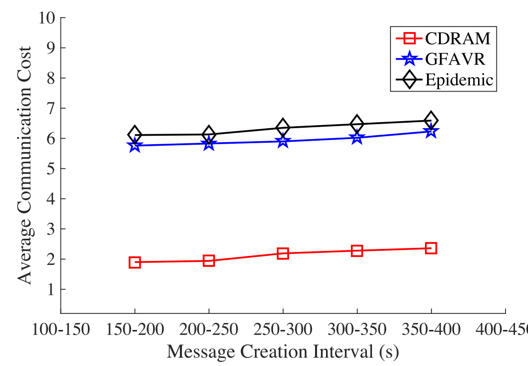


(b) Tokyo

Fig. 6. Average delivery ratio vs. different message interval.



(a) Manhattan

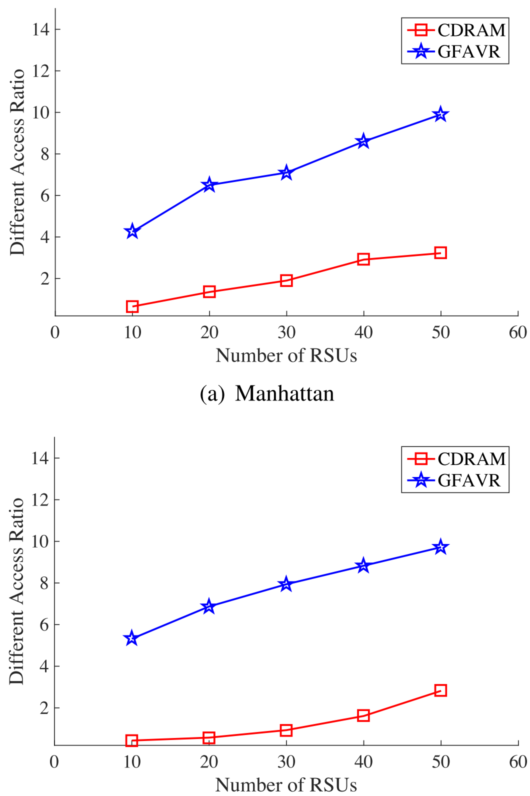


(b) Tokyo

Fig. 7. Average communication cost vs. different message interval.

2) Average Delivery Delay: From Fig. 5, we can see that the performance of CDRAM on average delivery delay has a large advantage compared with GFAVR and Epidemic routing. For example, the average delivery delay of CDRAM in Manhattan map is almost 50% and 80% lower than those of GFAVR and Epidemic routing respectively, when the message creation interval is between 200 s and 250 s in Fig. 5(a). When the message creation interval increases, delays of the three algorithms drop simultaneously. That is to say, less network resources are required to support the message transmission process if there are less messages in the network. Similar results can be obtained in the simulation based on Tokyo map. The reasons for the advantages brought by CDRAM mainly include the following aspects: a) CDRAM leverages BSs and RSUs to upload messages generated by vehicles, and estimates the expected delay beforehand to select a suitable transmission path. However, GFAVR and Epidemic routing methods are mostly based on the store-carry-and-forward transmission pattern; b) When RSUs are utilized to upload messages, CDRAM chooses clusters based on the cluster turning possibility and encounter turning possibility to transmit messages on the shortest paths. However, GFAVR only considers message transmission directions when it uploads messages based on RSUs, and Epidemic routing is merely a flood-based routing scheme.

3) Average Communication Cost: The performance on average communication cost of CDRAM is much lower than those of GFAVR and Epidemic routing as presented in Fig. 7. For instance, in Fig. 7(a), when the message creation interval is



(a) Manhattan

(b) Tokyo

Fig. 8. Access ratio vs. different number of RSUs.

between 350 s and 400 s, the average communication cost of CDRAM is 1.87, while the costs of GFAVR and Epidemic routing are 5.00 and 5.43 respectively. The reasons are as follows: a) CDRAM guarantees that a cluster only uploads a message of an occurred event, largely reducing the number of redundant messages uploading to TMS. However, GFAVR and Epidemic routing upload all the generated messages to TMS; b) CDRAM utilizes a biased credit-based incentive scheme to encourage vehicles to upload accurate messages, which reduces the number of uploading messages.

