This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2019.2904036, IEEE Internet of Things Journal

Self-Adaptive Clustering and Load-Bandwidth Management for Uplink Enhancement in Heterogeneous Vehicular Networks

Tianyu Wang, *Member, IEEE*, Xun Cao, *Member, IEEE*, and Shaowei Wang, *Senior Member, IEEE*

***Abstract*—Due to the diversity of traffic scenes and high mobility of vehicles, the propagation environment between moving vehicles and road side access points can be highly dynamic, which causes unstable uplink connectivity and time-varying uplink data rates in vehicular networks. In this paper, we study the uplink performance of heterogenous vehicular networks, which integrate Dedicated Short-Range Communications (DSRC) and Long Term Evolution Vehicle-to-Everything (LTE V2X) into a single vehicular network to provide high reliability, low latency, and wide area coverage. Here, we adopt a cluster-based approach, in which DSRC and LTE are utilized to provide vehicle-to-vehicle communications between vehicles within a cluster and vehicle-to-infrastructure communications between vehicles and access points, respectively. Specifically, a self-adaptive clustering method is proposed based on the iterative self-organizing data analysis technique algorithm, in which the number of clusters can automatically adjust to the optimal value according to the mobility information. Also, a joint load-bandwidth management scheme is proposed to distribute traffic load and bandwidth resources between DSRC and LTE. Simulation results show that the proposed algorithm outperforms the traditional section-based and K-means clustering methods, and a tradeoff between average uplink data rate and signaling overhead can be achieved.**

***Index Terms*—Heterogeneous vehicular networks, 802.11p, clustering, load distribution, bandwidth allocation**

I. Introduction

Recently, major national governments and industrial organizations have begun to formulate policies and implement large-scale demonstration to push forward the development of Intelligent Transportation Systems (ITS) industry. In the U.S., the National Highway Traffic Safety Administration issued a Notice of Proposed Rulemaking for vehicle safety using vehicular communications [1], which is expected to become an effective rule in 2019. In Europe, the CAR-2-CAR Communication Consortium announces that the cooperative ITS will start initial deployment in 2019 [2]. In China, an area of 90 square kilometers in Shanghai, named National Intelligent Connected Vehicle Pilot Zone, has been put into operation to test intelligent and connected vehicles on public roads since 2016 [3]. As the key technology of ITS, the study of vehicular communications has made great progress in the last two decades, which makes vehicular networks a promising solution to address ITS issues from road safety, traffic efficiency, and innovative applications such as automatic drive and cloud-based on-board entertainment.

In the existing technologies of vehicular communications, Dedicated Short-Range Communications (DSRC) [4] and Long Term Evolution Vehicle-to-Everything (LTE V2X) [5] are two of the most popular technologies, which are standardized and supported by IEEE and 3GPP, respectively. DSRC utilizes a modified version of the familiar 802.11 standard (i.e., 802.11p) as the physical layer and medium access control layer. Many field tests have shown that it is adequate for local-area communications, such as vehicle status warning and traffic hazard warning [6], but it also suffers from unreliable connectivity in wide area due to the contention-based mechanism and limited communication range. LTE V2X is an alternative technology that can provide long-term connectivity, high data rate, and wide area coverage for vehicular communications, in which Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) communications can be implemented either by traditional uplink and downlink LTE transmissions, or by direct sidelink transmissions supported by the PC5 interface [7]. However, the centralized architecture of LTE V2X can be highly inefficient for applications requiring frequent information exchange in local areas.

In order to combine the advantages of both technologies, Heterogeneous Vehicular Networks (HetVNETs) integrating DSRC with LTE have received great attentions from both academia to industry in recent years [8], and many studies have been proposed in terms of spectrum sharing, radio resource scheduling and MAC protocol design [9–14]. On the one hand, the heterogeneous architecture increases the flexibility and diversity of vehicular communications, and thus, may enhance the potential performance of vehicular networks. On the other hand, the heterogeneous architecture also means high complexity and large overhead of network management. Therefore, multi-radio load and resource management is the key issue in HetVNETs, for which a tradeoff between network performance and management overhead should exist.

In this paper, we consider the uplink transmissions of a HetVNET using both DSRC and LTE, the propagation envi-

Manuscript received December 17, 2018; revised February 9, 2019; accepted March 1, 2019. This work was partially supported by the National Natural Science Foundation of China (61801208, 61671233, 61627804), the Jiangsu Science Foundation (BK20170650), the Postdoctoral Science Foundation of China (BX201700118, 2017M621712), the Jiangsu Postdoctoral Science Foundation (1701118B), and the the open research fund of National Mobile Communications Research Laboratory (2019D02). *(Corresponding author: Shaowei Wang.)*

T. Wang is with the School of Electronic Science and Engineering, Nanjing University, Nanjing 210023, China, and also with the National Mobile Communications Research Laboratory, Southeast University, Nanjing 210096, China (e-mail: tianyu.alex.wang@nju.edu.cn).

X. Cao and S. Wang are with the School of Electronic Science and Engineering, Nanjing University, Nanjing 210023, China (email: caoxun@nju.edu.cn, wangsw@nju.edu.cn).

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2019.2904036, IEEE Internet of Things Journal

ronment of which can be highly unstable due to the diversity of traffic scenes and high mobility of vehicles. In order to enhance the uplink performance, we consider a cluster-based approach, in which cluster members (CMs) with low data rate V2I links offload their uplink traffic to cluster heads (CHs) with high data rate V2I links via V2V communications. Thus, CHs can relay the uplink traffic within a cluster by performing high-quality two-hop transmissions. In the first hop, DSRC is utilized to provide local V2V communications from CMs to CHs. In the second hop, LTE is utilized to provide wide-area V2I transmissions from CHs to access points. Here, we consider three aspects that can highly affect the performance of the cluster-based approach. The first is how vehicles are clustered and how the clusters are updated. The second is how traffic load is distributed between the V2I transmission directly to the access points and the V2V+V2I transmission relayed by CHs. The third is how bandwidth resources are allocated to the DSRC and LTE transmissions. The main contributions are as follows:

- We present a general system model for cluster-based uplink enhancement approaches in HetVNETs, for which a combinatorial optimization problem is formulated to jointly consider the vehicle clustering and load-spectrum management problems.
- Based on the Iterative Self-Organizing Data Analysis Technique Algorithm (ISODATA), a self-adaptive clustering method is proposed, in which mobility information (vehicle location and speed) is utilized to form clusters and the number of clusters is automatically adjusted.
- The joint load distribution and bandwidth allocation problem is formulated as a numerical optimization problem, for which an efficient optimization method is proposed to optimize the load distribution and bandwidth allocation between DSRC and LTE communications.
- We provide a variety of simulation results to show that the proposed self-adaptive approach outperforms the existing section-based and K-means clustering algorithms, and a tradeoff between uplink throughput and signaling overhead can be achieved.

