Cluster-Based Cooperative Data Service for VANETs

Yongyue Shi[1,2], Xiao-hong Peng[2], Hang Shen[1], and Guangwei Bai[1(✉)]

[1] Department of Computer Science and Technology,
Nanjing Tech University, Nanjing, China
{hshen,bai}@njtech.edu.cn

[2] School of Engineering and Applied Science, Aston University, Birmingham, UK
{shiy9,x-h.peng}@aston.ac.uk

Abstract. Vehicular Ad-hoc Network (VANET) plays an important role in improving traffic safety and efficiency. Vehicles with sensors on board can collect traffic and environmental information of their driving areas and, meanwhile, they also want to achieve a similar type of information for their interested regions. This paper establishes a data service model to facilitate information exchanges within a vehicular network, where both vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications are involved. A new clustering algorithm which considers the mobility and the driving behavior is proposed in this model to enhance service efficiency and success rate. The performance of this model is evaluated through simulation.

Keywords: Cluster · V2X communications · Vehicular network

1 Introduction

In recent years, with the rapid development of Smart Cities and Intelligent Transportation Systems (ITS) [1], a new and modern transportation paradigm is formed aiming to make traveling on the road safer, more efficient and comfortable. The Vehicular Ad-hoc Network (VANET), extended from the Mobile Ad-hoc Network (MANET), is designed to improve the quality of experience for both drivers and passengers. Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications (together abbreviated as V2X) are two main communications modes in VANETs. The roadside unit (RSU) is a stationary server installed along the road to provide information services via V2I communications.

The traffic and environmental information differs in different areas but remains largely unchanged within a shorter range of traveling distance. Therefore, collecting the local data and exchanging with RSUs to learn other traffic areas across vehicular networks help drivers learn about the real-time traffic/environmental information ahead, and is an effective solution for reducing road congestion and improving the driving experience. The Dedicated Short Range Communications (DSRC) scheme has been developed to support both V2V and V2I communications (together as V2X).

C. Li and S. Mao (Eds.): WiCON 2017, LNICST 230, pp. 119–129, 2018.
https://doi.org/10.1007/978-3-319-90802-1_10

In general, the 5.9 GHz DSRC refers to a suite of standards for Wireless Access in Vehicular Environments (WAVE) [2], which include IEEE 802.11p, IEEE 1609.1/.2/.3/.4 protocols and the SAE J2735 message set dictionary. The high mobility of vehicles in addition to a large number of transmission terminals in an ad-hoc network presents a great challenge in V2X communications, in terms of high likelihood of congestion in data delivery and exchange in this environment.

This challenge can be addressed by the clustering method in V2X approaches. A VANET model with clusters (circled) is illustrated in Fig. 1, showing information exchanges between cluster heads and RSUs. The clustering method simplifies the data transmission structure in a complex network and increases the capacity of a system as it can better utilize the resources available. A cluster-based data service model via cooperative transmission in V2X is proposed in this paper, which includes both local information collection/submission and data downloading from RSU. We will show that the combined clustering and V2X methods can outperform the conventional schemes without using clusters, in terms of the service delivery efficiency.

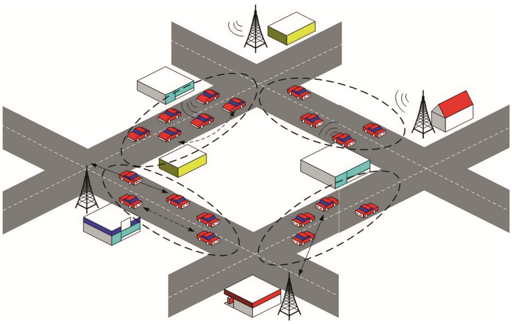

Fig. 1. A VANET model with clusters.

The rest of the paper is organized as follows. Section 2 introduces the related work in V2X communications and cluster-based dissemination methods. Section 3 presents the new clustering algorithm and Sect. 4 describes the proposed data service model. Section 5 provides simulation results and performance analysis. Finally, the paper is concluded in Sect. 6.

