A City-Wide Real-Time Traffic Management System: Enabling Crowdsensing in Social Internet of Vehicles

Xiaojie Wang, Zhaolong Ning, Xiping Hu, Edith C.-H. Ngai, Lei Wang, Bin Hu, and Ricky Y. K. Kwok

Abstract

As an emerging platform based on ITS, SIoV is promising for applications of traffic management and road safety in smart cities. However, the end-to-end delay is large in store-carry-and-forward-based vehicular networks, which has become the main obstacle for the implementation of large-scale SIoV. With the extensive applications of mobile devices, crowdsensing is promising to enable real-time content dissemination in a city-wide traffic management system. This article first provides an overview of several promising research areas for traffic management in SIoV. Given the significance of traffic management in urban areas, we investigate a crowdsensing-based framework to provide timely response for traffic management in heterogeneous SIoV. The participant vehicles based on D2D communications integrate trajectory and topology information to dynamically regulate their social behaviors according to network conditions. A real-world taxi trajectory analysis-based performance evaluation is provided to demonstrate the effectiveness of the designed framework. Furthermore, we discuss several future research challenges before concluding our work.

Introduction

With the development of ubiquitous networks and pervasive computing, social networks and mobile Internet can be seamlessly integrated as a city-wide platform, known as an Internet of Things (IoT) system. The Internet of Vehicles (IoV), deemed as the deep integration of vehicular networks and IoT, is hopeful for the applications of traffic management and road safety in urban areas to establish an intelligent transportation system (ITS). With the rapid development of technologies in sensing, computing, and networking, tremendous volumes of data are generated in a city-wide system, including not only real-time traffic information and human mobility information, but also socialized connections [1]. Thus, the Social IoV (SIoV) emerges, intending to effectively handle real-time traffic information, as well as utilize updated data processing and mining techniques for information delivery. Many countries all over the world have paid attention to the establishment of SIoV systems, such as ERTICO-ITS in Europe. In industry, vehicle-to-vehicle (V2V) communication testbed systems have been developed by worldwide automakers, including BMW, Volvo, and Toyota.

A typical urban SIoV system is illustrated in Fig. 1. Various kinds of information can be delivered to drivers and passengers via SIoV (e.g., emergency information, music, and videos), making their trips safe and enjoyable. Public transportation in the urban environment is equipped with mobile routers (MRs) for wireless access. In Fig. 1, the buses and coaches are equipped with MRs, and the passengers inside are equipped with smart terminals (e.g., smartphones or tablets) to connect to the Internet through access points (APs). Generally, an SIoV system leverages technologies based on vehicular ad hoc networks (VANETs), such as V2V and vehicle-to-infrastructure (V2I) communications, for message exchange. For the highway scenario, vehicles make wireless connections to the Internet through fixed roadsde units (RSUs), and they generally move at a relatively constant speed. Therefore, the main difference between urban and highway scenarios is that the mobility of vehicles in urban areas is more complicated and difficult to predict. In addition, handoffs among heterogeneous network accesses are common in an urban system.

Real-time traffic management is significant for SIoV in smart cities to relieve traffic congestion and guarantee the timeliness of emergency information. Its design is challenging mainly due to the following reasons:

- Since the movements of vehicles are uncertain and the corresponding network topology is highly dynamic, it is impossible to realize real-time traffic management by merely depending on the wireless communications among vehicles.
- Driven by human beings, vehicles may reveal social behaviors that reflect the emotions of individuals. Although vehicles do not have constraints on battery and storage in theory, there may be concerns about the fuel consumption and travel time on their journeys. Therefore, social behaviors bring new connotations in IoV.

The authors provide an overview of several promising research areas for traffic management in SIoV. Given the significance of traffic management in urban areas, they investigate a crowdsensing-based framework to provide timely response for traffic management in heterogeneous SIoV. The participant vehicles based on D2D communications integrate trajectory and topology information to dynamically regulate their social behaviors according to network conditions.

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Traffic control is a major concern in city transportation, since the number of vehicles on roads is increasing rapidly, causing serious environmental and traffic problems (e.g., air pollution and traffic congestion). Therefore, real-time traffic control systems are advocated, which monitor traffic conditions on roads and implement intelligent management schemes.