The rest of this paper is organized as follows: In Section II, we review the related work and point out the difference of our work from the existing literature. In Section III, we provide the system model and formulate a general combinatorial optimization problem for cluster-based uplink enhancement approaches. To solve the problem, we propose a self-adaptive clustering method based on ISODATA and a joint load-bandwidth management scheme based on numerical optimization, respectively, in Sections IV and V. Simulation results are provided in Section VI to validate the efficiency of the proposed approach. Finally, we conclude the paper in Section VII.

II. Related Works

Due to the dynamic topology of vehicular networks, clustering has been considered as an important technique in the literature of vehicular ad hoc networks (VANETs) [15]. In VANETs, clusters are usually formed to increase connectivity

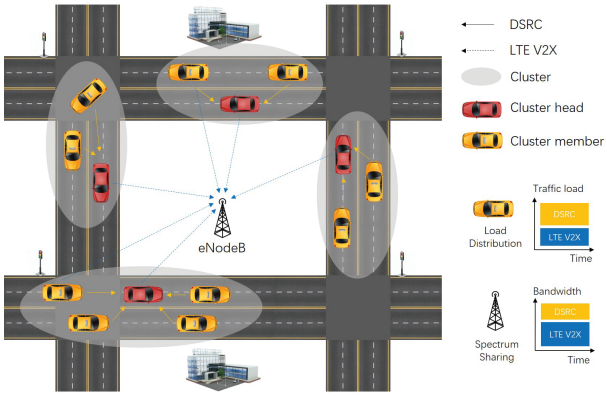


Fig. 1. Vehicle clustering and load-spectrum management for uplink enhancement in heterogenous vehicular networks.

between vehicles in a large area, for which multi-hop transmissions are performed between CHs to improve routing performance and reduce redundant transmissions [16, 17]. However, in HetVNETs, large-area connectivity can be supported by direct LTE communications between vehicles and eNodeBs, and clustering is usually introduced to further improve the uplink performance by forming high-performance two-hop transmissions consisting of both V2V and V2I links [18–20].

In [18], the authors propose a gateway selection algorithm to relay the uplink traffic of source vehicles via gateway vehicles, in which V2I channel quality, load of gateway candidates and V2V connectivity duration are jointly considered by using a fuzzy logic method. In [19], the authors develop a Markov queueing model for analyzing the performance of two-hop uplink transmissions, in terms of throughput, packet delay and packet dropping rate. They assume that vehicles in the same road section form a cluster, and the vehicle closest to the section center is selected as the CH. In [20], the authors propose a K-means clustering method as well as a CH selection algorithm based on relative mobility metric, which yield a significant improvement of safety data dissemination compared to LTE-only and DSRC-only networks.

In this paper, a cluster-based approach is proposed to offload uplink traffic from CMs to CHs via DSRC V2V transmissions, which then send the traffic to the access points via LTE V2I transmissions. Here, we jointly consider the vehicle clustering problem and the load-spectrum management problem between DSRC and LTE, for which self-adaptive methods are proposed for vehicle clustering and load-spectrum management. Compared to the existing methods, the proposed approach can adapt to the dynamic environment of vehicular networks by adjusting the number of clusters, the distribution of traffic load and the allocation of bandwidth resources. Simulation results show that the proposed cluster-based approach outperforms the traditional section-based and K-means clustering methods, and a tradeoff between uplink throughput and signaling overhead can be achieved.

III. System Model

As shown in Fig. 1, we consider the uplink of a HetVNET consisting of multiple vehicles and one eNodeB, in which

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2019.2904036, IEEE Internet of Things Journal

all vehicles are equipped with both DSRC and LTE terminals. Vehicles can transmit directly to the eNodeB via LTE communications, or they can form clusters to offload uplink traffic to the CH via DSRC V2V communications, which then relays the traffic within the corresponding cluster to the eNodeB via LTE communications. We assume that the traffic load of each vehicle can be arbitrarily distributed between the direct V2I and the indirect V2V+V2I communications, and the total uplink bandwidth can be arbitrarily allocated to the corresponding DSRC and LTE transmissions.

We denote by $S = \{1, 2, \ldots, N\}$ as the set of all vehicles. Thus, the cluster structure is given by a partition of the vehicle set S, denoted by $L = \{C_1, C_2, \ldots, C_{|L|}\}$, in which each vehicle $i \in S$ belongs to one and only one cluster $C \in L$, i.e., $\bigcup_{i=1}^{|T|} C_i = S$ and $C_i \cap C_j = \emptyset, \forall i \neq j$. We denote by $\mathcal{P}(S)$ as the set of all partitions of S, and thus, we have

$$L \in \mathcal{P}(S). \tag{1}$$

We assume that the uplink data rate requirement of each vehicle $i \in S$ is limited by R_i. As we noted, for any cluster $C \in L$, the uplink load traffic R_i of CM $i \in C$ is distributed between the V2I transmission directly to the eNodeB and the V2V+V2I transmission relayed by the CH, which is denoted by R_i^{LTE} and R_i^{DSRC}, respectively. Thus, we have

$$R_i^{LTE} + R_i^{DSRC} \leq R_i, \forall i \in S. \tag{2}$$

The total uplink bandwidth is given by W. We denote by W_0 as the bandwidth allocated to DSRC V2V transmissions and W_i as the bandwidth allocated to the LTE transmission of vehicle i. Thus, we have

$$W_0 + \sum_{i \in S} W_i \leq W. \tag{3}$$

Here, we assume that the cluster structure L, the load distribution $\{R_i^{LTE}\}_i, \{R_i^{DSRC}\}_i$ and the bandwidth allocation $\{W_i\}_i$ are periodically decided by the eNodeB at the beginning of each time period, and they stay unchanged during the entire time period.

A. Mobility Model

We assume a time-discrete model in which the system is divided into slots with equal length. The location of vehicle $i \in S$ at time slot t, denoted by $\mathbf{x}_i(t)$, is fixed during a time slot. We assume that each time period contains T time slots, within which the mobility of vehicle i can be seen as a uniform rectilinear motion with velocity $\mathbf{v}_i$. Thus, the mobility of vehicle i in a time period can be modeled by a motion function, given by

$$\mathbf{x}_i(t) = \mathbf{x}_i(1) + (t-1)\mathbf{v}_i, t = 1, 2, \ldots, T. \tag{4}$$

We assume that each vehicle $i \in S$ periodically reports its mobility information $(\mathbf{x}_i(1), \mathbf{v}_i)$ to the eNodeB at the beginning of each time period. The eNodeB calculates the trajectory $\mathbf{x}_i(1), \mathbf{x}_i(2), \ldots, \mathbf{x}_i(T)$ of each vehicle $i \in S$, and use them to calculate the optimal $L, \{R_i^{LTE}\}_i, \{R_i^{DSRC}\}_i$ and $\{W_i\}_i$ for the considered time period.

B. DSRC Model

The performance of V2V channels can be influenced by a variety of environmental factors, such as the distance between vehicles, the doppler effect, the antenna heights, the LOS conditions, etc. For simplicity without loss of generality, we adopt a disk model, in which vehicles can communicate with each other within distance D. Also, we assume that the Arbitration Inter-Frame Space (AIFS) and the length of data frame are fixed, and the corresponding spectrum efficiency of DSRC transmission is uniformly given by η_0.