2 Related Work

There have been many research works dedicated to the performance improvement of vehicular communications. In V2V communications, adaptive data dissemination methods are used in vehicular networks with different densities [3], to reduce the retransmission times efficiently, with the help of a store and forward function. The idea of cooperation is to combine V2V with V2I, such as in a typical scenario [4] where the RSU provides services to passing vehicles via V2I communications and any vehicle is able to share its cached data with neighboring vehicles via V2V communications.

Network coding is also applied in this work to increase transmission efficiency, but its evaluation ignores the latency caused by the failed services.

In [5], more RSUs are considered to broadcast messages timely. Vehicles within the coverage of RSUs will receive the information seamlessly via the V2I mode and those which outside this transmission distance forward the information via V2V. The key point here is to decide the handover mechanism for ensuring stable connections.

The Lowest-ID clustering algorithm is used to select the cluster head (CH) based on the fixed ID number of each vehicle within the communication range [6]. This algorithm is not suitable in VANET due to high mobility and restricted routes for vehicles. A three-layer CH selection algorithm is proposed for multimedia services in a VANET [7], where clusters are formed based on the interest preferences of vehicle passengers. This scheme, however, cannot achieve a high efficiency when the requirements in the operation differ too much.

3 Clustering Algorithm

In a MANET, CHs can be selected by considering the position, neighbors, mobility, and battery power of the nodes in the network, and applying an algorithm called "combined weight" [8]. But in VANETs, the factors to consider are different due to the high mobility and the road structures, so we propose a new clustering algorithm which applies a new weighting method, which is more dedicated to VANETs.

There are three types of the nodes (vehicles) in a VANET: free node (FN), cluster head (CH), and cluster member (CM). The clustering algorithm considers only the one-hop neighbors of each node, the cluster size is decided by the number of CH's neighbors. The factors that could affect the selection of CH include position, velocity, connectivity and driving behavior.

The position of each node is obtained from GPS devices. The average distance between CH and CM should be short to keep CH close to the center of a cluster. The average relative distance between a node n_i and its neighbors, P_i, is given by:

$$P_i = \frac{1}{n}\sum\nolimits_{j=1}^{n}\sqrt{(x_j - x_i)^2 + (y_j - y_i)^2} \tag{1}$$

where n is the number of neighbors of node n_i, and x and y are coordinate values of two involved nodes.

The velocity of CH should be close to the average velocity of the cluster, so it can represent the cluster's mobility for building stable connections with its members. The stability, V_i, is represented by the difference between the velocity of a candidate node v_j and the average velocity of the traffic flow, i.e.:

$$V_i = \left| v_i - \frac{1}{n}\sum\nolimits_{j=1}^{n} v_j \right| \tag{2}$$

where v_j is the velocity of the j-th neighbour of n_i.

Each node can have a different number of neighbors, denoted by N_i, reflecting the connectivity of n_i. The ideal connectivity is defined as λ, which represents the maximum number of neighboring nodes within one hop without causing traffic congestion, and is given by:

$$\lambda = 2R_t \times 133 \times n_l/1000 \tag{3}$$

where R_t is the transmission range, n_l is the number of lanes. The value 133 represents the highest possible density (vehicles/(lane·km) [9]. The actual connectivity denoted as C_i, is then given by:

$$C_i = |N_i - \lambda| \tag{4}$$

The last factor involved is driving behavior, which shows how stable a vehicle is when running along the road in terms of the average acceleration of the vehicle a_i. The driving behavior denoted as D_i is then defined as:

$$D_i = |a_i| \tag{5}$$

These four factors are considered to have the same influence on the CH selection, so the final weighting metric W_i should be the sum of all normalized P_i, V_i, C_i and D_i:

$$W_i = P_i' + V_i' + C_i' + D_i' \tag{6}$$

$$P_i' = \frac{P_i}{P_{\max i}},\ V_i' = \frac{V_i}{V_{\max}},\ C_i' = \frac{C_i}{\sigma},\ D_i' = \frac{D_i}{D_{\max i}} \tag{7}$$

where P_{max} is the distance between the i-th vehicle and the farthest vehicle from it, V_{max} is the speed limitation by traffic rules that a vehicle can reach in the flow, D_{max} is the maximum absolute value of acceleration the vehicle can reach when it is running. A smaller W_i indicates higher suitability for the CH.