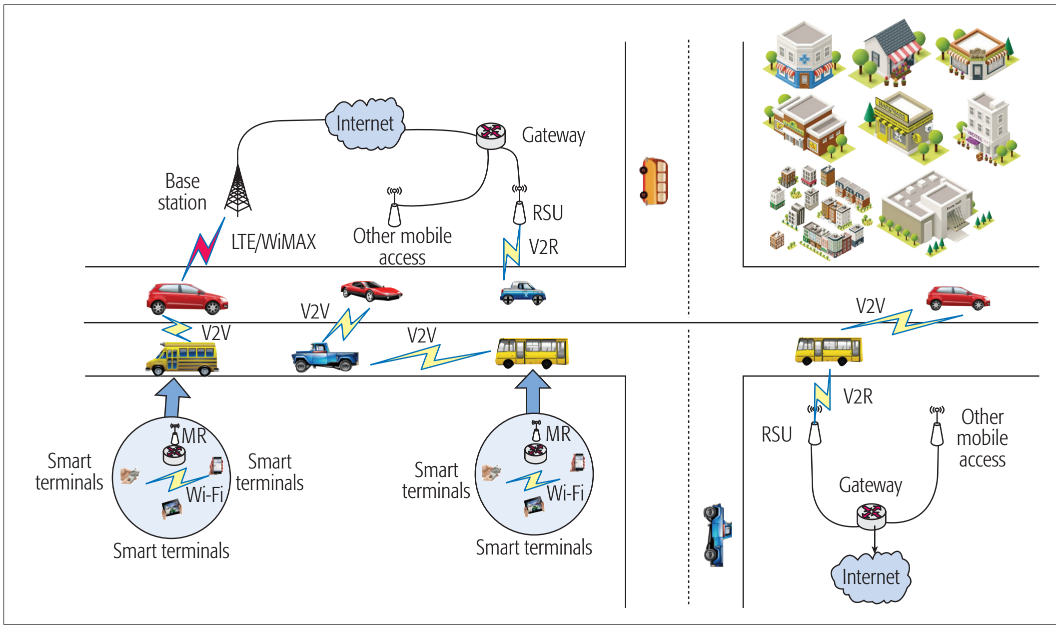

Figure 1. Network structures of SIoV in an urban area.

- On one hand, message transmission by low-cost WiFi or Bluetooth may cause large end-to-end delay; on the other hand, message forwarding by cellular networks not only occupies its limited bandwidth, but also costs additional fees. Thus, how to take advantage of different network access modes in heterogeneous SIoV is challenging.

This article intends to establish a device-to-device (D2D)-enabled real-time traffic management system by crowdsensing in SIoV so that a traffic management server (TMS) can take prompt actions on timely feedback of abnormal events (e.g., traffic jams and car accidents) through vehicles on the road. Specifically, a crowdsensing-based real-time traffic management framework in heterogeneous SIoV, called CREAM, is designed for smart cities. We first provide an overview of several promising research fields for traffic management in SIoVs. Then we establish a D2D-enabled system model for SIoV and present a crowdsensing-based method of traffic management in heterogeneous SIoV, which can largely shorten the response time by cooperative message uploading. To demonstrate the effectiveness of the designed framework, performance evaluations based on real-world taxi trajectory analyses are conducted to compare CREAM with two boundary conditions. Finally, we discuss several challenges and open issues for real-time content dissemination in heterogeneous SIoV to provide a guideline for further studies.

Overview of Traffic Management in SIoV

Traffic management in urban areas is fundamental to achieve smart travel and establish green cities. In the following, we mainly discuss four promising research areas for traffic management in SIoV.

Traffic Control System

Traffic control is a major concern in city transportation, since the number of vehicles on roads is increasing rapidly, causing serious environmental and traffic problems (e.g., air pollution and traffic congestion). Therefore, real-time traffic control systems are advocated, which monitor traffic conditions on roads and implement intelligent management schemes such as adaptive traffic light control and driving policy recommendation. A real-time traffic monitoring system is constructed in [2], where V2I communications are enabled to collect real-time traffic information, and a cluster-based approach is developed to reduce the communication overhead. Different from the majority of research heavily relying on vehicular communications, a traffic monitoring system based on bus riders carrying mobile phones is designed [3]. The road traffic conditions along the bus routes can be deduced by the crowdsourced information from the phones of riders.

Traffic Anomaly Detection

For drivers, it is significant to automatically detect potential risk when driving, because drivers' attention may not always be deeply focused, and dangers may be neglected. To maintain a safe trip, efficient traffic anomaly detection schemes call for investigation. Many efforts have been made to design detection systems that focus on specific kinds of events, such as road surface damage or unsafe driving behaviors. Currently, researchers are devoted to finding ways to detect various kinds of events by robust systems. For example, a sparse coding approach under the constraint of spatial localization is proposed to detect anomalies in traffic scenes [4]. It can detect abnormal events by constructing an anomaly map robust to the dynamic changes of vehicle movements.

