Cluster-Based Content Distribution Integrating LTE and IEEE 802.11p with Fuzzy Logic and Q-Learning

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***Abstract*—**There is an increasing demand for distributing a large amount of content to vehicles on the road. However, the cellular network is not sufficient due to its limited bandwidth in a dense vehicle environment. In recent years, vehicular ad hoc networks (VANETs) have been attracting great interests for improving communications between vehicles using infrastructure-less wireless technologies. In this paper, we discuss integrating LTE (Long Term Evolution) with IEEE 802.11p for the content distribution in VANETs. We propose a two-level clustering approach where cluster head nodes in the first level try to reduce the MAC layer contentions for vehicle-to-vehicle (V2V) communications, and cluster head nodes in the second level are responsible for providing a gateway functionality between V2V and LTE. A fuzzy logic-based algorithm is employed in the first-level clustering, and a Q-learning algorithm is used in the second-level clustering to tune the number of gateway nodes. We conduct extensive simulations to evaluate the performance of the proposed protocol under various network conditions. Simulation results show that the proposed protocol can achieve 23% throughput improvement in high-density scenarios compared to the existing approaches.

I. Introduction

With the rapid emergence of vehicular Internet of Things (IoT) applications, such as real-time traffic information update, software upgrade, and map data update, there is a demand for downloading a

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large amount of contents to the vehicles. However, it is difficult for cellular networks to support all the communications due to the following two reasons. Firstly, the vehicles could be deployed in a highly dense manner at some urban road segments. Secondly, for rural areas, the cellular network is not designed to support a large number of user terminals. In cellular networks, the spectrum efficiency drops drastically along with the increase of the user density. Therefore, the integration of infrastructure-less communication technologies with Long Term Evolution (LTE) becomes a necessity to ensure quality-of-service (QoS) for vehicles.

Vehicular ad hoc networks (VANETs) have attracted tremendous attentions in recent years. In addition to safety applications which can be achieved by vehicle-to-vehicle (V2V) communications, VANETs could also be an important part of vehicle-to-cloud communications by integrating V2V with vehicle-to-infrastructure (V2I) communications [1]–[16]. As a type of infrastructure, road side units (RSUs) provide the Internet access to VANETs. In literature, there have been many protocols discussing the problem of content distribution with vehicle-to-roadside (V2R) communications, where the vehicle mobility is a big challenge. Due to the limited link life time, it is difficult for a vehicle to download the data when driving through the coverage of an RSU. Existing approaches mainly focus on collaborative downloading in which multiple vehicles download different parts of the data and then exchange them over the VANETs until all the intended receivers acquire the data [13]–[16].

The RSU deployments are expected to be costly, and we hence consider a framework that does not rely on RSUs. A possibility is to use cellular interface installed on vehicles for providing Internet access to the VANETs. However, it is not practical to shift all communications to LTE due to both the cost of cellular transmissions and the performance concern as previously mentioned. This motivates us to introduce a hybrid architecture of LTE and IEEE 802.11p [17], which is an approved amendment to the IEEE 802.11 standard for wireless access in vehicular environments.

There are two main technical obstacles for the integration of LTE with IEEE 802.11p. Firstly, the selection of gateway nodes should take into account the overall network performance of the LTE as well as the V2V. Secondly, the route creation from a vehicle to a gateway is challenging due to vehicle mobility and varying node density. The vehicle mobility and inter-vehicle wireless link quality should be seriously accounted for the selection of a route. For certain hours or road segments, vehicles are densely deployed, and therefore the number of concurrent sending nodes is expected to be huge. In IEEE 802.11p, the increase in the number of sending nodes leads to the performance degradation due to the exponential backoff based contention scheme at the MAC layer. Different techniques have been proposed to address the V2V routing problem, such as QoS-aware routing [4], opportunistic routing [5], street-centric approach [6], RSU controlled approach [7], geographical routing [8] or clustering [9]–[12]. Although there are some studies about the hybrid architecture of LTE and IEEE 802.11p [18]–[20], the problems of performance and gateway selection in a high-density vehicular network are left under-explored.

In this paper, we propose a cluster-based protocol integrating LTE with IEEE 802.11p for the content distribution in vehicular networks. The main contributions are briefly summarized in the following.

- We propose a two-level clustering approach where the first level is used to solve the MAC layer contention in IEEE 802.11p-based V2V communications under a high-density condition, and the second level is responsible for selecting gateway nodes which bridge V2V and LTE.
- We employ a fuzzy logic-based algorithm for the selection of first-level cluster head nodes considering the vehicle velocity, the vehicle distribution, and the channel condition between vehicles. The clusters are generated in a distributed way based on the hello message exchanges, and no cluster joining/leaving message is required.
- The proposed protocol uses a Q-learning algorithm to tune the number of second-level cluster head nodes and therefore the protocol is able to quickly adapt to various scenarios with different LTE bandwidths and different vehicle densities.
- We perform extensive simulations to evaluate the proposed protocol by comparing with other baselines.

The remainder of the paper is organized as follows. Section II gives a brief outline of related work. In section III, we describe the proposed protocol in details. Simulation results are presented in section IV. Finally, we draw our conclusions in section V. The words "vehicle" and "node" are used interchangeably throughout the paper.

II. Related Work

The efficiency of content distribution in a hybrid LTE and IEEE 802.11p vehicular network depends on the LTE gateway selection and the V2V route creation. To the best of our knowledge, there is no work that jointly addresses cooperative downloading, vehicle clustering and hybrid protocols integrating LTE with V2V communications, though the literature investigates them separately.

A. Cooperative Downloading in VANETs

There are a number of studies for content downloading from RSUs. Li et al. [13] have discussed the use of broadcast communications and symbol level network coding for the content distribution in VANETs. Although broadcast communications can distribute the same content to multiple receivers, it is difficult to derive a high modulation and coding scheme which determines the transmission speed. Luan et al. [14] have proposed a large-scale infrastructure for vehicular content distribution utilizing wireless buffer devices deployed on the roadside, and a distributed algorithm to determine the content replication strategy. Some works discuss the incentives for the cooperation. Wang et al. [15] have proposed a coalition game-based cooperative protocol for the problem of popular content distribution in VANETs. In order to encourage cooperation, a multi-path forwarding scheme with reputation-based incentive has been proposed in [16]. All these studies propose to use RSUs as the gateways to the Internet, and address the content distribution problem given limited connection time between a vehicle and a stationary RSU. This paper discusses the problem of integration of LTE with V2V communications in which the gateway nodes are mobile. The proposed protocol facilitates efficient content distribution by using a distributed clustering approach which takes into account jointly the vehicle mobility, the vehicle distribution, and the link qualities between vehicles.