4) Access Ratio: Fig. 8 shows the access ratio of CDRAM and GFAVR, reflecting the resource utilization of RSUs and BSs. From Fig. 8(a), we can observe that the access ratio of CDRAM rises when the number of RSUs increases. That is to say, there are more chances for vehicles to upload messages through RSUs when the number of RSUs increases. In addition, the access ratio of GFAVR is higher than that of CDRAM. This is because GFAVR utilizes BSs to upload messages when message TTL are expiring. Since GFAVR mainly utilizes RSUs to upload messages, the access ratio of CDRAM is lower than that of GFAVR.

VII. Conclusion

With the objective of providing timely response for traffic management in large-scale IoV systems, we present an optimization method for content dissemination based on heterogeneous network access. A crowdsensing-based system is constructed at first, aiming to collect occurred events in a cooperative manner. A cluster-based traffic management is further designed by making a tradeoff between traffic loads in cellular networks and transmission delay caused by RSU uploading. Then, a delay-sensitive routing scheme is presented to minimize the transmission delay for V2V communication pattern with RSU uploading. At last, routing analyses based on two real city-road maps have been conducted to demonstrate the effectiveness of our framework.

Our work assumes that the messages generated by vehicles are trustful. However, this may not be always satisfied, because some fake or false information may be diffused in the network to confuse normal vehicles and TMS. In order to make the system more robust, we will devote into data trust evaluation for IoV systems in the further work.

Appendix A

Proposition 1: If $y_i(t, s)$ is a decreasing function with time t, the local objective is compatible with the global objective. With the local objective, vehicles can maximize their profit, and the global objective can also be achieved simultaneously.

Proof: If BSs are utilized for message uploading, the utility of a cluster l is computed by $U_l^B = y_i(t, s) \cdot (1 - e^{-x_m c_m \Delta t})$, and the total message uploading time t can be minimized. If RSUs are selected to upload messages, $U_l^R = y_i(t + \Delta t, s)$ holds, and the total uploading time mainly depends on Δt, where Equation (8) should be satisfied:

$$y_i\left(t, s\right) \cdot \left(1 - e^{-x_m c_m \Delta t}\right) \leq y_i\left(t + \Delta t, s\right). \tag{8}$$

Since $y_i(t, s)$ is a decreasing function with time t, $y_i(t + \Delta t, s)/y_i(t, s)$ can be simplified as $\Delta y_i(\Delta t)$. It is also a decreasing function with time Δt, and its value is always above 0. Therefore, a function with argument Δt can be drawn:

$$f\left(\Delta t\right) = \Delta y_i\left(\Delta t\right) + e^{-x_m c_m \Delta t} - 1 \geq 0. \tag{9}$$

A maximum transmission delay T for RSU-based uploading policy can be deduced from Equation (9), i.e., $\Delta t \leq T$. That is to say, if RSUs are selected to upload messages, $U_l^R \geq y_i\left(t + T, s\right)$ holds. As a result, vehicles will try their best to shorten the transmission delay in order to maximize their utilities. In addition, with the objective of reaching the global objective, we need to minimize the uploading time for each message in terms of shortening the response time of TMS. Therefore, the local objective is compatible with the global objective. For the sake of reaching the global objective, we merely need to consider the local objective in the routing decision process. ■

Appendix B

Theorem 1: Based on the reward function in equation (4), the theoretical maximum transmission delay is $T = \frac{\ln(e^{x_m c_m} + e^{\gamma})}{\gamma + x_m c_m - 1}$.

Proof: From the proof of Proposition 1, we can obtain that if RSUs are employed to upload messages, Inequation (10) should be satisfied:

$$\lambda s \cdot e^{-\gamma t} \cdot \left(1 - e^{-x_m c_m \Delta t}\right) \leq \lambda s \cdot e^{-\gamma (t + \Delta t)}. \tag{10}$$