Path Planning

By regulating people's travel behavior, traffic problems can be effectively alleviated in SIoV for smart cities. However, planning an efficient real-time path is still challenging. A real-time path planning algorithm is designed in [5] by stochastic Lyapunov optimization, which not only reduces the travel cost by avoiding vehicles from getting stuck in

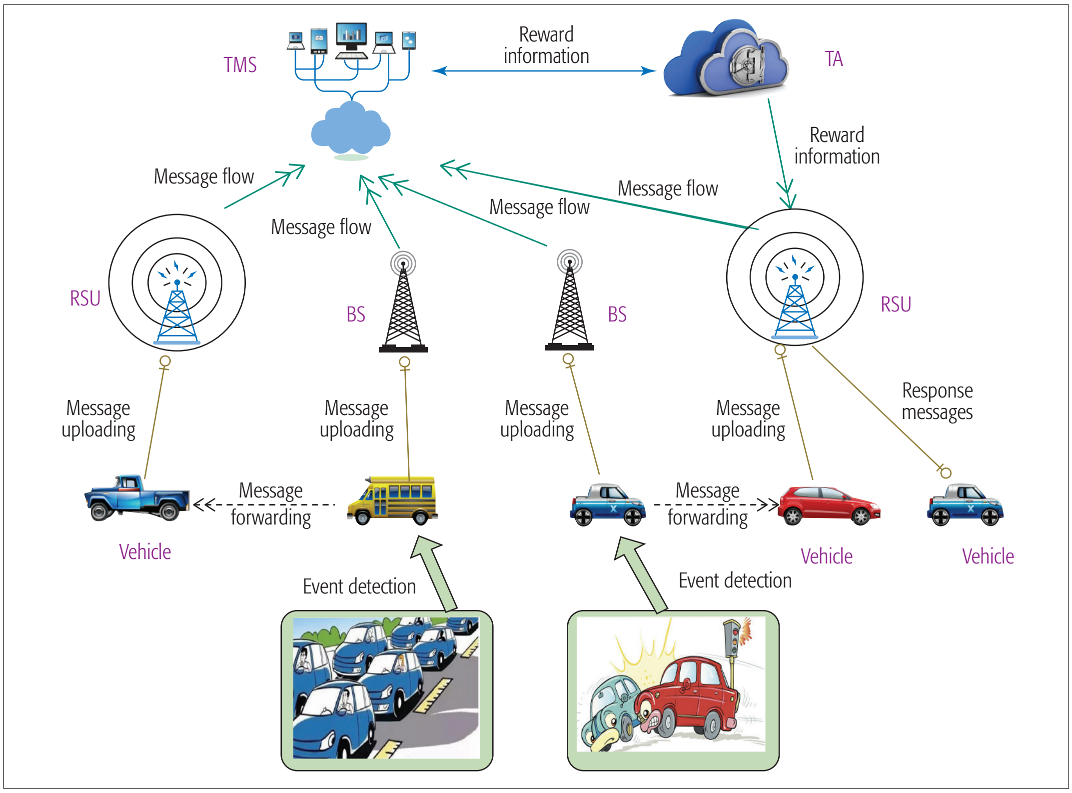

Figure 2. System model of D2D-enabled SIoV.

Information dissemination in location-based services (e.g., location-based traffic alerts) is significant to reduce delivery delay and improve transmission efficiency. Traditional algorithms always adopt distance-based methods, while current schemes have developed other metrics to improve the system performance.

congestion, but also improves the spatial utilization of road networks. To fulfill real-time navigation, a secure navigation method is studied in [6] by leveraging spatial crowdsensing in fog-based VANETs. The fog nodes manage the crowdsensing tasks and select suitable routes according to the collected real-time traffic information.

Information Dissemination

Information dissemination in location-based services (e.g., location-based traffic alerts) is significant to reduce delivery delay and improve transmission efficiency. Traditional algorithms always adopt distance-based methods, while current schemes have developed other metrics to improve the system performance. For example, by integrating both contact-level and social-level information for message routing, ZOOM decides the next hop relay node according to the most appropriate mobility information [7]. A software-defined architecture in SIoV is presented in [8], where the cellular infrastructure guarantees that vehicles can quickly into the social network, and the vehicular network can fulfill data communication.

Crowdsensing-Based Real-Time Traffic Management

The objective of our framework is to guarantee that TMS can take prompt actions by providing timely feedback to occurring events through vehicles.

System Model

The system model of our D2D-enabled SIoV is illustrated in Fig. 2. It includes five major components: vehicles, RSUs, base stations (BSs), TMS, and trust authority (TA).

For each vehicle, onboard units (OBUs) are equipped for wireless communications. D2D transmission is mainly considered for V2V communications in our system, since it is regarded as a vital technology to relieve the workload of existing cellular network infrastructures. When vehicles are in location proximity, they can directly transfer data (including multimedia) via D2D communications.