In DSRC, the spectrum is shared in a distributed way by using a contention-based access scheme. The probability that a transmitting node successfully accesses the spectrum without collisions from other transmissions is a decreasing function of the number of nodes n in the network, which is given by [21]

$$P(n) = \frac{n}{m^n} \sum_{i=1}^{m-1} (m-i)^{n-1}, \forall n > 1, \tag{5}$$

in which m is the number of contention windows.

We denote by h_C as the CH of cluster $C \in L$. At any time slot t, the transmissions of CMs within distance D to CH h_C may collide with each other at h_C, the set of which is denoted by $n_C(t)$. By using the mobility information, $n_C(t)$ can be calculated by

$$\begin{aligned} n_C(t) = \big|\{j \in S \mid |\mathbf{x}_j(t) - \mathbf{x}_{h_C}(t)| \leq D \\ \text{and } j \neq h_{C'}, \forall C' \in L\}\big|, \forall C \in L. \end{aligned} \tag{6}$$

Thus, for any CM $i \in C$, the number of interfering DSRC nodes is equal to the number of nodes colliding at CH h_C, and the collision-free probability is then given by $P(n_C(t))$.

We note that each CM $i \in C$ share the same set of interfering nodes. Thus, the probability that the DSRC bandwidth is successfully occupied by CM i is given by $P(n_C(t))/n_C(t)$ [22]. Therefore, the DSRC V2V capacity of any CM $i \in C$ at time slot t is given by

$$C_i^{V2V}(t) = \frac{\eta_0 W_{DSRC}}{n_C(t)} P(n_C(t)). \tag{7}$$

Since the DSRC V2V capacity during a time period is limited by the minimal capacity in each time slot, the DSRC V2V capacity of any CM $i \in C$ is given by

$$C_i^{V2V} = \min_t C_i^{V2V}(t). \tag{8}$$

C. LTE Model

We assume that all vehicles can communicate with the eNodeB. For simplicity without loss of generality, we assume that the spectrum efficiency of V2I channel is unchanged within a time period, which is denoted by η_i for vehicle $i \in S$. In practice, parameter η_i can be estimated by the eNodeB based on the channel measurements of vehicle i from previous time periods. To simplify our problem, we assume that the vehicle $i \in C$ with the highest V2I spectrum efficiency η_i is selected as the CH h_C in each time period, i.e., $h_C = \arg\max_{i \in C} \eta_i, \forall C \in L$. We denote by S_{CH} and S_{CM} as the set of CHs and CMs, respectively, i.e.,

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2019.2904036, IEEE Internet of Things Journal

$S_{CH} = \{h_{C_1}, \ldots, h_{C_{|L|}}\}$ and $S_{CM} = S \setminus S_{CH}$. The LTE V2I capacity of vehicle $i \in S$ is given by

$$C_i^{V2I} = \eta_i W_i. \tag{9}$$

D. Problem Formulation

Here, we consider the optimal cluster structure and load-bandwidth distribution that maximize the total throughput of the considered HetVNETs, which is formulated as follows:

$$\max_{L, W_i, R_i^{LTE}, R_i^{DSRC}} \sum_{i=1}^{N} \left(R_i^{LTE} + R_i^{DSRC}\right), \tag{10a}$$

$$\text{s.t. } R_i^{DSRC} \leq C_i^{V2V}, \forall i \in S, \tag{10b}$$

$$\sum_{i \in C} R_i^{DSRC} + R_{h_C}^{LTE} \leq C_{h_C}^{V2I}, \forall C \in L, \tag{10c}$$

$$R_i^{LTE} \leq C_i^{V2I}, \forall i \in S, \tag{10d}$$

$$\text{constraints } (1), (2), (3), \tag{10e}$$

in which constraints (10b) and (10c) guarantee the uplink data rate of the V2I transmission directly to the eNodeB, and constraint (10d) guarantees the uplink data rate of the V2V+V2I transmission relayed by CHs. Due to the combinatorial property of the cluster structure L, problem (10) is generally NP-hard. In this paper, we adopt a two-step approach to solve the problem, in which the vehicle clustering problem and the corresponding load-bandwidth management problem are solved separately. Note that the optimal cluster structure and load-bandwidth distribution should be updated periodically, as the network parameters will change with the movement of vehicles.

IV. Self-Adaptive Clustering Based on Mobility Information

In cluster-based approaches, the number of clusters can highly effect the performance of DSRC V2V and LTE V2I transmissions. If a small number of clusters is formed, a large number of vehicles become CMs, which need to compete for the DSRC bandwidth to offload their uplink traffic to CHs. Thus, the DSRC performance is degraded due to the increasing collisions among V2V transmissions. If a large number of clusters is formed, the number of vehicles within a cluster is decreased. Thus, the LTE performance of CHs is degraded due to the decreasing diversity of V2I channels within a cluster. In order to optimize the uplink performance, the number of clusters should be dynamically adjusted such that the performance of DSRC and LTE transmissions can be balanced. However, in traditional K-means clustering methods, the number of clusters is a predefined parameter that cannot be changed. Therefore, we propose a self-adaptive clustering method, in which the number of clusters is dynamically adjusted according to the mobility information.

A. General Description

ISODATA is first proposed to facilitate the modelling and tracking of weather patterns, which extends the traditional K-means algorithm by self-adaptively updating the number of clusters in each iteration [23–25]. In the K-means algorithm, samples are assigned to the cluster with the closest cluster center in each iteration, and the cluster centers then update according to the newly formed clusters. The iterative process continues until the clusters become stable. Compared to the K-means algorithm, three additional procedures are introduced in ISODATA, i.e., cluster elimination, cluster unification and cluster division. We explain these procedures as follows:

- Cluster elimination: If the number of nodes within a cluster is below a threshold, the cluster is eliminated and the corresponding nodes are assigned to other clusters with the closest cluster center. Cluster elimination can accelerate the iterative process by eliminating the clusters with few nodes.
- Cluster unification: If the distance between two cluster centers is below a threshold, the two corresponding clusters are merged into a single cluster containing all nodes of the two clusters. Cluster unification can decrease the number of clusters when clusters are close to each other.
- Cluster division: If the average distance to the cluster center of the nodes in a cluster is above a threshold, the cluster is split into two new clusters, the centers of which are calculated according to the original cluster center and the standard deviation of the distance to the original cluster center. The nodes of the original cluster are assigned to the new clusters according to their distances to the new cluster centers. Cluster division can increase the number of clusters when the nodes in the same cluster are far from each other.

In the proposed clustering algorithm, we extend the basic ISODATA to the T-dimensional mobility data $\mathbf{X}_i = (\mathbf{x}_i(1), \mathbf{x}_i(2), \ldots, \mathbf{x}_i(T))$. In addition, the three procedures in the original ISODATA are modified according to the considered problem given in Subsection III-D. To simplify our notations, the location $\mathbf{x}_i(t)$ of a vehicle i at a slot t is always treated as a scalar in this section.