B. Clustering or Backbone-Based Approaches

A recent survey on the VANET clustering techniques can be found in [9]. Togou et al. [10] have proposed CDS-SVB, a connected dominating set (CDS) based stable virtual backbone creation approach which selects backbone vehicles by considering vehicle speed and spatial distribution to ensure stability as well as low dissemination delay. Since backbones are generated one-by-one (early generated backbone specify the next backbone node), the backbone formation algorithm of CDS-SVB is not fully distributed. As a result, the change of backbone vehicles occurs frequently in a highly dynamic vehicular network. In [11], the stable CDS-based routing protocol (SCRP) has been proposed based on CDS-SVB. SCRP connects the backbone vehicles at intersections with bridge vehicles which maintain the whole network information and calculate the delay for transmitting data packets over road segments. Different weights are assigned to road segments by considering the link life time, the delay, and the hop count. SCRP requires the global network topology for the backbone creation which is difficult to achieve in fast changing networks. The corresponding communication overhead has not been discussed adequately as well. MoZo, a clustering approach established on the similarity of vehicle movements, has been proposed in [12]. MoZo constructs multiple moving zones by grouping the vehicles that have similar movement patterns. Since explicit joining request and response messages are required to maintain the moving zones, the zone maintenance overhead could be large in highly dense or mobile environment in order to manage up-to-date information of the zone members at each zone captain side. The common problem of the existing approaches is the cluster maintenance overhead (cluster joining/leaving messages). Our proposed protocol solves this problem by conducting clustering using a totally distributed approach where only hello messages are used for information exchange.

C. Hybrid Protocol Integrating LTE and V2V Communications

Zhioua et al. [18] have proposed a gateway selection for a joint VANET and LTE-Advanced (LTE-A) hybrid network architecture. However, [18] is based on a strong assumption that the VANET is already clustered. Feteiha et al. [19] have investigated the performance of a cooperative vehicular relaying system over the LTE-A downlink session from the physical layer perspective. Similar hybrid architecture has also been discussed for disseminating VANET safety messages [20]. There are only a few studies about the hybrid of LTE and V2V as mentioned above, and none of these protocols address the unicast content distribution in this kind of networks. The proposed protocol can achieve better performance than the existing approaches by using a fuzzy logic-based clustering, and a Q-Learning-based gateway node selection.

III. Proposed Protocol

A. Assumption

Each node is equipped with a positioning device and two wireless interfaces, namely, LTE interface and IEEE 802.11p interface. All nodes know the road map information and the average transmission range for V2V communications as in IEEE 802.11p. Each node sends its own location information, neighbor information (the number of vehicles driving toward the same direction as in subsection III-C), and velocity information using beacon messages with a predefined interval, which is 1 second by default. We assume a connected network topology where at least one multi-hop path exists between any two nodes. As a reliable transmission is the most important requirement of content distribution, which is from an LTE base station (BS) to a vehicle, we consider unicast communications for V2V communications which are easier to conduct retransmissions as compared to broadcast communications. As shown in Fig. 1, the contents are transmitted from an LTE BS to a gateway node, and then transmitted to multiple vehicles in vicinity simultaneously using V2V communications.

B. Problem Definition and Protocol Overview

We consider the problem of sending data from the cloud to vehicles, which is very important for vehicular IoT applications.

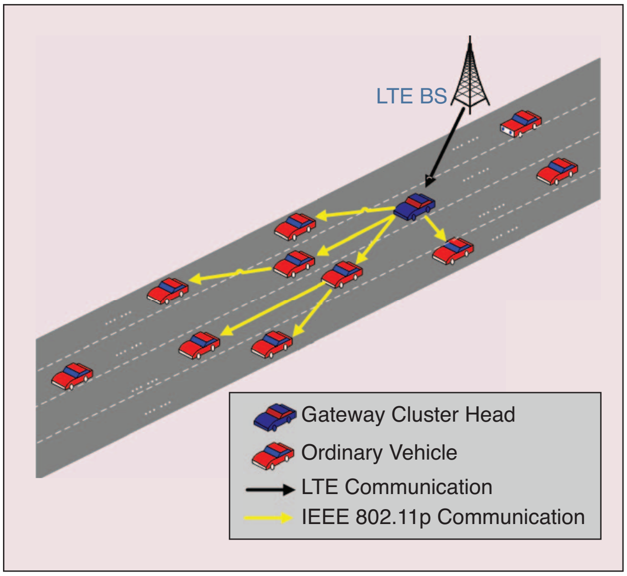

FIGURE 1 Content distribution with LTE and IEEE 802.11p.

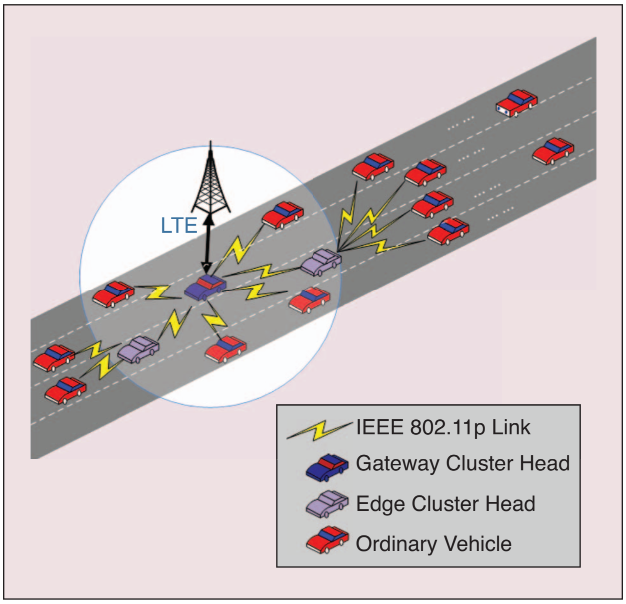

FIGURE 2 Integration of LTE and IEEE 802.11p with clustering (the edge cluster head nodes are generated by the first-level clustering, and the gateway cluster head nodes are generated by the second-level clustering).

More specifically, the problem can be simplified as the transmission from an LTE BS to vehicles.

In the proposed protocol, as shown in Fig. 2, instead of each vehicle sending data to a BS using LTE interface, only the gateway vehicles utilize LTE interface and communicate with other vehicles through V2V communications. IEEE 802.11p is used for the V2V communications, and the communications could be multi-hop. Whether a vehicle should act as a gateway or not is decided by a hierarchical clustering approach where two types of cluster head nodes are defined, specifically, edge cluster head nodes (first-level clustering) and gateway cluster head nodes (second-level clustering). Edge cluster head nodes are responsible for providing IEEE 802.11p communications between its cluster members and the gateway cluster heads. Gateway cluster heads are responsible for providing LTE communications to other vehicles.