4 Cluster-Based Service Model

The proposed system model is a combination of both V2V and V2I. RSUs are located in different sections of a road and share a database server in the back-end as shown in Fig. 2. Vehicles act as nodes in the VANET concerned.

The database server stores the traffic and environmental information of different regions and is updated by each RSU periodically for the traffic situations, weather conditions and road status, etc. Vehicles are grouped into clusters to collect information and request for services. CH is selected to collect and aggregate information from cluster members (CMs) and disseminate service packets to CMs after receiving data from RSUs. Only CH can directly communicate with RSUs.

To reduce the transmission overhead, CH does not keep the list of its members, every CM stores the CH's ID to identify its cluster. When CH broadcasts the service packets,

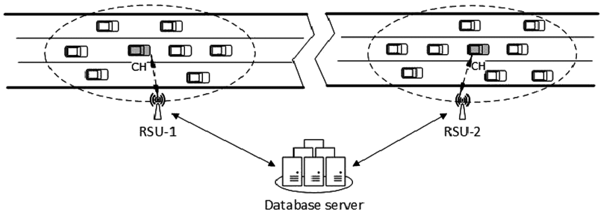

Fig. 2. Cluster-based service model.

the CMs who have the same CH ID and the targeted service ID will receive the service packets.

The system follows the standards of IEEE 802.11p, which specify 7 channels with 10 MHz bandwidth, including one control channel for exchanging control messages and safety information, and 6 service channels for delivering service data.

This system model enables real-time information sharing and reduces energy consumption because it shifts a significant amount of transmissions from V2I to V2V thanks to the cluster approach adopted. Only RSUs need to communicate with CHs, resulting in reduced transmission collision and energy consumption as well.

The whole cluster-based service model includes three main subsystems for data management, cluster operation, and service delivery, as described below.

4.1 Data Management Subsystem

4.1.1 Packets Classification

- Vehicle information packet (VIP): It carries the basic vehicle information: vehicle ID, velocity, position, etc.
- Cluster Head Announcement (CHA): CHA is broadcast by a node with a weight low enough to be a CH.
- Cluster Head Maintain (CHM): A node with the smallest W_i is selected as CH, and it then sends CHM to all its neighbours to declare its identity (CH ID).
- Service Data Packet (SDP): It consists the head (CH ID, packet ID, sender ID and time stamp.) and context (actual data to transmit).

4.1.2 Data Integration

The traffic/environmental information includes the average speed of the current flow, position, weather and traffic conditions, which is obtained by collecting relevant data from onboard sensors. The collected information is aggregated by CH as it has both universality and particularity. Each RSU maintains a database to store the service information collected from CHs and will also periodically update information from other servers. This information service helps drivers to choose better routes and avoid congestions and accidents. They can also be aware of the travel time they will spend.

4.2 Cluster Operation Subsystem

4.2.1 Cluster Forming

Any node whose status is free node (FN) can start the cluster forming process by sending out VIP, based on which each node can calculate its weight W_i. If a node achieves a smaller W_i than the weight threshold, $W_{Threshold}$ (i.e. $W_i < W_{Threshold}$), it will send CHA to neighbors to announce that. Any node that receives the CHA will compare the weight (W_i) with its own and send another CHA to argue if it has a smaller W_i. Otherwise, the node will keep waiting for CHM from others to confirm the CH ID. After sending a CHA, if a node has not received any argument after a threshold window T_w, it sends CHM to declare its identity as CH of its neighbors. Every node which receives this CHM will mark the CH ID as its head ID. If a node receives another CHM shortly after the one from the first CH, it would decide the new CH by comparing their weights.

4.2.2 Cluster Maintaining

As CH does not keep the list of its members, it detects the W_i periodically to maintain the CH status: if there are no obvious changes of its acceleration and $W_i < W_{Threhold}$ still stands, it resends its CHM to confirm its CH ID; otherwise, it sends VIP to start a new cluster forming process and changes its status as FN.