B. Definitions

We first give some definitions that will be used in the proposed clustering algorithm. We denote by $\mathbf{X}_C = (\mathbf{x}_C(1), \mathbf{x}_C(2), \ldots, \mathbf{x}_C(t))$ as the trajectory of the center vehicle of cluster $C \subseteq S$, w, the t-th element of which is defined by the geometrical center of vehicles in cluster C at slot t, given by

$$\mathbf{x}_C(t) = \frac{1}{|C|} \sum_{i \in C} \mathbf{x}_i(t). \tag{11}$$

Thus, the center vehicle $\mathbf{X}_C$ represents the mean trajectory of vehicles in cluster C.

We denote by $D(\mathbf{X}_i, \mathbf{X}_j)$ as the distance between two vehicles $\mathbf{X}_i$ and $\mathbf{X}_j$, which is defined by the Euclidean distance between the trajectory vectors $\mathbf{X}_i$ and $\mathbf{X}_j$ in T dimension space, given by

$$D(\mathbf{X}_i, \mathbf{X}_j) = \sqrt{\sum_{t=1}^{T} |\mathbf{x}_i(t) - \mathbf{x}_j(t)|^2}. \tag{12}$$

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2019.2904036, IEEE Internet of Things Journal

Thus, the distance $D(\mathbf{X}_i, \mathbf{X}_j)$ measures the similarity between vehicle i and vehicle j, and the distance $D(\mathbf{X}_{C_a}, \mathbf{X}_{C_b})$ measures the similarity between cluster C_a and cluster C_b.

We denote by $D(C)$ as the radius of cluster $C \subseteq S$, which is defined by the average Euclidean distance between the trajectory vectors of vehicles in cluster C and the center vehicle, given by

$$D(C) = \frac{1}{|C|} \sum_{i \in C} \sqrt{\sum_{t=1}^{T} |\mathbf{x}_C(t) - \mathbf{x}_i(t)|^2}. \tag{13}$$

Also, we denote by $\boldsymbol{\sigma}(C) = (\sigma_1(C), \sigma_2(C), \ldots, \sigma_T(C))$ the fluctuation of cluster $C \subseteq S$, the t-th element of which is defined by the standard deviation of the locations $\mathbf{x}_i(t)$ of vehicles $i \in C$ at slot t, given by

$$\sigma_t(C) = \sqrt{\frac{1}{|C|} \sum_{i \in C} |\mathbf{x}_C(t) - \mathbf{x}_i(t)|^2}. \tag{14}$$

Thus, the radius $D(C)$ measures how the vehicles in cluster C deviate from the center vehicle, and the fluctuation $\boldsymbol{\sigma}(C)$ measures how the vehicles in cluster C deviate from each other.

As we noted, the distance between CMs and the CH should be limited within D to maintain the V2V connectivity. Formally, we say cluster $C \subseteq S$ is feasible if

$$\max_{i \in C, 1 \le t \le T} |\mathbf{x}_i(t) - \mathbf{x}_{h_C}(t)| \le D. \tag{15}$$

C. Cluster Elimination

As we noted, decreasing the size of clusters can protect DSRC transmissions by decreasing the number of competing CMs. In addition, in rural areas with low-density traffic, vehicles can only form small clusters or even singular clusters due to the sparse distribution of vehicles. Thus, the size of cluster should not be limited by a minimal value as in the original ISODATA.

Cluster C is eliminated if it is not feasible, i.e., constraint (15) is not satisfied. The corresponding vehicles in cluster C should be properly assigned to other clusters. For any vehicle $i \in C$, we denote by C_i^* as the cluster that is closest to vehicle i, i.e.,

$$C_i^* = \underset{C' \in L, C' \neq C}{\arg\min} \; D(\mathbf{X}_{C'}, \mathbf{X}_i). \tag{16}$$

We assign vehicle i to cluster C_i^* if the newly formed cluster $\hat{C}_i^* = C_i^* \cup i$ is a feasible cluster. Otherwise, vehicle i forms a singular cluster $\{i\}$ containing itself.

D. Cluster Unification

Cluster unification merges two clusters that are similar to each other into a single cluster. As we noted, as the number of vehicles within a cluster is increased, the LTE V2I performance of the CH is improved due to increasing diversity of V2I channels. While at the same time, the DSRC V2V performance is degraded due to the increasing collision among V2V transmissions. For any cluster C, the V2I channel capacity of CH h_C is an increasing function of the cluster size $|C|$, which is approximated by a log function $\log(1+|C|)$. The V2V channel capacity for CMs in C is a decreasing function of the average number of colliding vehicles $n_C = \sum_{t=1}^{T} n_C(t)/T$, which is approximated by a negative exponent function e^{-n_C}. Thus, we propose a unification criterion that is related to both $|C|$ and n_C.

For any two disjoint clusters $C_a, C_b \subseteq S$, we denote by $C_u = C_a \cup C_b$ as the potential cluster formed by the cluster unification of C_a and C_b. We define the effective distance between C_a and C_b as follows:

$$\begin{aligned} & D^*(\mathbf{X}_{C_a}, \mathbf{X}_{C_b}) \\ = & \frac{|C_a| \log(1+|C_a|) + |C_b| \log(1+|C_b|)}{|C_u| \log(1+|C_u|)} \\ & \times \frac{|C_a| e^{-n_{C_a}} + |C_b| e^{-n_{C_b}}}{|C_u| e^{-n_{C_u}}} \times D(\mathbf{X}_{C_a}, \mathbf{X}_{C_b}). \end{aligned} \tag{17}$$

We note that the effective distance $D^*(\mathbf{X}_{C_a}, \mathbf{X}_{C_b})$ is smaller than the distance $D(\mathbf{X}_{C_a}, \mathbf{X}_{C_b})$ if the V2I and V2V performance are improved by the cluster unification.

Cluster C_a, and cluster C_b are unified if the effective distance $D^*(\mathbf{X}_{C_a}, \mathbf{X}_{C_b})$ is below a threshold θ_D, i.e.,

$$D^*(\mathbf{X}_{C_a}, \mathbf{X}_{C_b}) \le \theta_D, \tag{18}$$

and the potential cluster C_u is a feasible cluster. Otherwise, the unification is not performed.