The edge cluster head nodes are selected based on a fuzzy logic algorithm that takes into account vehicle mobility, vehicle distribution, and signal qualities between vehicles. The fuzzy logic algorithm ensures that the selected edge cluster head nodes are stable. Each edge cluster head node employs a Q-learning algorithm to decide whether working as a gateway cluster head node or not. The reward is allocated by the BS according to the number of connected vehicles. Each cluster head node (including both edge cluster head and gateway cluster head) distributes the reward to its neighbors by using V2V communications. The decision to connect to the BS directly (or to a neighboring cluster head node) is made at each cluster head node by considering the reward the node can get by performing the corresponding action. The number of gateway nodes is tuned by the Q-learning algorithm according to the number of receivers, the quality of V2V links, and the available LTE bandwidth.

C. Dynamic Clustering and Edge Cluster Head Selection

We use an approach where edge cluster heads are selected using a distributed algorithm. Cluster joining/leaving procedure is conducted with low overhead as we do not use any cluster joining/leaving messages for the maintenance of cluster member information. After cluster heads are determined, each cluster head announces the number of cluster members using the hello messages. We evaluate the suitability of a vehicle acting as cluster head by using a fuzzy logic-based approach. In the evaluation, we take into account three different factors: 1) the moving speed of vehicles, 2) the density of vehicles that are moving toward the same direction as the current vehicle, and 3) the average channel condition between the current vehicle and its neighbors. The first two factors are used to ensure that the generated cluster heads are stable. The third factor is to give a higher priority to the vehicles which could provide better wireless links to cluster members (for example, such as the buses or trucks with higher antenna can provide longer line-of-sight distance). Since the evaluation involves multiple factors, it is difficult to use a simple mathematical criterion for a fair calculation. Therefore, we use a fuzzy logic-based approach for the evaluation by combining these three factors.

The edge cluster heads are selected based on the information shared with hello messages. Each node attaches the information about its velocity and channel condition information. Upon reception of a hello message, each node calculates a competency value (fitness value for being a cluster head) for itself and each one-hop neighbor. The node which has the largest competency value in its vicinity declares itself as a cluster head using hello messages. As shown in Fig. 3, by employing the cluster head-based forwarding, multiple source nodes ($S1$, $S2$, $S3$ and $S4$) select the same nodes as the forwarder nodes, resulting in a more efficient MAC layer contention.

We generate the cluster heads by considering the connectivity between cluster heads. Each node calculates a competency value for its neighbors which are within the range of $\frac{1}{2}R$ where R is the average transmission range for V2V communications in meters. R is determined by the wireless transceivers installed at vehicles. A vehicle declares itself set as a cluster head if its competency value is the largest in the $\frac{1}{4}R$ region. This means that there would be at least two cluster head vehicles in each R distance, ensuring the connection between two neighboring cluster head vehicles is

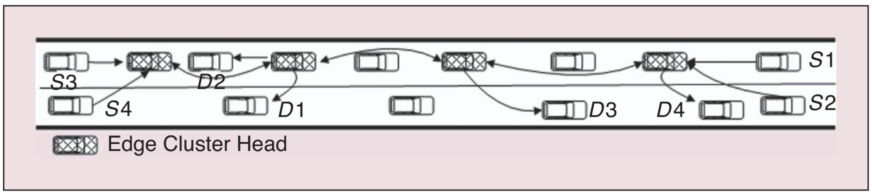

FIGURE 3 Forwarding packets with cluster head nodes ($S1$, $S2$, $S3$ and $S4$ are the source nodes; $D1$, $D2$, $D3$ and $D4$ are the corresponding destinations).

reliable. If the vehicles are uniformly distributed, there would be one cluster head for each $\frac{1}{2}R$ region.

D. Fuzzy Logic-Based Competency Calculation

The competency value calculation consists of three steps. First, the velocity factor, leadership factor, and signal quality factor are calculated for each one-hop neighbor who is within the range of $\frac{1}{2}R$. Next, we use predefined membership functions to convert the factors to fuzzy values, and use predefined fuzzy rules to calculate the final fuzzy value for each neighbor. Last, the fuzzy value is converted to a numerical value (competency value) based on fuzzy output membership function.

1) First Step—Calculating Three Factors

The velocity factor, leadership factor, and signal quality factor are calculated based on the information of hello messages received from neighbors.

Velocity Factor (VF): Upon reception of a hello message from node m, node s calculates $VF(s,m)$

$$VF(s,m) = \frac{|v(m)| - \min_{y\in N_s} |v(y)|}{\max_{y\in N_s} |v(y)|}, \tag{1}$$

where N_s is the neighbor set of node s, and $v(\cdot)$ denotes the velocity. A smaller VF indicates a lower velocity. The update of VF is conducted periodically with the interval of one second based on a weighted exponential moving average,

$$VF_i(s,m) \leftarrow (1-\alpha)\times VF_{i-1}(s,m) + \alpha \times VF_i(s,m), \tag{2}$$

where i is the interval index. $VF_{i-1}(s,m)$ and $VF_i(s,m)$ denote the previous value and current value of VF respectively. VF is initialized to 1, and α is set to 0.7 based on our simulation results.

Leadership Factor (LF): $LF(s,m)$ is calculated as

$$LF(s,m) = \frac{c(s)}{\max_{y\in N_s} c(y)}, \tag{3}$$

where $c(s)$ shows the number of vehicles moving toward the same direction as the node s. A higher LF means that the node is more suitable for being a cluster head node. The initial value of LF is 0. For every hello message reception, LF is updated using a weighted exponential moving average,

$$LF_i(s,m) \leftarrow (1-\alpha)\times LF_{i-1}(s,m) + \alpha \times LF_i(s,m). \tag{4}$$

Signal Quality Factor (SQF): For simplicity, we calculate SQF using the hello packet reception ratio. Each node maintains a counter to calculate the number of hello messages received from all neighbors located within R distance. Since the hello messages are sent during a predefined time interval (i.e., 1 second by default), each node is able to calculate the reception ratio of the hello messages. This ratio is used to estimate the channel condition, and exchanged among neighbors with hello messages. The SQF differentiates different vehicles by setting a higher evaluation value on a vehicle which has the better signal condition (for example a cluster head vehicle with the higher antenna could provide longer line-of-sight distance to cluster members and therefore could result in higher hello packet reception ratio between the cluster head and members). The SQF is initialized to 0, and updated as

$$SQF(s) = \frac{\#\text{ of hellos received from the neighbors}}{\#\text{ of hellos sent by the neighbors}},$$
$$SQF_i(s) \leftarrow (1-\alpha)\, SQF_{i-1}(s) + \alpha \times SQF_i(s). \tag{5}$$

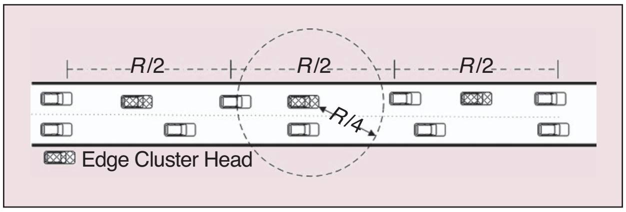

FIGURE 4 An example of edge cluster head selection.