RSUs are deployed alongside the main roads to connect passing vehicles within their communication coverage. Through RSUs, vehicles can upload messages to TMS. Due to the expensive installation costs, there may not be enough RSUs to cover all the communication ranges of vehicles. Herein, we assume that an RSU can obtain the locations of neighboring RSUs.

BSs are regulated by mobile operators, which can provide almost full coverage in urban areas. They can also provide wireless access services for vehicles to TMS through LTE cellular networks. However, sending messages through cellular networks is not cost effective. If the message size is large, it will cause network traffic congestion.

When TMS receives messages from vehicles, it first validates message truthfulness. If the received messages are trustworthy, TMS informs individuals in the traffic management office to take actions, for example, assigning additional traffic police to a congested road for guidance.

TA is assumed to be fully trusted by all parties in the D2D-enabled SIoV. Its function is to register the participant vehicles and initialize the virtual money a vehicle has. TA is considered to have powerful and sufficient storage capacity to protect itself. Moreover, the credit manager in TA is responsible for virtual money allocation to reward vehicles.

When a vehicle detects a traffic jam, accident, or damage to the road surface on its route, the driver or passengers can utilize specific pre-installed software inside the vehicle to record this event in the form of texts, pictures, or even short videos. Then the record is packaged into a message, denoted by three factors: location, time, and description.

Problem Formulation

We consider that when a vehicle detects an event, it generates a message that describes detailed information about the event. Then it makes a choice about whether to upload the message to TMS by RSUs or by BSs. At first, the individual utility is compared between policies based on RSUs and BSs. Then, if a BS is chosen for the uploading process, the vehicle will immediately upload the message without any delay. Otherwise, a geographical routing scheme is leveraged to forward the message through D2D-enabled inter-vehicle communications, taking both topology and mobility information into consideration. In order to encourage vehicles to report events on roads, a biased credit-based incentive scheme is designed according to message accuracy and timeliness. After abstracting the accurate information from the sensed data, TMS takes action immediately. We can model the above process as an optimization problem, with the objective of minimizing the expected response time of TMS. It can be computed by the difference between the time of the last message received by TMS to restore a complete event and the occurrence time of the event. It should satisfy the total social benefits in the network being positive, aiming to encourage vehicles to cooperate in message forwarding. For vehicles, they are not aware of the entire network topology and can only acquire the movements of some neighboring vehicles. Therefore, our method can be fulfilled in a distributed manner.

Biased Credit-Based Incentive Mechanism

A biased credit-based incentive scheme is proposed to encourage vehicles to transmit messages in a cooperative manner. Virtual money is employed as rewards based on vehicles' contributions to the decision of TMS.

If a vehicle uploads a useful message before TMS takes action, it will be rewarded. Similar to the definition in [9], the utility of a vehicle represents its benefits by uploading messages to TMS, and is based on server rewards and the uploading cost. It can be computed by the payment of TMS, that is, a function of the report quality and the elapsed time from the occurrence time of the event to the time when the message is received. It has relationships with the size of the uploaded message, the uploading cost of BSs for each message unit, and the reduced response delay caused by the policy based on RSUs compared to that based on BSs. In other words, the reduced response delay also represents the time when a message routes from the current vehicle to the nearest RSU. If the vehicle utilizes RSUs to upload a message, the adjustment factor of the payment function equals 1. Otherwise, the adjustment factor is computed by the value of a vehicle's inputs. Therefore, vehicles are stimulated to participate in event detection and make accurate reports for maximizing their benefits. The neighboring vehicles, which help forward messages, also can be rewarded. The final rewards for the relay vehicles can be split from the utility of the vehicle who records the event. Since plenty of existing works have studied how to reward neighboring vehicles for message forwarding, we do not specify it since it is not our main focus.

Crowdsensing-Based Data Collection

The crowdsensing-based data collection scheme is specified in this subsection for real-time traffic management.

Message Generation: When a vehicle detects a traffic jam, accident, or damage to the road surface on its route, the driver or passengers can utilize specific pre-installed software inside the vehicle to record this event in the form of texts, pictures, or even short videos. Then the record is packaged into a message, denoted by three factors: *location*, *time*, and *description*. Location indicates the event occurrence location, time represents the event occurrence time, and *description* gives a detailed event description. After that, the vehicle needs to make a choice about the uploading strategy.

Uploading Strategy for Vehicles: There are two choices for a vehicle to upload messages to TMS: one is to connect to TMS through RSUs directly; the other is to access the cellular network by BSs. For the first choice, the vehicle needs to conduct a geographical routing scheme for message forwarding; thus, a long distance may exist between the location of the vehicle and that of an RSU. Fortunately, it is free for vehicles to upload messages to TMS. When a vehicle decides to upload messages through BSs, it can send out the messages almost without any delay, but additional cost exists for cellular data transmission.