E. Cluster Division

Cluster division split a cluster with deviating CMs into two disjoint clusters. We denote by $\delta_{max}(C)$ as the maximum fluctuation of cluster $C \subseteq S$ during the time period, which is given by

$$\delta_{max}(C) = \max_{1 \le t \le T} \delta_t(C), \tag{19}$$

and the corresponding slot is denoted by $t^*(C)$, i.e.,

$$t^*(C) = \underset{1 \le t \le T}{\arg\max} \, \delta_t(C). \tag{20}$$

Cluster C is divided into cluster C_a and cluster C_b if the radius is above the average radius of all clusters, i.e.,

$$D(C) \ge \frac{1}{N} \sum_{C' \in L} |C'| D(C'). \tag{21}$$

We denote by $\hat{\mathbf{X}}_{C_a}$ and $\hat{\mathbf{X}}_{C_b}$ as the virtual center vehicles of cluster C_a and cluster C_b, the t-th element of which are given by

$$\hat{\mathbf{x}}_{C_a}(t) = \begin{cases} \mathbf{z}_C(t) + \delta_{max}(C), & t = t^*(C), \\ \mathbf{z}_C(t), & t \neq t^*(C), \end{cases} \tag{22}$$

and

$$\hat{\mathbf{x}}_{C_b}(t) = \begin{cases} \mathbf{z}_C(t) - \delta_{max}(C), & t = t^*(C), \\ \mathbf{z}_C(t), & t \neq t^*(C). \end{cases} \tag{23}$$

Vehicle $i \in C$ is assigned to C_a if it is closer to $\hat{\mathbf{X}}_{C_a}$, i.e.,

$$D(\hat{\mathbf{X}}_{C_a}, \mathbf{X}_i) < D(\hat{\mathbf{X}}_{C_b}, \mathbf{X}_i). \tag{24}$$

Otherwise, it is assigned to cluster C_b.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2019.2904036, IEEE Internet of Things Journal

F. Self-Adaptive Vehicle Clustering Algorithm

Algorithm 1 Self-Adaptive Vehicle Clustering Algorithm

Initialize the expected number of clusters K and the maximal number of iterations M.
Set the number of initial clusters N_0.
Calculate the initial cluster structure $L_0 = \{C_1^0, C_2^0, \ldots, C_{N_0}^0\}$: Randomly select N_0 vehicles with trajectories $\mathbf{X}_{1'}, \mathbf{X}_{2'}, \ldots, \mathbf{X}_{N_0'}$ as the virtual center vehicles of each cluster in L_0; Assign vehicle $i \in S$ to cluster C_j^0 if $\mathbf{X}_{j'}$ is the closest center vehicle to vehicle i, i.e., $D(\mathbf{X}_i, \mathbf{X}_{j'}) \geq D(\mathbf{X}_i, \mathbf{X}_{k'}), \forall 1 \leq k \leq N_0$.
for $m = 1, 2, \ldots$ **do**
  Set the number of clusters $N_m = N_{m-1}$ at the m-th iteration.
  Calculate the cluster structure $L_m = \{C_1^m, C_2^m, \ldots, C_{N_m}^m\}$ at the m-th iteration: Set $\mathbf{X}_{C_1^{m-1}}, \mathbf{X}_{C_2^{m-1}}, \ldots, \mathbf{X}_{C_{N_{m-1}}^{m-1}}$ as the virtual center vehicles of each cluster in L_m; Assign vehicle $i \in S$ to cluster C_j^m if $\mathbf{X}_{C_j^{m-1}}$ is the closest center vehicle to vehicle i, i.e., $D(\mathbf{X}_i, \mathbf{X}_{C_j^{m-1}}) \geq D(\mathbf{X}_i, \mathbf{X}_{C_k^{m-1}}), \forall 1 \leq k \leq N_{m-1}$.
  if $\{m$ is odd and $N_m \leq 2K\}$ **then**
    Calculate the radius $D(C_i^m)$ and fluctuation $\boldsymbol{\sigma}(C_i^m)$ of each cluster $C_i^m \in L_m$ as in (13) and (14).
    for each cluster $C_i^m \in L_m$ **do**
      if (21) is satisfied **then**
        Divide cluster C_i^m as in Section IV-E and update N_m and L_m.
      end if
    end for
  end if
  if $\{m$ is odd and $N_m > 2K\}$ or $\{m$ is even$\}$ **then**
    Calculate the effective distance $D^*(\mathbf{X}_{C_i^m}, \mathbf{X}_{C_j^m})$ for each cluster pair in L_m as in (17), and list them in ascending order, i.e., $D^*(\mathbf{X}_{C_{i_1}^m}, \mathbf{X}_{C_{j_1}^m}), D^*(\mathbf{X}_{C_{i_2}^m}, \mathbf{X}_{C_{j_2}^m}), \ldots$
    for $k = 1, 2, \ldots$ **do**
      if (18) is satisfied **then**
        Unify cluster $C_{i_k}^m$ and cluster $C_{j_k}^m$ as in Section IV-D and update N_m and L_m.
      end if
    end for
  end if
  for each $C_i^m \in L_m$ **do**
    if cluster C_i^m is not feasible as in (15) **then**
      Eliminate cluster C_i^m as in Section IV-C and update N_m and L_m.
    end if
  end for
end for

The proposed self-adaptive clustering algorithm is formally given as in Algorithm 1. As we can see, an expected number of clusters is predefined by K, which is utilized to avoid unexpected cluster structures with too many or too few clusters. Specifically, the number of clusters of the output cluster structure is strictly limited within $[K/2, 2K]$. In practice, parameter K can be approximated by analyzing historical data. Also, we have the maximal number of iterations given by M, which is limited due to the computational complexity of the algorithm.

In the iterative process, the initial number of clusters and the corresponding cluster structure are given randomly. In each iteration, vehicles are reassigned based on their distances to the center vehicles of previous clusters. Then, cluster divisions, cluster unifications, and cluster eliminations are performed sequentially to adjust the cluster structure. Specifically, cluster eliminations are performed at the end of each iteration to avoid infeasible cluster structures, while cluster divisions and cluster unifications are performed alternately. If the iteration index m is odd and the number of clusters is not too many (i.e., $N_m \leq 2K$), cluster divisions are performed for clusters whose radius is above the average radius of all clusters. If the iteration index m is even or the number of clusters is too many (i.e., $N_m > 2K$), cluster unifications are performed in ascending order of the effective distance, such that clusters closer to each other are unified with higher priority. Note that the algorithm should be performed periodically as the vehicles move along the road, but the initial cluster structure L_0 can be replaced by the calculated cluster structure L_M in the last time period.

V. Joint Load Distribution and Bandwidth Allocation

Given the cluster structure $L = \{C_1, C_2, \ldots, C_{|L|}\}$ satisfying (1), the considered problem (10) is reduced to a joint load distribution and bandwidth allocation problem, which is given by

$$\max_{W_i, R_i^{LTE}, R_i^{DSRC}} \sum_{i=1}^{N} \left(R_i^{LTE} + R_i^{DSRC}\right), \tag{25a}$$

$$\text{s.t. } R_i^{DSRC} \leq C_i^{V2V}, \forall i \in S, \tag{25b}$$

$$\sum_{i \in C} R_i^{DSRC} + R_{h_C}^{LTE} \leq C_{h_C}^{V2I}, \forall C \in L, \tag{25c}$$

$$R_i^{LTE} \leq C_i^{V2I}, \forall i \in S, \tag{25d}$$

$$R_i^{LTE} + R_i^{DSRC} \leq R_i, \forall i \in S, \tag{25e}$$

$$\sum_{i=0}^{N} W_i \leq W. \tag{25f}$$

In this section, we decompose problem (10) into three subproblems as in the following subsections.