2) Second Step—Fuzzification and Fuzzy Rules

The fuzzy membership functions are defined as shown in Fig. 5. The linguistic variables of the VF are defined as {Slow, Medium, Fast}. Similarly, the linguistic variables for the LF and SQF are defined as {Good, Fair, Poor} and {Good, Medium, Bad} respectively.

Each node calculates the rank (a competency value for being a cluster head) of each neighbor based on the IF/THEN rules as defined in Table I. The linguistic variables for the rank are defined as {Perfect, Good, Acceptable, Unpreferable, Bad, Very Bad}. For example, in Table I, Rule 1 is expressed as follows.

IF *Velocity* is Slow, *Leadership* is High, and *signal quality* is Good **THEN** *Rank* is Perfect.

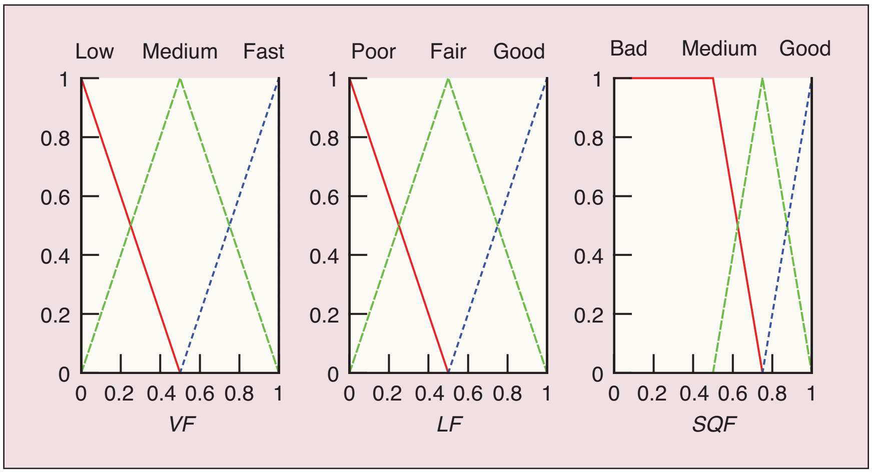

FIGURE 5 Fuzzy membership functions (left: *VF*, middle: *LF*, right: *SQF*).

It is possible that multiple rules apply at the same time. In this case, we use the Min-Max method to calculate their evaluation results. More specifically, we use the minimal value of the antecedent as the final degree for each rule. For combing the degrees of multiple rules, we take the maximal value of multiple rules as the final degree.

TABLE 1 Rule base.

	VELOCITY	LEADERSHIP	SIGNAL QUAL.	RANK
RULE1	SLOW	GOOD	GOOD	PERFECT
RULE2	SLOW	GOOD	MEDIUM	GOOD
RULE3	SLOW	GOOD	BAD	UNPREFERABLE
RULE4	SLOW	FAIR	GOOD	GOOD
RULE5	SLOW	FAIR	MEDIUM	ACCEPTABLE
RULE6	SLOW	FAIR	BAD	BAD
RULE7	SLOW	POOR	GOOD	UNPREFERABLE
RULE8	SLOW	POOR	MEDIUM	BAD
RULE9	SLOW	POOR	BAD	VERYBAD
RULE10	MEDIUM	GOOD	GOOD	GOOD
RULE11	MEDIUM	GOOD	MEDIUM	ACCEPTABLE
RULE12	MEDIUM	GOOD	BAD	BAD
RULE13	MEDIUM	FAIR	GOOD	ACCEPTABLE
RULE14	MEDIUM	FAIR	MEDIUM	UNPREFERABLE
RULE15	MEDIUM	FAIR	BAD	BAD
RULE16	MEDIUM	POOR	GOOD	BAD
RULE17	MEDIUM	POOR	MEDIUM	BAD
RULE18	MEDIUM	POOR	BAD	VERYBAD
RULE19	FAST	GOOD	GOOD	UNPREFERABLE
RULE20	FAST	GOOD	MEDIUM	BAD
RULE21	FAST	GOOD	BAD	VERYBAD
RULE22	FAST	FAIR	GOOD	BAD
RULE23	FAST	FAIR	MEDIUM	BAD
RULE24	FAST	FAIR	BAD	VERYBAD
RULE25	FAST	POOR	GOOD	BAD
RULE26	FAST	POOR	MEDIUM	VERYBAD
RULE27	FAST	POOR	BAD	VERYBAD

3) Last Step—Defuzzification

The output membership function is defined as in Fig. 6. The Center of Gravity (COG) method [21] is used for the defuzzification. As shown in Fig. 6, the value of x coordinate corresponding to the centroid is the final defuzzified value, which indicates the competency value of the node.

E. Q-learning-Based Gateway Cluster Head Selection

1) Model for Q-Learning Algorithm

We use a Q-learning algorithm to determine whether an edge cluster head should work as a gateway or not. The model for the Q-learning algorithm is defined as follows. The entire network is the environment. The edge cluster heads are the learning agents. Each agent learns the environment by exchanging hello messages with other agents. The action at each node is to select the next hop node for the data transmission. This next hop could be either an LTE BS or a neighbor edge cluster node. Therefore, the set of neighboring edge cluster head nodes is the possible actions allowed at each agent. Each node maintains a Q-Table where each Q-value $[Q(s_t, m)]$ shows the value for choosing m as the next hop to the BS at the state s_t.

2) Update of Q-Table

Each node has to maintain a Q-value for each state and action. Here, the node density (number of neighbor nodes) in the vicinity of the current node is defined as the state. For simplicity, as shown in Fig. 7, we map the number of nodes to a discrete set $\{0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0\}$, and use the corresponding value as the value of state. If the number of neighbors is 18, the value of state is 0.4. C_{min} and C_{max} are defined as 5 and 45 by default considering the transmission range of each vehicle. Action is the selection of next hop where the next hop could be BS or a neighboring edge cluster head

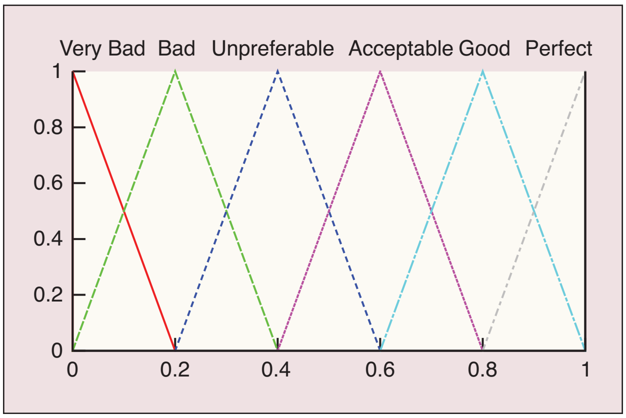

FIGURE 6 Output membership function.