By removing the same item from both sides of the inequation (10), we have:

$$1 - e^{-x_m c_m \Delta t} \leq e^{-\gamma \Delta t}. \tag{11}$$

By reorganizing the inequation, inequation (11) becomes:

$$\frac{1}{e^{x_m c_m \Delta t}} + \frac{1}{e^{-\gamma \Delta t}} \geq 1. \tag{12}$$

$$\Longrightarrow \frac{e^{x_m c_m \Delta t} + e^{\gamma \Delta t}}{e^{x_m c_m \Delta t} \cdot e^{\gamma \Delta t}} \geq 1. \tag{13}$$

$$\Longrightarrow e^{\Delta t}\left(e^{x_m c_m} + e^{\gamma}\right) \geq e^{(x_m c_m + \gamma)\Delta t}. \tag{14}$$

$$\Longrightarrow \left[e \sqrt[\Delta t]{e^{x_m c_m} + e^{\gamma}}\right]^{\Delta t} \geq \left(e^{x_m c_m + \gamma}\right)^{\Delta t}. \tag{15}$$

$$\Longrightarrow e \sqrt[\Delta t]{e^{x_m c_m} + e^{\gamma}} \geq e^{x_m c_m + \gamma}. \tag{16}$$

$$\Longrightarrow \left(e^{x_m c_m} + e^{\gamma}\right)^{\frac{1}{\Delta t}} \geq e^{x_m c_m + \gamma - 1}. \tag{17}$$

By taking logarithm on both sides of Inequation (17), it becomes:

$$\frac{1}{\Delta t} \ln\left(e^{x_m c_m} + e^{\gamma}\right) \geq x_m c_m + \gamma - 1. \tag{18}$$

$$\Longrightarrow \Delta t \leq \frac{\ln\left(e^{x_m c_m} + e^{\gamma}\right)}{\gamma + x_m c_m - 1}. \tag{19}$$

That is,

$$T = \frac{\ln\left(e^{x_m c_m} + e^{\gamma}\right)}{\gamma + x_m c_m - 1}. \tag{20}$$

Then, the theorem can be proved. ■

Appendix C

Theorem 2: The expected path delay, caused by message m^a delivered from CH to the nearest RSU along with the intersections $o_1 \rightarrow o_2 \cdots \rightarrow o_k$, can be calculated by:

$$E\left(t_{v_j^{CH} \rightarrow RSU}\right) = \sum_{i=1}^{k-1} Y - \sum_{i=1}^{k-1} (t + Y)\, p_{i,i+1}(t). \tag{21}$$

Proof: We denote the maximum waiting time in a road intersection by t. That is to say, if message m^a arrives at the road intersection at time t_0, it needs to be delivered to the right road segment before time $t_0 + t$. Otherwise, the message will be dropped. Therefore, the expected delay of each road segment can be computed by:

$$E(t_{i,i+1}) = \int_0^t \left(\tau + t_{i,i+1}^R\right) f_{i,i+1}(\tau)\, d\tau, \tag{22}$$

where $t_{i,i+1}^R$ is the average travel time of a vehicle along a road segment $l_{i,i+1}$, and can be calculated by $t_{i,i+1}^R = d_{i,i+1}/E(R)$. The symbol $d_{i,i+1}$ is the length of road segment $l_{i,i+1}$. The function $f_{i,i+1}(\tau)$ is the Probability Density Function (PDF) of the waiting time of message m^a at road intersection i directing to a next intersection $i+1$. Since the traffic flow entering a road segment follows a Poisson process with an average arrival rate $\lambda_{i,i+1}$, i.e., $f_{i,i+1}(\tau) = \lambda_{i,i+1} e^{-\lambda_{i,i+1}\tau}$, the expected delivery delay of each road segment is:

$$E(t_{i,i+1}) = \frac{1}{\lambda_{i,i+1}} - \left(t + \frac{1}{\lambda_{i,i+1}} + t_{i,i+1}^R\right) e^{-\lambda_{i,i+1} t} + t_{i,i+1}^R. \tag{23}$$

Furthermore, the expected delivery delay of a path can be calculated as follows:

$$E\left(t_{v_j^{CH} \rightarrow RSU}\right) = \sum_{1}^{k-1} E(t_{i,i+1})$$
$$= \sum_{i=1}^{k-1} \left(\frac{1}{\lambda_{i,i+1}} - \left(t + \frac{1}{\lambda_{i,i+1}} + t_{i,i+1}^R\right) e^{-\lambda_{i,i+1} t} + t_{i,i+1}^R\right). \tag{24}$$