A. Optimal Load Distribution

Theorem 1. *Given the bandwidth allocation $W_0, W_1, \ldots, W_N$ satisfying (25f), the optimal load distribution R_i^{LTE*}, R_i^{DSRC*} of each vehicle $i \in S$ in problem (25) is given as follows:*

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2019.2904036, IEEE Internet of Things Journal

- *If vehicle i is the CH of cluster $C \in L$, i.e., $i = h_C$, we have*
$$R_{h_C}^{LTE*} = \min\left\{R_{h_C}, C_{h_C}^{V2I}\right\}, \tag{26}$$
and
$$R_{h_C}^{DSRC*} = 0. \tag{27}$$
- *If vehicle i is a CM of cluster $C \in L$, i.e., $i \in S_{CM} \cap C$, we define $C_{h_C}^{V2I,left} = C_{h_C}^{V2I} - R_{h_C}^{LTE*}$ as the total LTE V2I capacity left for relaying the uplink traffic of CMs in cluster C. For any CM $j \in C$, we define $\bar{R}_j^{LTE} = \min\{R_j, C_j^{V2I}\}$ as the upper bound of the LTE load. Also, we define $\bar{R}_j^{DSRC} = \min\{R_j - \bar{R}_j^{LTE}, C_j^{V2V}\}$ as the upper bound of the DSRC load when the LTE load is maximized, and list them in ascending order $\bar{R}_{j_1}^{DSRC} \leq \bar{R}_{j_2}^{DSRC} \leq \ldots \leq \bar{R}_{j_{|C|-1}}^{DSRC}$. Thus, we have*
$$R_i^{LTE*} = \bar{R}_j^{LTE}, \tag{28}$$
and
$$R_i^{DSRC*} = \begin{cases} \bar{R}_i^{DSRC}, & A_1 > 0, \\ \bar{R}_i^{DSRC}, & A_1 \leq 0 \text{ and } j(i) < j_k \\ A_2, & A_1 \leq 0 \text{ and } j(i) = j_k, \\ 0, & A_1 \leq 0 \text{ and } j(i) > j_k \end{cases} \tag{29}$$
in which $A_1 = C_{h_C}^{V2I,left} - \sum_{j=j_1}^{j_{|C|-1}} \bar{R}_j^{DSRC}$, $A_2 = C_{h_C}^{V2I,left} - \sum_{j=j_1}^{j_{k-1}} \bar{R}_j^{DSRC}$, and j_k satisfies $\sum_{j=j_1}^{j_{k-1}} \bar{R}_j^{DSRC} < C_{h_C}^{V2I,left}$ and $\sum_{j=j_1}^{j_k} \bar{R}_j^{DSRC} \geq C_{h_C}^{V2I,left}$.

Proof. Equations (26) and (27) can be easily proved, since CHs can only use LTE V2I transmissions. We define $R_i^{uplink} = R_i^{LTE} + R_i^{DSRC}$ as the total uplink throughput of CM $i \in S_{CM}$. Thus, by substituting the bandwidth allocation $W_0, W_1, \ldots, W_N$, the load distribution (26) and (27), and R_i^{uplink} into problem (25), we have

$$\max_{R_i^{LTE}, R_i^{uplink}} \sum_{i \in S_{CM}} R_i^{uplink}, \tag{30a}$$
$$\text{s.t. } R_i^{uplink} \leq A_3, \forall i \in S_{CM}, \tag{30b}$$
$$\sum_{i \in C \cap S_{CM}} R_i^{uplink} \leq A_4, \forall C \in L, \tag{30c}$$
$$R_i^{LTE} \leq \min\left\{R_i, C_i^{V2I}\right\}, \forall i \in S_{CM}. \tag{30d}$$

in which $A_3 = \min\left\{C_i^{V2V} + R_i^{LTE}, R_i\right\}$ and $A_4 = C_{h_C}^{V2I,left} + \sum_{i \in C \cap S_{CM}} R_i^{LTE}$. As we see in problem (30), the objective function (30a) is maximized only if the LTE load R_i^{LTE} of each CM $i \in S_{CM}$ is maximized, and thus, equation (28) is proved. By substituting (28) into problem (30), we have

$$\max_{R_i^{DSRC}} \sum_{i \in S_{CM}} R_i^{DSRC}, \tag{31a}$$
$$\text{s.t. } R_i^{DSRC} \leq \bar{R}_j^{DSRC}, \forall i \in S_{CM}, \tag{31b}$$
$$\sum_{i \in C \cap S_{CM}} R_i^{DSRC} \leq C_{h_C}^{V2I,left}, \forall C \in L, \tag{31c}$$

As we see in problem (31), the objective function (31a) is maximized only if the sum DSRC load $\sum_{i \in C \cap S_{CM}} R_i^{DSRC}$ in each cluster $C \in L$ is maximized, and thus, and equation (29) is proved. Therefore, Theorem 1 is proved. □

As we can see from Theorem 1, in order to maximize the total uplink throughput for a given bandwidth allocation, each CM $i \in S_{CM}$ first utilizes its allocated bandwidth W_i to transmit as much traffic as possible via LTE V2I transmissions, and then utilizes the DSRC bandwidth W_0 to offload the rest traffic to its CH. Also, each CH $i \in S_{CH}$ first utilizes its allocated bandwidth W_i to transmit its own traffic R_{h_C} via LTE V2I transmission and then distribute the unutilized LTE V2I capacity to relay the DSRC traffic of its CMs.

B. Optimal LTE Bandwidth Allocation

Lemma 1. *Given the DSRC bandwidth $W_0 \leq W$ and the total LTE bandwidth $W_C \leq W - W_0$ of cluster $C \in L$, we define $\bar{L}_i^{DSRC} = \min\{R_i, C_i^{V2V}\}$ as the upper bound of CM i's DSRC load, and $W_C^{LTE} = (R_{h_C} + \sum_{i \in S_{CM} \cap C} \bar{L}_i^{DSRC})/\eta_{h_C}$ as the maximal LTE bandwidth required by the CH. Also, we define $\bar{L}_i^{LTE} = R_i - \bar{L}_i^{DSRC}$ as the upper bound of CM i's LTE load when the DSRC load is maximized, and list the LTE spectrum efficiency of vehicles in cluster C in descending order $\eta_{h_C} \geq \eta_{j_1} \geq \eta_{j_2} \geq \ldots \geq \eta_{j_{|C|-1}}$. Thus, we have*

- *If $W_C \leq W_C^{LTE}$, the optimal LTE bandwidth allocation of cluster C is given by*
$$W_i^* = \begin{cases} W_C, & i = h_C, \\ 0, & i \in C \cap S_{CM}. \end{cases} \tag{32}$$
- *If $W_C > W_C^{LTE}$, the optimal LTE bandwidth allocation of cluster C is given by*
$$W_i^* = \begin{cases} W_C^{LTE}, & i = h_C, \\ \bar{L}_i^{LTE}/\eta_i, & i \in C \cap S_{CM}, j(i) < j_k, \\ A_5, & i \in C \cap S_{CM}, j(i) = j_k, \\ 0, & i \in C \cap S_{CM}, j(i) > j_k, \end{cases} \tag{33}$$
in which $A_5 = W_C - W_C^{LTE} - \sum_{j=j_1}^{j_{k-1}} \bar{L}_j^{LTE}/\eta_j$ and j_k satisfies $\sum_{j=j_1}^{j_{k-1}} \bar{L}_j^{LTE}/\eta_j < W_C - W_C^{LTE}$ and $\sum_{j=j_1}^{j_k} \bar{L}_j^{LTE}/\eta_j \geq W_C - W_C^{LTE}$.