When a node becomes a CM, it stores the ID of the current CH. If it keeps overhearing CHM from the same CH, no changes will be made. If CM continuously overhears two CHMs from another CH, it changes its CH ID and becomes a member of a new cluster. If CM overhears no CHM after a threshold, it would switch to FN and sends out VIP.

4.3 Service Delivery Subsystem

Vehicles on the road may have different regions of interest and tend to learn the environmental and traffic conditions in those regions in advance. They also collect current traffic information from their onboard sensors and are responsible for reporting the information with a high priority (e.g. an accident) to its CH.

Each vehicle generates request packets containing the vehicle ID, request ID and region ID. Every CM sets the receiver ID as the CH ID and submits the requests along with the emergent information (if it has) to CH and then waits for service delivery. On receiving the packets, CH integrates the collected information and forward it all together with the requests of CMs to RSU.

When receiving the SDP packet from CH, RSU updates the database with the collected information and sends the service packets requested to CH. CH will continuously broadcast each service packet to its members. Upon overhearing the relative ID for its request, CM will save the packet and the request is satisfied. If CM still cannot obtain the service data after a waiting time period, this request is failed and after checking its cluster status this CM will send a request to CH again.

In this paper, the following three metrics are applied to evaluate the performance of the proposed system.

- Service ratio (γ). It is the ratio of the number of successful delivered requests n_s to the total number of requested services n, to evaluate the effectiveness of the V2X system, which is given by:

$$\gamma = \frac{n_s}{n} \tag{8}$$

- Average service delay (τ). It is defined as the average duration from a vehicle submitting a service request to it finally receiving the service packets, i.e.:

$$\tau = \frac{\sum_{i=1}^{n_s} t_{si} + n_{us} \cdot t_p}{n_s} \tag{9}$$

where t_{si} is the time duration of the i-th successful service transmission, n_{us} is the number of unsuccessful service requests, and t_p is the waiting time a vehicle spends for the service which is not delivered.

- Throughput (η). It is a widely applied metric to evaluate the transmission efficiency of a system, defined as the average size of data successfully delivered over a unit time.

$$\eta = \frac{p_s}{T} \tag{10}$$

where p_s is the total size of delivered service packets, T is the total service time.

5 Simulation and Results Analysis

5.1 Simulation Setup

The traffic scenario in this paper is set to be a single direction road with three lanes as is shown in Fig. 2. The average velocity of each lane is set as 60 km/h, 80 km/h and 100 km/h, respectively. Based on the Greenshield's Model in traffic flow theory [10], the velocity and the density of vehicles are linearly related to the condition of uninterrupted traffic flow, i.e.:

$$v = v_f - \frac{v_f}{d_c} \cdot d \tag{11}$$

where v and d are the velocity and density of vehicles, respectively. v_f is the maximum velocity a vehicle can reach in a lane, d_c is the traffic density under congested, which is 133 vehicles/(lane·km) as mentioned in Sect. 3. For different flow velocities, the distribution of vehicle density of each lane is shown in Fig. 3, from which six driving scenarios are designed with data entered in Table 1.

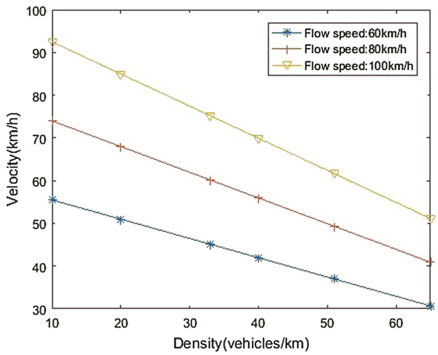

Fig. 3. Relation between velocity and density with different flow speeds.