After a vehicle generates a message by sensing an abnormal event en route, it needs to choose the uploading strategy in time since the reward decays over time. For example, when a vehicle generates a message at a specific time and uploads the message via BSs, its utility depends on current uploading time; if RSUs are employed, the corresponding utility is based on message generation time and the receiving delay. Actually, the receiving delay includes two parts: the transmission delay from its current location to the nearest RSU and the uploading delay for the RSU. Since the uploading delay is much shorter than the transmission delay, the receiving delay can be approximatively computed by merely considering the transmission delay. Consequently, if the corresponding utility based on BSs is greater than that based on RSUs, the vehicle uploads the generated message by BSs; otherwise, it uploads the message by RSUs. However, how to estimate the receiving delay beforehand is an important issue. The following section specifies the estimation of the transmission delay caused by the geographical routing scheme.

Server Response: When TMS receives a message, it checks message accuracy, for example, the occurrence location, time, and detailed description of the reported event. We can integrate a data trustworthiness assurance method [10] with our crowdsensing scheme to ensure message accuracy. Thus, TMS will form a response message and send it to vehicles through RSUs if an accurate description of an event can be obtained. When a vehicle passes an RSU, it can receive the response message.

In addition, TMS rewards the vehicles contributing to event reports based on the transmission delay and accuracy of the event description. We can formulate the function of reward as a decaying exponential function with the parameters of

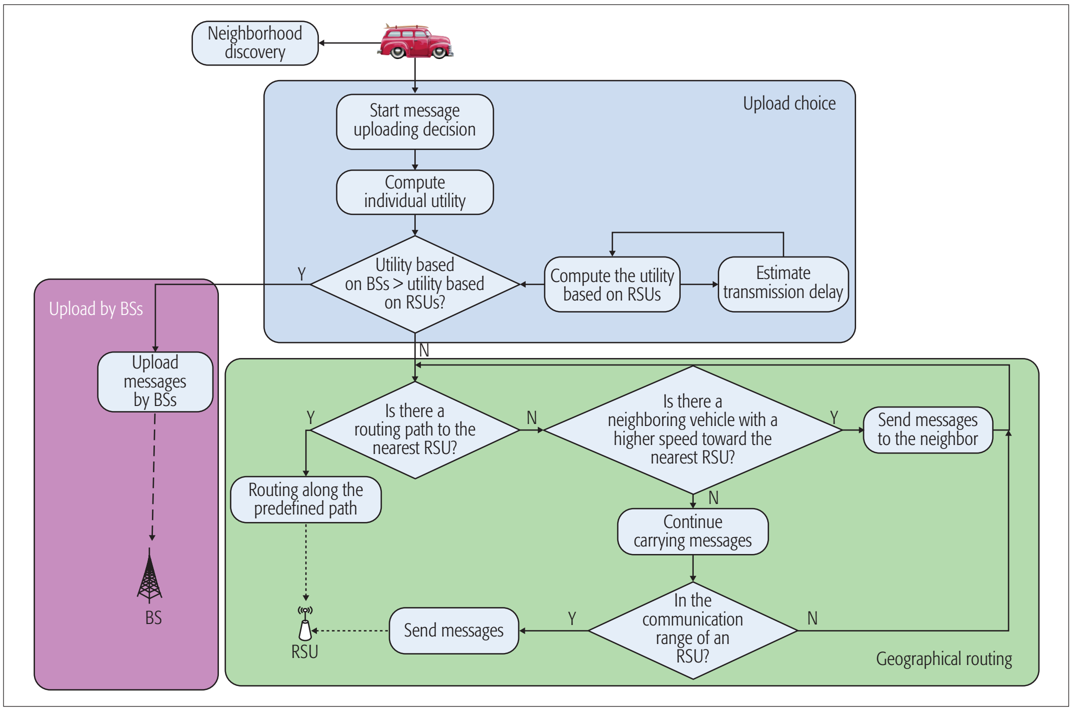

Figure 3. V2V-based message forwarding process.

When a vehicle intends to utilize RSUs to upload messages, a V2V-based routing algorithm should be designed to forward messages to the nearest RSU. Initially, the vehicle conducts a neighborhood discovery process to find its one- or two-hop neighbors. Based on the collected information, either a predefined routing path or a dynamic carry-and-forward scheme can be selected.

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Geographical Routing

When a vehicle intends to utilize RSUs to upload messages, a V2V-based routing algorithm should be designed to forward messages to the nearest RSU. Initially, the vehicle conducts a neighborhood discovery process to find its one- or two-hop neighbors. Based on the collected information, either a predefined routing path or a dynamic carry-and-forward scheme can be selected. In the following, the detailed process is described.