Proof. Consider a LTE bandwidth allocation $W_{h_C}, W_1, W_2, \ldots, W_{|C|-1}$ satisfying $W_{h_C} < W_C^{LTE}$. If there exists a CM $i \in C$ such that $W_i > 0$ and $R_i^{DSRC*} < \bar{L}_i^{DSRC}$ according to Theorem 1, we define $\Delta W_i = \min\{(\bar{L}_i^{DSRC} - R_i^{DSRC*})/\eta_{h_C}, W_i\}$ as the bandwidth that can be transferred from vehicle i's LTE transmissions to vehicle i's DSRC transmissions. Then, there exists a new allocation $W'_{h_C}, W'_1, W'_2, \ldots, W'_{|C|-1}$ in which

$$W'_{h_C} = W_{h_C} + \Delta W_i, \tag{34}$$
$$W'_i = W_i - \Delta W_i, \tag{35}$$

and $W'_k = W_k, \forall k \neq i, h_C$, such that

$$R_i'^{DSRC*} = R_i^{DSRC*} + \eta_{h_C} \Delta W_i, \tag{36}$$
$$\begin{aligned} R_i'^{LTE*} &\geq R_i^{LTE*} - \eta_i \Delta W_i \\ &\geq R_i^{LTE*} - \eta_{h_C} \Delta W_i, \end{aligned} \tag{37}$$

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2019.2904036, IEEE Internet of Things Journal

and $R_k'^{DSRC*} = R_k^{DSRC*}, R_k'^{LTE*} = R_k^{LTE*}, \forall k \neq i$, according to Theorem 1. Thus, the new allocation is at least no worse than the original allocation. Therefore, for any optimal allocation $W_{h_C}^*, W_1^*, W_2^*, \ldots, W_{|C|-1}^*$ satisfying $W_{h_C}^* < W_C^{LTE}$, we have $W_i = 0$ for any CM i satisfying $R_i^{DSRC*} < \bar{L}_i^{DSRC}$ according to Theorem 1.

Consider a LTE bandwidth allocation $W_{h_C}, W_1, W_2, \ldots, W_{|C|-1}$ satisfying $W_{h_C} < W_C^{LTE}$ and $W_i = 0$ for any CM $i \in C$ satisfying $R_i^{DSRC*} < \bar{L}_i^{DSRC}$ according to Theorem 1. If there exists two CMs $i_1, i_2 \in C$ such that $R_{i_1}^{DSRC*} = \bar{L}_{i_1}^{DSRC}, W_{i_1} > 0$ and $R_{i_2}^{DSRC*} < \bar{L}_{i_2}^{DSRC}, W_{i_2} = 0$, we define $\Delta W_{i_1,i_2} = \min\{(\bar{L}_{i_2}^{DSRC} - R_{i_2}^{DSRC*})/\eta_{h_C}, W_{i_1}\}$ as the maximal bandwidth that can be transferred from vehicle i_1's LTE transmissions to vehicle i_2's DSRC transmissions. Then, there exists a new allocation $W_{h_C}', W_1', W_2', \ldots, W_{|C|-1}'$ in which

$$W_{h_C}' = W_{h_C} + \Delta W_{i_1,i_2}, \tag{38}$$

$$W_{i_1}' = W_{i_2} - \Delta W_{i_1,i_2}, \tag{39}$$

and $W_k' = W_k, \forall k \neq i_1, h_C$, such that

$$R_{i_1}'^{DSRC*} = R_{i_1}^{DSRC*}, \tag{40}$$

$$\begin{aligned} R_{i_1}'^{LTE*} &\geq R_{i_1}^{LTE*} - \eta_{i_1}\Delta W_{i_1,i_2} \\ &\geq R_{i_1}^{LTE*} - \eta_{h_C}\Delta W_{i_1,i_2}, \end{aligned} \tag{41}$$

$$R_{i_2}'^{DSRC*} = R_{i_2}^{DSRC*} + \eta_{h_C}\Delta W_i, \tag{42}$$

$$R_{i_2}'^{LTE*} = R_{i_2}^{LTE*} = 0, \tag{43}$$

and $R_k'^{DSRC*} = R_k^{DSRC*}, R_k'^{LTE*} = R_k^{LTE*}, \forall k \neq i_1, i_2$, according to Theorem 1. Thus, the new allocation is at least no worse than the original allocation. Therefore, for any optimal allocation $W_{h_C}^*, W_1^*, W_2^*, \ldots, W_{|C|-1}^*$ satisfying $W_{h_C}^* < W_C^{LTE}$, we have $W_i = 0$ for any CM $i \in C$. Thus, equation (32) is proved.

Consider a LTE bandwidth allocation $W_{h_C}, W_1, W_2, \ldots, W_{|C|-1}$ satisfying $W_{h_C} = W_C^{LTE}$. If there exists two CMs $i_1, i_2 \in C$ with $j(i_1) < j(i_2)$ such that $W_{i_1} < \bar{L}_{i_1}^{LTE}/\eta_{i_1}$ and $W_{i_2} > 0$, we define $\delta W_{i_1,i_2} = \min\{\bar{L}_{i_1}^{LTE}/\eta_{i_1} - W_{i_1}, W_{i_2}\}$ as the maximal bandwidth that can be transferred from vehicle i_2's LTE transmissions to vehicle i_1's LTE transmissions. Then, there exists a new allocation $W_{h_C}', W_1', W_2', \ldots, W_{|C|-1}'$ in which

$$W_{i_1}' = W_{i_1} + \delta W_{i_1,i_2}, \tag{44}$$

$$W_{i_2}' = W_{i_2} - \delta W_{i_1,i_2}, \tag{45}$$

and $W_k' = W_k, \forall k \neq i_1, i_2$, such that

$$R_{i_1}'^{LTE*} = R_{i_1}^{LTE*} + \eta_{i_1}\delta W_{i_1,i_2}, \tag{46}$$

$$\begin{aligned} R_{i_2}'^{LTE*} &\geq R_{i_2}^{LTE*} - \eta_{i_2}\delta W_{i_1,i_2} \\ &\geq R_{i_2}^{LTE*} - \eta_{i_1}\delta W_{i_1,i_2}, \end{aligned} \tag{47}$$

and $R_k'^{LTE*} = R_k^{LTE*}, \forall k \neq i_1, i_2$ and $R_k'^{DSRC*} = R_k^{DSRC*}, \forall k \in C$, according to Theorem 1. Thus, the new allocation is at least no worse than the original allocation. Therefore, for any optimal allocation $W_{h_C}^*, W_1^*, W_2^*, \ldots, W_{|C|-1}^*$ satisfying $W_{h_C}^* = W_C^{LTE}$, we have $W_i = \bar{L}_i^{LTE}/\eta_i$ for any CM i satisfying $j(i) < j(k)$ if there exists a CM k such that $W_k < \bar{L}_k^{LTE}/\eta_k$. Thus, equation (33) is proved. Therefore, Lemma 1 is proved. □

As we can see from Lemma 1, in order to maximize the total uplink throughput of a cluster C for a given DSRC bandwidth, the total LTE bandwidth of cluster C is first allocated to the CH h_C to transmit its own traffic R_{h_C} as well as to relay the DSRC traffic R_i^{DSRC*} when each CM $i \in C \cap S_{CM}$ makes full use of the DSRC bandwidth. Then, the rest LTE bandwidth is allocated sequentially to each CM $i \in C \cap S_{CM}$ from highest spectrum efficiency η_{j_1} to the lowest spectrum efficiency $\eta_{j_{|C|-1}}$ to satisfy its LTE traffic requirement R_i^{LTE*}.