Table 1. Density and velocity for each lane

Scenario		Average velocity (km/h)	Average density (vehicles/km)
1	Lane1	55.49	11.08
	Lane2	73.98	11.63
	Lane3	92.48	10.64
2	Lane1	50.98	22.17
	Lane2	67.97	21.61
	Lane3	84.96	21.28
3	Lane1	45.11	33.25
	Lane2	60.15	32.23
	Lane3	75.18	33.30
4	Lane1	41.95	42.12
	Lane2	55.93	41.56
	Lane3	69.92	41.23
5	Lane1	36.99	53.20
	Lane2	49.32	51.53
	Lane3	61.65	51.87
6	Lane1	30.67	66.50
	Lane2	40.90	65.03
	Lane3	51.12	48.21

The communication model is based on DSRC and the parameters of PHY layer and MAC layer are configured according to IEEE 802.11p. It operates in the 5.9 GHz band, there are one 10 MHz control channel and four 10 MHz service channels involved in this model. The transmission range is 300 m for vehicles and 600 m for RSU. Each message is 500 bits. Every vehicle randomly generates up to 7 to 12 requests and submits to the CH when entering the transmission range of the RSU.

The control group model which has no clusters is set in the simulation for the purpose of comparison with the proposed model, as shown in Fig. 4. The vehicles in the communication range of an RSU directly sends requests and information collected to RSU and wait for service packets. The RSU updates the traffic information to the database servers.

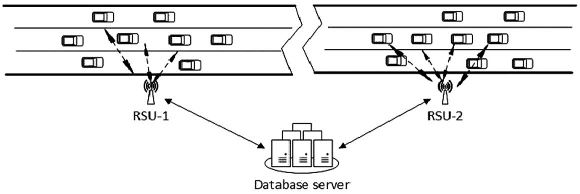

Fig. 4. Control group model.

5.2 Results Analysis

Figure 5 shows the service ratio of two different models (with and without clusters), for 6 different scenarios listed in Table 1. As we can see, the clustered system has achieved much higher and more stable service ratio than the control group in all scenarios. With clusters, the number of transmission links between vehicles and the RSU (V2I) is much reduced, resulting in much less collision than the control group. In the scenarios with higher vehicle densities, more requests are generated, and more communications process lead to the decrease of the service ratio in the control groups. However, the proposed model decreases the collision in V2I, while the cost in V2V among vehicles is much less than it in V2I as well, so the service ratio remains relatively stable. In addition, CH stores the service data, so it can serve the CMs even after they have left the coverage of the RSU as long as they are in the same cluster.

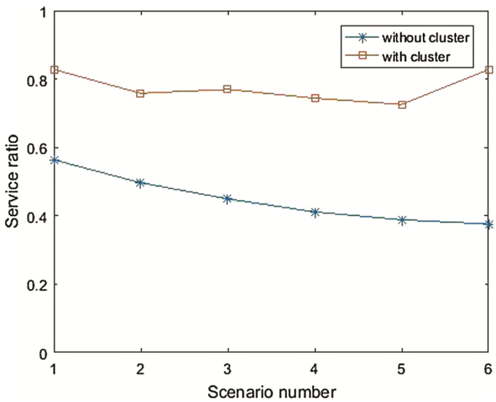

Fig. 5. Service ratio under different scenarios.

The average service delay of the two models under different scenarios is shown in Fig. 6. The delay consists of two parts: one is the time spent on delivering service data, and the other is the time spent on waiting for retransmitting the requested service due to the failed previous transmission. The RSU in the control group serves requests from all vehicles, so there is a higher probability of collision than the clustered model, hence the higher number of unsuccessful services n_{us}. In the cluster-based approach, only CH involves direct communication with RSU, which is the main reason for low latency in its V2I communications. In addition, vehicles in the same cluster requesting the same service can be served concurrently through broadcasting by CH.

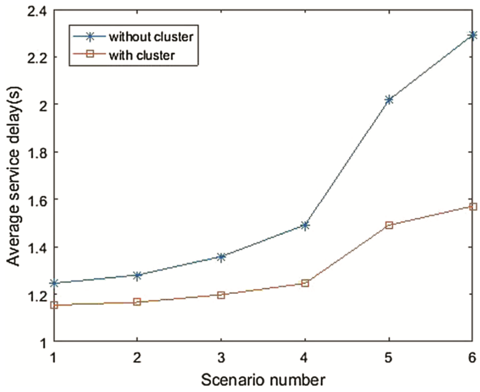

Fig. 6. Average service delay under different scenarios.