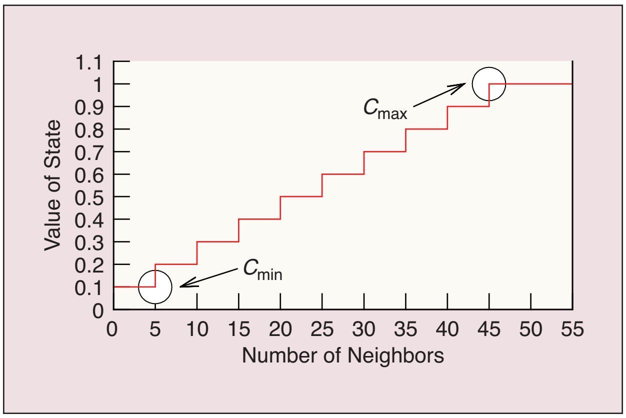

FIGURE 7 Mapping between the number of nodes and state value.

node (note that a gateway cluster head node is a special type of edge cluster node).

Q-Table is updated periodically with the interval of 1 second. Each non-gateway cluster head node updates its Q-Table upon reception of a hello message which is transmitted through the IEEE 802.11p link (each hello message contains the maximal Q-value which will be explained later in this subsection). In contrast, since each gateway cluster head is directly connected to the BS, the corresponding Q-Table is updated independent of hello messages but with the same interval. The initial value for each Q-value is 0. After reception of a hello message from node m, node l updates the corresponding Q-value to the RSU as

$$\begin{aligned} Q_l(s_t, m) \leftarrow &\ \alpha \times HRR(l, m) \\ &\times \{Rwd + \gamma \times \max_{y \in N_m} Q_m(s_{t+1}, y)\} \\ &+ (1-\alpha) \times Q_l(s_t, m), \end{aligned} \tag{6}$$

where $HRR(l, m)$ is the reception ratio of hello messages sent from node m to l. For $Q_l(s_t, m)$, the value on the left hand side of the arrow shows the new one, and the value on the right-hand side shows the previous one (the same for Eq. 8 which will be given later). N_m denotes the neighbor set of node m. s_t and s_{t+1} are the current state and the next state respectively.

The learning rate (α) is 0.7, and the discount factor (γ) is 0.9. $\max_{y \in N_m} Q_m(s_{t+1}, y)$ is the maximal Q-value of m to node RSU. The reward Rwd is calculated as

$$Rwd = \begin{cases} \min\left(\dfrac{BW_{LTE}}{BW_{11p} \times |N_{BS}|}, 1\right), & \text{if } l \in N_{BS} \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

where BW_{LTE} is the achievable downlink bandwidth of LTE (300 Mbps), and BW_{11p} is the maximum achievable throughput of IEEE 802.11p link (27 Mbps). N_{BS} denotes the set of devices connected to BS, and $\min(\cdot, \cdot)$ shows the minimum of two values. If node m is a neighbor of the BS, the reward is positive and otherwise 0. As shown in Eq. 6, the reward is discounted by two elements which are the number of hops from the BS, and the link quality [$HRR(l, m)$ in Eq. 6]. First, the algorithm discounts the reward with the hop count. Therefore, a smaller hop count results in a larger reward and larger Q-value. Second, the reward is also discounted with the packet loss probability of each link which constitutes the communication route.

The Q-value for a given action is determined by the discounted reward. If a vehicle is directly connected to the BS, the vehicle can get a positive reward. However, the value of the reward is decreased with the increase of the number of devices. Therefore, when the number of devices is large, a vehicle can increase its discounted reward by connecting to a neighboring gateway instead of directly connecting to the BS.

Each Q-value is a representation of the propriety of selecting a node as the next packet forwarding node in terms of multi-hop performance. Since the routing agent selects the node which shows the largest Q-value as the next forwarding node, the protocol is able to choose the route which is expected to achieve the best performance in terms of integration of LTE and IEEE 802.11p.

F. Route Selection at a Noncluster-Head Node

A noncluster-head node selects a neighboring cluster head node (edge cluster head or gateway cluster head) as the next hop for accessing the Internet instead of directly connecting with an LTE BS. The route selection is based on a Q-learning algorithm where the reward is distributed by the cluster head nodes. Each non-cluster-head node maintains a Q-Table in which each entry shows the value of using a neighboring cluster head node as the next hop node. Since the reward will be disseminated by a cluster head node, each non-cluster-head only has to update the corresponding information upon reception of hello messages, and then chooses the next hop which is with the largest Q-value. Since a non-cluster-head does not directly connect with the BS, the direct reward is 0, and therefore, the Q-value update at the current node c is shown as

$$\begin{aligned} Q_c(s_t, m) \leftarrow &\ \alpha \times HRR(c, m) \times \gamma \\ &\times \max_{y \in N_m} Q_m(s_{t+1}, y) \\ &+ (1-\alpha) \times Q_c(s_t, m). \end{aligned} \tag{8}$$

Here, node m is a neighboring cluster head node, and $\max_{y \in N_m} Q_m(s_{t+1}, y)$ is the discounted reward the current node can receive.

IV. Simulation Results

We used ns-2.34 [22] to conduct simulations in freeway scenarios (see Table II). We used a freeway that had two lanes in each direction [23]. The distance between any two adjacent lanes was 5 m. Nakagami propagation model was used to simulate channel fading [24]. The parameters of Nakagami Model are shown in Table III, where parameter names are the variable names in ns-2.34. Based on parameters given in [24], we set the average transmission range for V2V communications as 250 m. Although the transmission range can be up to 1000 m in IEEE 802.11p, we believe this setting is plausible for evaluating unicast protocols as longer distance could be difficult to use an efficient modulation and coding scheme.

The proposed protocol was compared with "LTE", "Random (10% GW)", "Random (10 GW)", and "CDS-SVB" [10]. "LTE"

TABLE 2 Simulation environment.

TOPOLOGY	2000 m, 4 LANES
NUMBER OF NODES	100–500
INTENDED RECEIVERS	RANDOMLY SELECTED 20% OF NODES
MAXIMUM VELOCITY	100 km/h
MOBILITY GENERATION	REF. [23]
MAC	IEEE 802.11P MAC (27 Mbps)
PROPAGATION MODEL	NAKAGAMI MODEL
SIMULATION TIME	1500 s

TABLE 3 Parameters of nakagami model.

GAMMA0_	GAMMA1_	GAMMA2_	D0_GAMMA_	D1_GAMMA_
1.9	3.8	3.8	200	500
M0_	**M1_**	**M2_**	**D0_M_**	**D1_M_**
1.5	0.75	0.75	80	200

denotes that the every vehicle uses LTE for the content distribution (all vehicles work as gateways). In "Random (10% GW)", 10 percent of the vehicles are randomly selected as gateway nodes. "Random (10 GW)" represents the case when the number of gateway nodes is fixed to 10. "CDS-SVB" uses a connected dominating set based approach to generate the gateways by taking into account vehicle velocity in the gateway selection.