Neighborhood Discovery: The vehicle takes advantage of the periodic beacon messages to acquire the information of its nearby vehicles. The Neighborhood Discovery Protocol (NHDP) [11] and standard packet format [12] can be utilized. From the received beacon messages, we can learn the addresses of one-hop neighbors, link state, location, speed, direction and the final destination. These received messages will be stored in the vehicle's buffer for a specific period. An analysis based on taxi traces in Shanghai shows that one vehicle can contact other vehicles within several minutes [13]. Therefore, we set the period to store the beacon messages as five minutes.

Message Forwarding: if a predefined routing path from the vehicle to its nearest RSU can be formed by analyzing the historical beacon messages, the generated message can be forwarded through this path. Specifically, a predefined path is only one or two hops based on NHDP. Otherwise, a dynamic carry-and-forward scheme can be selected. The source vehicle sends the message to a vehicle that has a movement direction toward the nearest RSU at the highest speed. The whole routing decision process is illustrated in Fig.3. The time complexity of our routing algorithm is in proportion to the square of the total number of vehicles. Since each vehicle searches nearby vehicles during each time slot, the number of its neighboring vehicles equals that of total vehicles minus one at most.

Transmission Delay Estimation: If a predefined routing path can be obtained, the transmission delay can be estimated by the speed of relay vehicles. For example, if three relay vehicles are selected, the total transmission delay is computed by the sum of the transmission delay between every two relay vehicles, which can be computed by the mathematic solution of the meeting problem. If no neighbor is available, the total transmission delay is estimated by the vehicle's traveling time from the current location to the nearest RSU. If only a one-hop neighbor exists, the total transmission delay is computed by the traveling time of the neighboring vehicle from the current location to the nearest RSU.

Performance Evaluation

We utilize a real-world dataset, the Roma/taxi dataset [14], to evaluate network performance for the designed framework. This dataset contains traces of taxi cabs in Rome, Italy, including GPS coordinates of 316 taxis collected over 30 days. The simulation time is set to 168 h, and the D2D transmission range is 40 m. The message size is set between 10 MB and 40 MB, while the message time to live (TTL) is 2 h. The unit cost of a message is 0.01/kB. We run each simulation setting 100 times and calculate the average value.

The performance of average delivery ratio is shown in Fig. 4. Average delivery ratio is defined as the percentage of answered messages compared to the total number of generated messages. We can find that average delivery ratios of CREAM and RSU_only increase gently, while BaseStation_only is almost stable with 1. The reason is that with fewer newly generated messages, there are more available network resources for message transmission. Obviously, vehicles can upload messages immediately when they utilize BSs. Therefore, the average delivery ratio is almost equal to 1 by BS uploading. We can observe that the delivery ratios of CREAM are close to those of BaseStation_Only, and are much higher than those of RSU_Only. For example, when the message interval is 500–600 s, the delivery ratio of CREAM is 0.9, while that of RSU_Only is only 0.6. This illustrates that merely depending on the traditional ad hoc transmission mode (e.g., V2V or V2I) is not efficient since the delay may be large and messages may not be delivered successfully within their TTL.

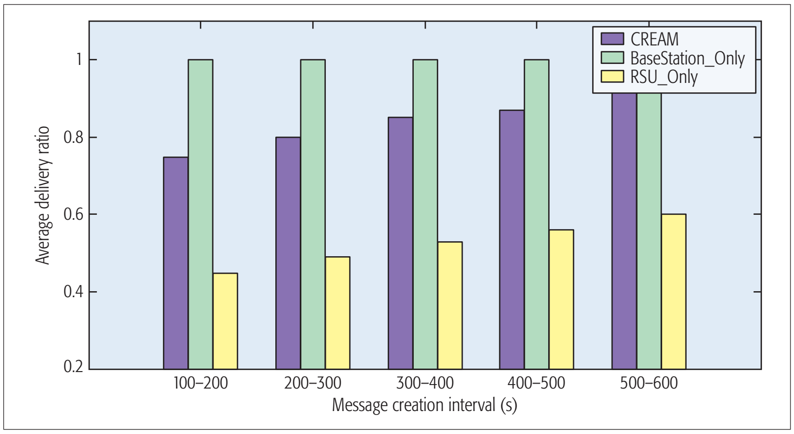

Figure 4. The performance of average delivery ratio.