Figure 7 shows that the clustered system clearly outperforms the system without clusters in throughput for all scenarios. With the increase of vehicle densities, the transmission efficiency is affected in both groups, but the clustered model exhibits better performance than the non-clustered model in general. This is because the former can handle more requests in the same transmission duration and has fewer collisions in each cluster.

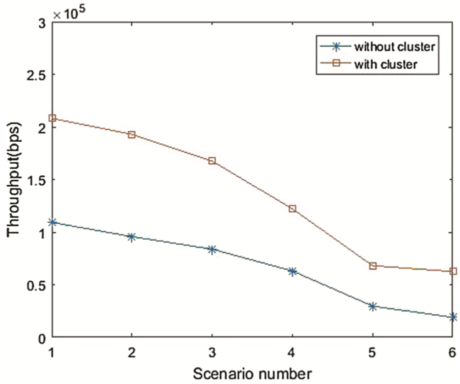

Fig. 7. Throughput under different scenarios.

6 Conclusion

In this paper, a cluster-based traffic/environmental information service model in VANETs has been proposed. The model covers the forming and maintaining of clusters and the service delivery through cluster-based V2X. The clustering and CH selection processes are based on the mobility of vehicles to ensure the stability and efficiency of data exchange and service delivery. As only CHs are responsible for direct communication with the RSU and disseminating service data to other vehicles in the network, the cluster-based V2X model presented in this work can significantly enhance service delivery efficiency through reducing transmission congestion and the average service delay. Simulation results have demonstrated a substantial performance improvement of this approach, compared to the conventional schemes without using clusters. The new evaluation metrics used in this work have also produced more realistic and accurate results for performance assessment.

Acknowledgement. The authors gratefully acknowledge the support and financial assistance provided by the National Natural Science Foundation of China under Grant Nos. 61502230 and 61073197, the Natural Science Foundation of Jiangsu Province under Grant No. BK20150960, the Natural Science Foundation of the Jiangsu Higher Education Institutions of China under Grant No. 15KJB520015.

References

1. Kumar, V., Mishra, S., Chand, N.: Applications of VANETs: present & future. Commun. Netw. **5**, 12 (2013)
2. Consortium, D.I.: DSRC technology and the DSRC industry consortium (DIC) prototype team. White Paper. Technical report (2005)
3. Leal, M.A., Röckl, M., Kloiber, B., de Ponte Müller, F., Strang, T.: Information-centric opportunistic data dissemination in vehicular Ad Hoc networks. In: Proceedings of 13th International IEEE Conference on Intelligent Transportation Systems, pp. 1072–1078 (2010)
4. Liu, K., Ng, J.K.-Y., Wang, J., Lee, V.C., Wu, W., Son, S.H.: Network-coding-assisted data dissemination via cooperative vehicle-to-vehicle/-infrastructure communications. IEEE Trans. Intell. Transp. Syst. **17**, 1509–1520 (2016)
5. Wang, Q., Fan, P., Letaief, K.B.: On the joint V2I and V2 V scheduling for cooperative VANETs with network coding. IEEE Trans. Veh. Technol. **61**, 62–73 (2012)
6. Jiang, M., Li, J., Tay, Y.: Cluster based routing protocol (CBRP). Draft-ietf-manet-cbrp-spec-01, txt, Internet Draft, IETF (1999)
7. Tal, I., Muntean, G.-M.: User-oriented cluster-based solution for multimedia content delivery over VANETs. In: Proceedings of IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), pp. 1–5 (2012)
8. Chatterjee, M., Das, S.K., Turgut, D.: WCA: a weighted clustering algorithm for mobile ad hoc networks. Cluster Comput. **5**, 193–204 (2002)
9. Artimy, M.M., Robertson, W., Phillips, W.J.: Connectivity in inter-vehicle ad hoc networks. In: Proceedings of Canadian Conference on Electrical and Computer Engineering, pp. 293–298 (2004)
10. Kuhne, R.D.: Foundations of Traffic Flow Theory I: Greenshields' Legacy-highway traffic. In: Symposium on the Fundamental Diagram: 75 Years (Greenshields 75 Symposium) (2008)