Here gateway nodes are responsible for providing contents to non-gateway nodes, and it is possible for a non-gateway node to use multi-hop V2V communications to reach a gateway node. The number of LTE BSs was 1, which means that all the vehicles could be connected to the same BS. We set 20 percent of the vehicles as the intended receivers of the content. We evaluated the protocol performance for various vehicle densities, vehicle velocities, and LTE bandwidths.

In the following simulation results, the error bars indicate the 95% confidence intervals.

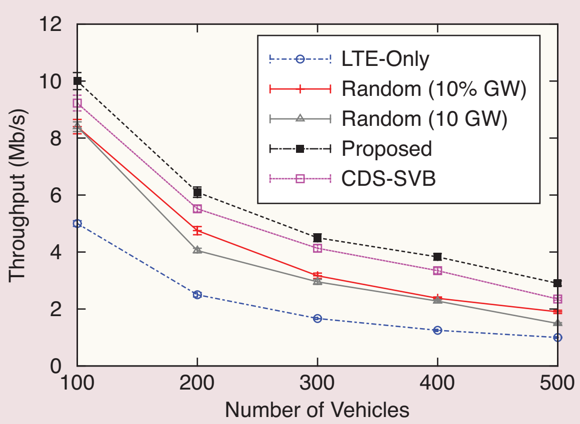

FIGURE 8 Throughput for various numbers of vehicles (20% of the vehicles are receivers of the content).

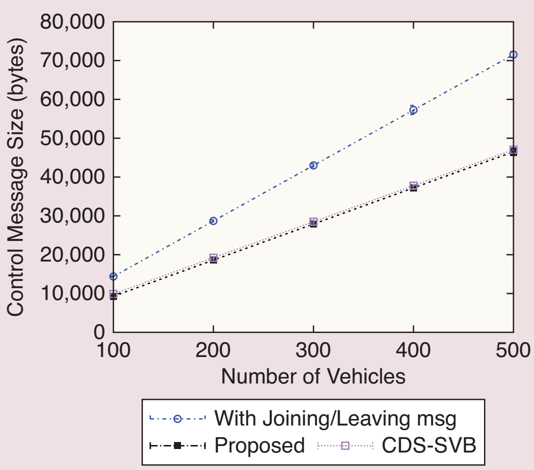

FIGURE 9 Control message size (bytes) per second for various numbers of vehicles.

A. Performance for Various Vehicle Densities

Fig. 8 shows the TCP throughput for various vehicle densities. The LTE bandwidth that can be allocated for the whole vehicular network was 100 Mbps (this is plausible considering there could be other types of user terminals in addition to the vehicles). We can observe that when the vehicle density is large, LTE cannot achieve high throughput because the bandwidth allocated for each vehicle is small. This explains the importance of utilizing V2V communications. "Random (10% GW)", "Random (10 GW)", and "CDS-SVB" cannot provide satisfactory throughput as these protocols do not take into account the link quality between a gateway node and vehicle. Since the proposed protocol considers the vehicle velocity and vehicle distribution in the gateway selection, the protocol shows 23% throughput improvement in high-density scenarios as compared to "CDS-SVB".

Fig. 9 shows the size of generated control messages (including hello messages and cluster joining/leaving messages) per second. As compared to the approaches which use explicit joining/leaving messages [12], the proposed protocol shows a significantly lower overhead. "CDS-SVB" conducts clustering of vehicles according to the vehicle velocity. In "CDS-SVB", each vehicle advertises its position information and velocity information. This overhead is similar to the proposed protocol. However, since the link qualities between vehicles are not addressed adequately in the clustering, "CDS-SVB" generates a large overhead when a link between two cluster head nodes breaks.

Fig. 10 and Fig. 11 show the number of gateway nodes, and the number of V2V hops versus the number of vehicles, respectively. With the increase of the number of gateway nodes, the available bandwidth for each gateway decreases while the route quality between a non-gateway vehicle and a gateway node improves. A smaller number (of gateway nodes) results in a higher bandwidth for each gateway but at the same time the overall network performance could drop due to the bottle neck at V2V communications (see Fig. 8). For the proposed protocol, there is no change in the number of gateways and the number of V2V hops for various numbers of vehicles. This is because 10 gateways with one-hop V2V link could provide the best performance given the joint effect of the number of gateways and the number of V2V hops. In order to explain the tradeoff between the number of gateways and the number of V2V hops, we evaluated the protocols in various LTE bandwidths in subsection IV-B.

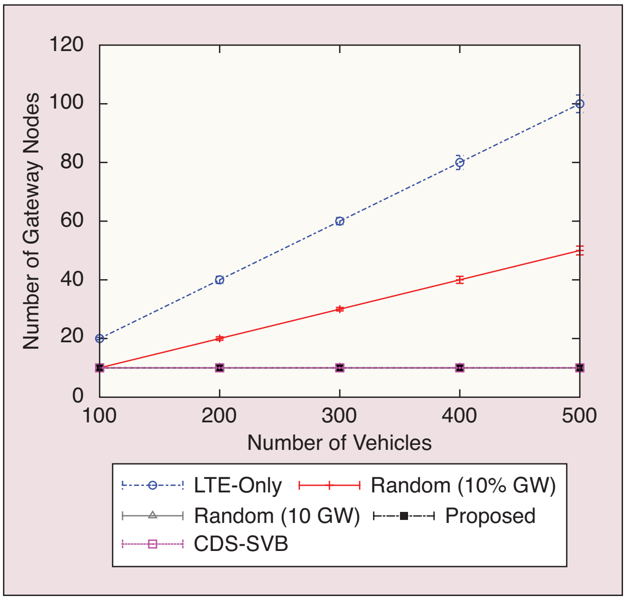

FIGURE 10 Number of gateway nodes for various numbers of vehicles ["Random (10 GW)", "CDS-SVB", and the proposed protocol overlap].

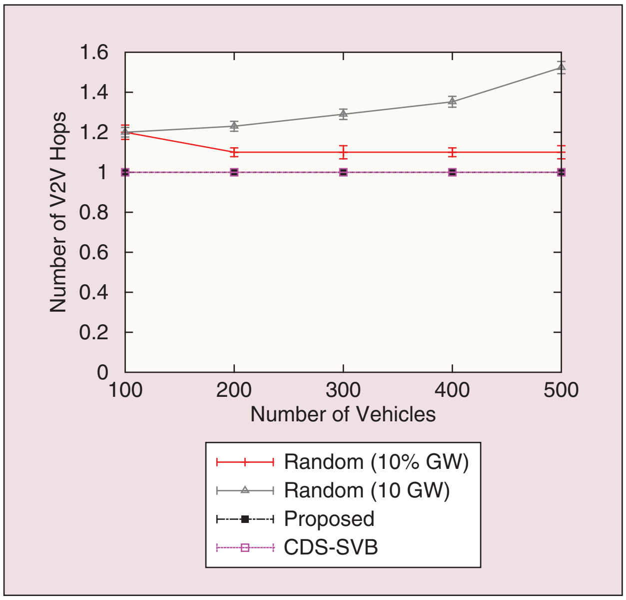

FIGURE 11 Number of V2V hops for various numbers of vehicles ("CDS-SVB", and the proposed protocol overlap).