We define that $Y = \frac{1}{\lambda_{i,i+1}} + t_{i,i+1}^R$ and $p_{i,i+1}(t) = e^{-\lambda_{i,i+1} t}$. Equation (22) can be rewritten by:

$$E\left(t_{v_j^{CH} \rightarrow RSU}\right) = \sum_{i=1}^{k-1} Y - \sum_{i=1}^{k-1} (t + Y)\, p_{i,i+1}(t), \tag{25}$$

which proves the theorem. ■

Appendix D

Theorem 3: Consider that there are δ directions at a road intersection o_i, i.e., $o_i \rightarrow o_j$, $o_i \rightarrow o_{j+1}$, $o_i \rightarrow o_{j+2}, \ldots, o_i \rightarrow o_{j-1+\delta}$, then:

- the cluster turning possibility of a cluster c_k at an intersection o_i can be calculated by:

$$P^c(c_k) = 1 - \prod_{j=1}^{\delta} \prod_{m=1}^{N_c} \left(1 - p_m^{i \rightarrow j} \cdot \beta_{ij}\right); \tag{26}$$

- the encounter turning possibility of a cluster c_k at an intersection o_i can be computed by:

$$P^e(c_k) = 1 - e^{-\frac{\left(\sum_{r=1}^{\delta} \sum_{j=1}^{\delta} \lambda_{rj} \cdot (1-\beta_{ri}) \cdot \beta_{ij}\right)\left(L_{c_k} + R'\right)}{E(v_c)}}. \tag{27}$$

Proof: We denote that the turning possibility of vehicle v_m in cluster c_k from intersection i to direction j by $p_m^{i \rightarrow j}$, and

$$\beta_{ij} = \begin{cases} 1, & l_{ij} \text{ is in the paths of } PH_s; \\ 0, & l_{ij} \text{ is not in the paths of } PH_s. \end{cases} \tag{28}$$

Then, the possibility of vehicle v_m not turning into a road segment l_{ij} in paths of PH_s can be calculated by $1 - p_m^{i \rightarrow j} \cdot \beta$. Since the turning possibility of each vehicle in cluster c_k is independent, the possibility of cluster c_k not turning into the road segment l_{ij} is $\prod_{m=1}^{N_c}(1 - p_m^{i \rightarrow j} \cdot \beta)$, where N_c represents the sum number of vehicles in cluster c_k. For all directions in the road intersection o_i, the possibility of cluster c_k not turning into the road segments at all δ directions is $\prod_{j=1}^{\delta} \prod_{m=1}^{N_c}(1 - p_m^{i \rightarrow j} \cdot \beta)$. Therefore, the cluster turning possibility is:

$$P^c(c_k) = 1 - \prod_{j=1}^{\delta} \prod_{m=1}^{N_c} \left(1 - p_m^{i \rightarrow j} \cdot \beta\right). \tag{29}$$

The possibility of cluster c_k not encountering road segment L_{rj}, which is not contained in the paths of PH_s, can be obtained by:

$$p^n(c_k) = 1 - \int_0^{\frac{L_{c_k}+R'}{E(v_c)}} \lambda_{rj} e^{-\lambda_{rj} t} dt = e^{-\lambda_{rj} \frac{L_{c_k}+R'}{E(v_c)}}, \tag{30}$$

where L_{c_k} is the length of cluster c_k, and R' is the effective communication distance of cluster c_k. The possibility of cluster c_k not encountering road segments excluding the paths of PH_s can be computed by:

$$P^n(c_k) = \prod_{r=1}^{\delta}\prod_{j=1}^{\delta} p^n(c_k) = e^{-\left(\sum_{r=1}^{\delta}\sum_{j=1}^{\delta} \lambda_{r,j}\cdot(1-\beta_{ri})\cdot\beta_{ij}\right)\left(L_{c_k}+R'\right)/E(v_c)}. \tag{31}$$

Consequently, the encounter turning possibility of c_k is:

$$P^e(c_k) = 1 - P^n(c_k) = 1 - e^{-\left(\sum_{r=1}^{\delta}\sum_{j=1}^{\delta} \lambda_{r,j}\cdot(1-\beta_{ri})\cdot\beta_{ij}\right)\left(L_{c_k}+R'\right)/E(v_c)}. \tag{32}$$

Therefore, Theorem 3 is proved. ∎

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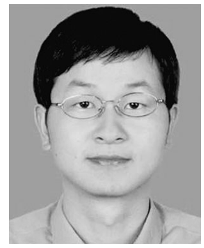

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