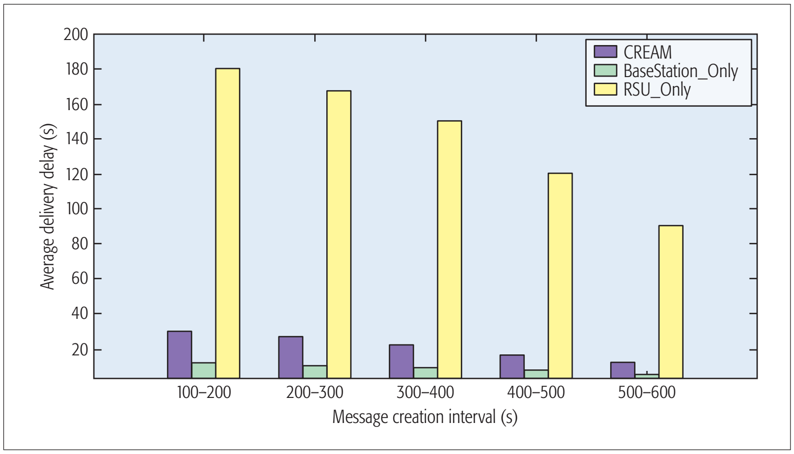

Figure 5. The performance of average delivery delay.

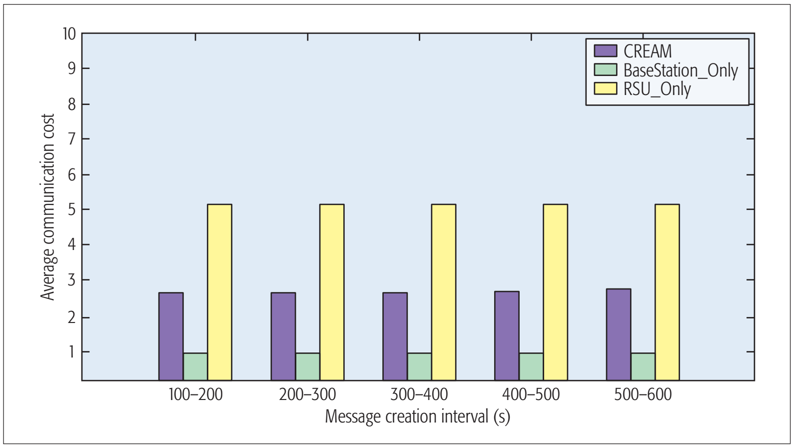

Figure 6. The performance of average communication cost.

As illustrated in Fig. 5, the average delivery delay of RSU_Only is much higher than those of the other two algorithms. Average delivery delay is defined as the average time duration that takes a message from the time it is generated to the time it gets a response from TMS. The reason is that there may be a long distance between vehicles carrying messages and RSUs. Although the BaseStation_Only algorithm is the most effective uploading solution, its cost is the largest. CREAM takes advantage of both BSs and RSUs, and its transmission delay can be significantly decreased.

The performance of average communication cost is shown in Fig. 6. Average communication cost represents the percentage of total message copies compared to the responded messages. It is shown that the average communication cost of RSU_Only is the highest, while that of CREAM is intermediate. The reason is that when BSs are utilized, it is not necessary to copy messages to neighboring nodes. However, a geographical routing algorithm is utilized for RSU-based routing, producing many message copies during the transmission process.

Research Challenges and Open Issues

This article states the initial step toward real-time content dissemination in heterogeneous SIoV for smart cities. Many open issues still deserve to be discussed.

Deep Analysis of Network Model: SIoV is promising for high-efficiency urban traffic management, and can provide efficient communications based on V2X communications. However, how to select the relay vehicles for V2V communications to reduce the transmission delay caused by the disconnection in a geographical routing scheme needs to be further investigated. In addition, how to build an accurate model by extracting network parameters from real-world datasets is necessary. For example, data-driven approaches can be developed to model vehicular networks to provide deep insight into their features and change rules in distinct scenarios [15].

Specific Metrics for Data Trust Evaluation: Data trust evaluation is necessary in the traffic management system, since there may be some fake or false information distributed in the network, which may confuse other vehicles and TMS. In order to obtain accurate results, some specific metrics need to be taken into consideration to evaluate data trust from both sides of vehicles and TMS, such as node reputation, the duration from the event occurrence time to the report time, and the distance from the location of the vehicle to the event occurrence location. In addition, different weights for each trust metric should be designed properly to obtain a fair trust level based on the collection of evidence.

Flexible Network Infrastructure: In order to realize distributed network management, traffic management in SIoV calls for a flexible, programmable, and scalable network infrastructure. Although software defined networking and network functions virtualization are promising to promote the performances of scalability, reliability, and agility in SIoV networks, they are centralized network management strategies. Thus, designing a unified flexible traffic management infrastructure in a distributed manner is challenging, since some vehicles may be selfish or malicious, and disturb normal network orders. For example, if a vehicle uploads a message with a virus to TMS, the traffic flows on roads can be rudely dispersed in a different direction, which may waste a lot of drivers' time. Therefore, how to prevent potential attacks and protect the privacy of vehicles in distributed SIoV systems calls for further investigation.