B. Performance for Various LTE Bandwidths

Fig. 12 and Fig. 13 show the throughput and the number of gateway nodes for various LTE bandwidths respectively. The number of vehicles was 200. The proposed protocol can efficiently tune the number of gateway nodes by using the Q-learning based approach. At the first step, gateway cluster head nodes are selected with the constraint that all noncluster head nodes can reach a gateway node by one-hop V2V communications. Next, the number of gateway nodes is tuned by switching some gateway nodes to non-gateway nodes.

When the LTE throughput at each gateway node is low, the proposed protocol intends to further utilize the V2V communications by using multi-hop transmissions. More specifically, some gateway nodes will find that it is more beneficial for them to connect to a neighbor gateway instead of working as a gateway by itself. However, when the LTE throughput is enough, the proposed protocol uses only one-hop V2V communications as the reward from the BS is larger. By integrating LTE and IEEE 802.11p-based V2V communications, the proposed protocol can provide the highest performance for various conditions.

C. Performance for Various Vehicle Velocities

Fig. 14 shows the throughputs for various vehicle velocities. Since the proposed protocol can select stable cluster head nodes, the performance is satisfactory for various velocities. The performance degradation of other protocols explains the importance of considering the link quality from a non-gateway vehicle to a gateway node. As shown in Fig. 15, by taking into account the vehicle velocity and the link qualities between two neighboring cluster head nodes, the proposed cluster head selection algorithm is able to achieve a low number of V2V route changes, which contributes to high TCP throughput.

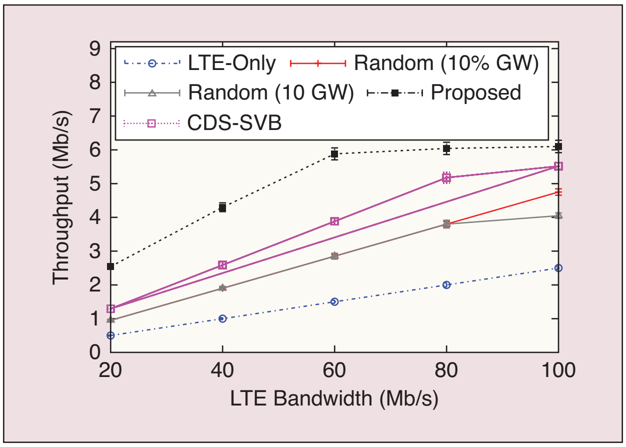

FIGURE 12 Throughput for various LTE bandwidths.

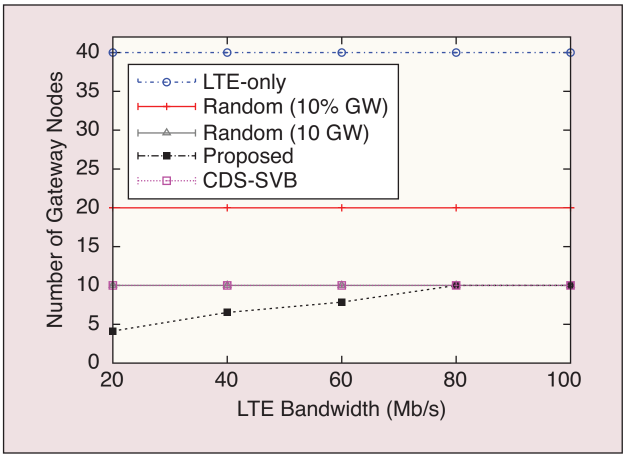

FIGURE 13 Number of gateway nodes for various LTE bandwidths ["Random (10 GW)" and "CDS-SVB" overlap].

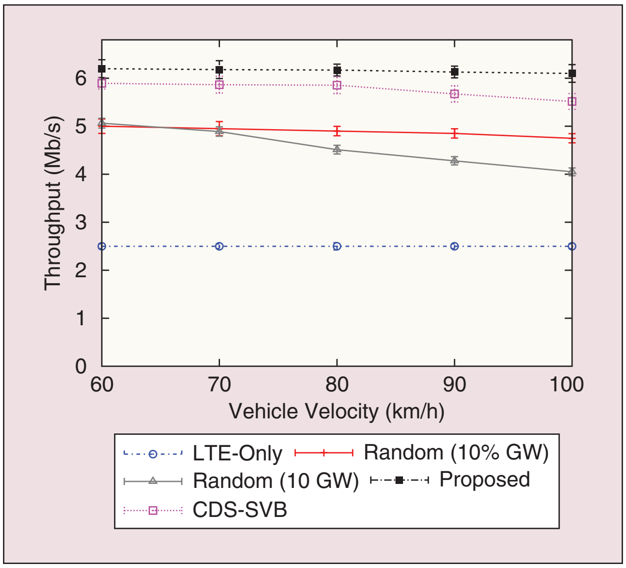

FIGURE 14 Throughput for various vehicle velocities.

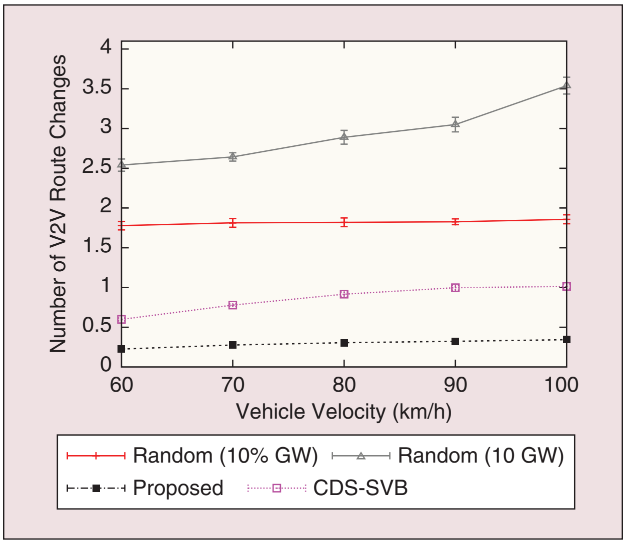

FIGURE 15 Number of V2V route changes (per second) for various vehicle velocities.