Efficient Experimental Testbed: Current research is mostly based on specific simulation platforms to evaluate the performance of the design scheme in SIoV systems (e.g., SUMO, OMNeT++). Although these platforms can provide a suitable simulation environment, it is still far from the real-world scenario. Therefore, an urgent requirement is the development of an experimental testbed. It is advocated to embrace different kinds of vehicles (e.g., taxis, buses, and private cars) as participating fleets, and a number of volunteers acting as drivers and passengers. Fortunately, the navigation software based on GPS, up-to-date road maps, and wireless communication technologies are available, making the real-world experimental testbed realizable.

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Conclusion

This article first declares research significance of traffic management in SIoV systems, and outlines several promising research areas. With the objective of providing timely response in heterogeneous SIoV for traffic management, this article constructs a crowdsensing-based real-time traffic management framework in a fully distributed manner. A dynamic-reward-based message uploading strategy for vehicles has also been designed to make a trade-off between traffic loads in cellular networks and transmission delay caused by RSU uploading. In addition, a real taxi trajectory analysis-based simulation has been conducted to demonstrate the effectiveness of our framework. Finally, we discuss some research challenges and open issues for further work.

Acknowledgments

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References

[1] Z. Ning *et al.*, "CAIS: A Copy Adjustable Incentive Scheme in Community-Based Socially-Aware Networking," *IEEE Trans. Vehic. Tech.*, vol. 66, no. 4, 2017, pp. 3406–19.

[2] R. Aissaoui *et al.*, "Advanced Real-Time Traffic Monitoring System Based on V2X Communications," *Proc. IEEE ICC*, 2014, pp. 2713–18.

[3] Z. Liu *et al.*, "A Participatory Urban Traffic Monitoring System: The Power of Bus Riders," *IEEE Trans. Intelligent Transportation Systems*, vol. 18, no. 10, 2017, pp. 2851–64.

[4] Y. Yuan *et al.*, "Anomaly Detection in Traffic Scenes via Spatial-Aware Motion Reconstruction," *IEEE Trans. Intelligent Transportation Systems*, vol. 18, no. 5, 2017, pp. 1198–1209.

[5] M. Wang *et al.*, "Real-Time Path Planning Based on Hybrid-VANET-Enhanced Transportation System," *IEEE Trans. Vehic. Tech.*, vol. 64, no. 5, 2015, pp. 1664–78.

[6] L. Wang *et al.*, "A Secure and Privacy-Preserving Navigation Scheme Using Spatial Crowdsourcing in Fog-Based VANETs," *Sensors*, vol. 17, no. 4, 2017, pp. 668–83.

[7] H. Zhu *et al.*, "ZOOM: Scaling the Mobility for Fast Opportunistic Forwarding in Vehicular Networks," *Proc. IEEE INFOCOM*, 2013, pp. 2832–40.

[8] H. Li *et al.*, "VeShare: A D2D Infrastructure for Real-Time Social-Enabled Vehicle Networks," *IEEE Wireless Commun.*, vol. 23, no. 4, Aug. 2016, pp. 96–102.

[9] T. Ng *et al.*, "Joint Optimization of Relay Strategies and Resource Allocations in Cooperative Cellular Networks," *IEEE JSAC*, vol. 25, no. 2, 2007, pp. 328–39.

[10] A. Dua *et al.*, "Towards Trustworthy Participatory Sensing," *Proc. USENIX HotSec*, 2009, pp. 1–6.

[11] T. Clausen *et al.*, "Mobile Ad Hoc Network Neighborhood Discovery Protocol," IETF RFC 6130, 2010.

[12] T. Clausen *et al.*, "Generalized Mobile Ad Hoc Network (MANET) Packet/Message Format," Internet-Draft, draft-ietf-manetpacketbb-02.txt, 2006; http://tools.ietf.org/pdf/draft-ietf-manet-packetbb-02.pdf.

[13] H. Zhu *et al.*, "Recognizing Exponential Inter-Contact Time in VANETs," *Proc. IEEE INFOCOM*, 2010, pp. 1–5.

[14] B. Lorenzo et al., CRAWDAD dataset roma/taxi (v.2014 07 17), 2014; http://crawdad.org/roma/taxi/20140717.

[15] Z. Ning *et al.*, "Vehicular Social Networks: Enabling Smart Mobility," *IEEE Commun. Mag.*, vol. 55, no. 5, May 2017, pp. 49–55.

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