V. Conclusions

We have proposed a novel protocol for content distribution in hybrid LTE and IEEE 802.11p vehicular networks. The protocol employs a two-level clustering approach where the first-level clustering is used to solve the MAC layer contention problem of IEEE 802.11p-based V2V communications in a high-density vehicular environment, and the second-level clustering is responsible for selecting gateway nodes which bridge V2V and LTE. We used a fuzzy logic algorithm in the first-level clustering to generate a stable cluster head nodes by taking into account vehicle velocity, vehicle distribution and link quality between vehicles. We further employed a Q-learning algorithm in the second-level clustering to tune the number of gateway nodes in order to achieve high overall network performance under various network conditions. Through computer simulations, we have confirmed that the proposed protocol can provide a better performance than the existing baselines in various scenarios, achieving 23% throughput improvement in high-density scenarios.

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References

[1] J. Cheng, J. Cheng, M. Zhou, F. Liu, S. Gao, and C. Liu, "Routing in Internet of vehicles: A review," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 5, pp. 2339–2352, Oct. 2015.

[2] R. Hajlaoui, H. Guyennet, and T. Moulahi, "A survey on heuristic-based routing methods in vehicular ad-hoc network: Technical challenges and future trends," *IEEE Sensors J.*, vol. 16, no. 17, pp. 6782–6792, Sept. 2016.

[3] S. Bitam, A. Mellouk, and S. Zeadally, "Bio-inspired routing algorithms survey for vehicular ad hoc networks," *IEEE Commun. Surv. Tutorial*, vol. 17, no. 2, pp. 843–867, Sept. 2015.

[4] M. H. Eiza, T. Owens, and Q. Ni, "Secure and robust multi-constrained QoS aware routing algorithm for VANETs," *IEEE Trans. Dependable Secure Comput.*, vol. 13, no. 1, pp. 32–45, Jan.–Feb. 2016.

[5] X. Zhang, X. Cao, L. Yan, and D. K. Sung, "A street-centric opportunistic routing protocol based on link correlation for urban VANETs," *IEEE Trans. Mobile Comput.*, vol. 15, no. 7, pp. 1586–1599, July 2016.

[6] X. M. Zhang, K. H. Chen, X. L. Cao, and D. K. Sung, "A street-centric routing protocol based on microtopology in vehicular ad hoc networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 7, pp. 5680–5694, July 2016.

[7] K. Liu, J. K. Y. Ng, V. C. S. Lee, S. H. Son, and I. Stojmenovic, "Cooperative data scheduling in hybrid vehicular ad hoc networks: VANET as a software defined network," *IEEE/ACM Trans. Netw.*, vol. 24, no. 3, pp. 1759–1773, June 2016.

[8] L. Zhu, C. Li, B. Li, X. Wang, and G. Mao, "Geographic routing in multilevel scenarios of vehicular ad hoc networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 9, pp. 7740–7753, Sept. 2016.

[9] C. Cooper, D. Franklin, M. Ros, F. Safaei, and M. Abolhasan, "A comparative survey of VANET clustering techniques," *IEEE Commun. Surv. Tutorial*, vol. 19, no. 1, pp. 657–681, Sept. 2016.

[10] M. A. Togou, A. Hafid, and P. K. Sahu, "A stable minimum velocity CDS-based virtual backbone for VANET in city environment," in *Proc. IEEE Local Computer Network Conf.*, pp. 510–513, 2014.

[11] M. A. Togou, A. Hafid, and L. Khoukhi, "SCRP: Stable CDS-based routing protocol for urban vehicular ad hoc networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 5, pp. 1298–1307, May 2016.

[12] D. Lin, J. Kang, A. Squicciarini, Y. Wu, S. Gurung, and O. Tonguz, "MoZo: A moving zone based routing protocol using pure V2V communication in VANETs," *IEEE Trans. Mobile Comput.*, vol. 16, no. 5, pp. 1357–1370, May 2017.

[13] M. Li, Z. Yang, and W. Lou, "CodeOn: Cooperative popular content distribution for vehicular networks using symbol level network coding," *IEEE J. Select. Areas Commun.*, vol. 29, no. 1, pp. 223–235, Jan. 2011.

[14] T. H. Luan, L. X. Cai, J. Chen, S. Shen, and F. Bai, "Engineering a distributed infrastructure for large-scale cost-effective content dissemination over urban vehicular networks," *IEEE Trans. Veh. Technol.*, vol. 63, no. 3, pp. 1419–1435, Mar. 2014.

[15] T. Wang, L. Song, Z. Han, and B. Jiao, "Dynamic popular content distribution in vehicular networks using coalition formation games," *IEEE J. Select. Areas Commun.*, vol. 31, no. 9, pp. 538–547, Sept. 2013.

[16] C. Lai, K. Zhang, N. Cheng, H. Li, and X. Shen, "SIRC: A secure incentive scheme for reliable cooperative downloading in highway VANETs," *IEEE Trans. Intell. Transp. Syst.*, vol. 18, no. 6, pp. 1559–1574, June 2017.

[17] *IEEE Standard for Information Technology—Local and Metropolitan Area Networks Specific Requirements, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments*, IEEE Standard 802.11p, 2010.

[18] G. Zhioua, N. Tabbane, H. Labiod, and S. Tabbane, "A fuzzy multi-metric QoS-balancing gateway selection algorithm in a clustered VANET to LTE advanced hybrid cellular network," *IEEE Trans. Veh. Technol.*, vol. 64, no. 2, pp. 804–817, Feb. 2015.

[19] M. F. Feteiha and H. S. Hassanein, "Enabling cooperative relaying VANET clouds over LTE-A networks," *IEEE Trans. Veh. Technol.*, vol. 64, no. 4, pp. 1468–1479, Apr. 2015.

[20] S. Ucar, S. C. Ergen, and O. Ozkasap, "Multihop-cluster-based IEEE 802.11p and LTE hybrid architecture for VANET safety message dissemination," *IEEE Trans. Veh. Technol.*, vol. 65, no. 4, pp. 2621–2636, Apr. 2016.

[21] C. Wu, S. Ohzahata, and T. Kato, "VANET broadcast protocol based on fuzzy logic and lightweight retransmission mechanism," *IEICE Trans. Commun.*, vol. E95-B, no. 2, pp. 415–425, Feb. 2012.

[22] The Network Simulator—ns-2. (2015). [Online]. Available: http://www.isi.edu/nsnam/ns/

[23] F. Bai, N. Sadagopan, and A. Helmy, "Important: A framework to systematically analyze the impact of mobility on performance of routing protocols for adhoc networks," in *Proc. 22nd Annu. Joint Conf. IEEE Computer Communications Societies*, 2003, pp. 825–835.

[24] A. Khan, S. Sadhu, and M. Yeleswarapu, "A comparative analysis of DSRC and 802.11 over vehicular ad hoc networks," Univ. California, Santa Barbara, CA, Project Rep., pp. 1–8, 2009.