Theorem 2. *Given the DSRC bandwidth $W_0 \leq W$, we define $\bar{L}_i^{DSRC}$ and $\bar{L}_i^{LTE}$ as in Lemma 1 for each CM $i \in S_{CM}$. For each CH $h_C \in S_{CH}$ of cluster $C \in L$, we denote by $\bar{L}_{h_C}^{LTE}$ as the maximal traffic that can be transmitted via the LTE link of CH h_C, which is given by*

$$\bar{L}_{h_C}^{LTE} = R_{h_C} + \sum_{i \in C \cap S_{CM}} \bar{L}_i^{DSRC}. \tag{48}$$

We list the LTE spectrum efficiency of all vehicles in descending order $\eta_{j_1}, \eta_{j_2}, \ldots, \eta_{j_N}$. Thus, the optimal LTE bandwidth allocation W_i^* of vehicle $i \in S$ is given by

$$W_i^* = \begin{cases} \bar{L}_i^{LTE}/\eta_i, & A_6 \leq 0, \\ \bar{L}_i^{LTE}/\eta_i, & A_6 > 0 \text{ and } j(i) < j_k, \\ A_7, & A_6 > 0 \text{ and } j(i) = j_k, \\ 0, & A_6 > 0 \text{ and } j(i) > j_k, \end{cases} \tag{49}$$

in which $A_6 = \sum_{j=j_1}^{j_N} \bar{L}_j^{LTE}/\eta_j - W$, $A_7 = W - \sum_{j=j_1}^{j_{k-1}} \bar{L}_j^{LTE}/\eta_j$, and j_k satisfies $\sum_{j=j_1}^{j_{k-1}} \bar{L}_j^{LTE}/\eta_j < W$ and $\sum_{j=j_1}^{j_k} \bar{L}_j^{LTE}/\eta_j \geq W$.

Proof. We assume that there exists two vehicles $i_1, i_2 \in S$, such that $j(i_1) < j(i_2)$, $W_{i_1} < \bar{L}_{i_1}^{LTE}/\eta_{i_1}$ and $W_{i_2} > 0$. According to Lemma 1, we have vehicles i_1 and i_2 belongs to different clusters, which we denote by C_1 and C_2, respectively. We define $\Delta W = \min\{\bar{L}_{i_1}^{LTE}/\eta_{i_1} - W_{i_1}, W_{i_2}\}$. Then, there exists a new allocation $W_1', W_2', \ldots, W_N'$ in which

$$W_{i_1}' = W_{i_1}' + \Delta W, \tag{50}$$

$$W_{i_2}' = W_{i_2}' - \Delta W, \tag{51}$$

and $W_k' = W_k, \forall k \neq i_1, i_2$, such that

$$\begin{aligned} &\sum_{i \in C_1} \left(R_i'^{DSRC*} + R_i'^{LTE*}\right) \\ &= \sum_{i \in C_1} \left(R_i^{DSRC*} + R_i^{LTE*}\right) + \eta_{i_1}\Delta W, \end{aligned} \tag{52}$$

$$\begin{aligned} &\sum_{i \in C_2} \left(R_i'^{DSRC*} + R_i'^{LTE*}\right) \\ &\geq \sum_{i \in C_2} \left(R_i^{DSRC*} + R_i^{LTE*}\right) - \eta_{i_2}\Delta W, \end{aligned} \tag{53}$$

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2019.2904036, IEEE Internet of Things Journal

and

$$\sum_{i\in C}\left(R_i'^{DSRC*}+R_i'^{LTE*}\right)= \sum_{i\in C}\left(R_i^{DSRC*}+R_i^{LTE*}\right) \tag{54}$$

for any cluster $C \in L, C \neq C_1, C_2$ according to Lemma 1 and Theorem 1. Thus, the new allocation is at least no worse than the original allocation. Therefore, for any optimal allocation $W_1^*, W_2^*, \ldots, W_N^*$, if there exists a vehicle $i \in S$ such that $W_i^* < \bar{L}_i^{LTE}$, we have $W_k^* = 0$ for any vehicle $k \in S$ satisfying $j(k) > j(i)$. Thus, Theorem 2 is proved. □

As we can see from Theorem 2, in order to maximize the total uplink throughput for a given DSRC bandwidth, the total LTE bandwidth is sequentially allocated to each vehicle $i \in S$ from the highest spectrum efficiency η_{j_1} to the lowest spectrum efficiency η_{j_N} to satisfy its LTE transmission requirement $\bar{L}_i^{LTE}$.

C. Optimal DSRC Bandwidth Allocation

Note that for any given DSRC bandwidth W_0, the optimal LTE bandwidth allocation $W_1^*, W_2^*, \ldots, W_N^*$ and the optimal load distribution $R_i^{DSRC*}, R_i^{LTE*}, i \in S$ are given by Theorem 2 and Theorem 1, respectively. The objective function of problem (25) is then decided by the DSRC bandwidth W_0. Note that the DSRC V2V capacity C_i^{V2V} increases with W_0 while the LTE capacity C_i^{V2I} decreases with W_0. There exists an optimal DSRC bandwidth W_0^* such that the corresponding DSRC and LTE capacity can match each other. Thus, by substituting Theorem 1 and Theorem 2 into problem (25), the optimal value of W_0^* can be calculated numerically by using classic optimization methods, e.g., conjugate gradient methods and simplex methods.

VI. Simulation Results

We consider a one-way road with length 5 km covered by a single LTE cell, on which vehicles enter from one end and leave from the other end. We assume that the traffic flow follows a poisson process with arrival rate λ and the speed of each vehicle is uniformly distributed between 10 m/s and 30 m/s. We assume that the data rate requirement of each vehicle is equally given by R_{up}. The total bandwidth is assumed to be 300 MHz, in which 200 MHz is originally assigned to LTE transmissions and 100 MHz is originally assigned to DSRC transmissions. The spectrum efficiency of DSRC transmissions is given by 10 bps/Hz and the communication range of DSRC transmission is given by 100 m. The spectrum efficiency of LTE transmissions is uniformly distributed between 2 bps/Hz and 5 bps/Hz.

In this section, we considered three different schemes to compare with our proposed scheme. The first is the non-clustering scheme, in which vehicles communicate directly to the eNodeB by using LTE transmissions with the original 200 MHz LTE bandwidth. The second is the section-based scheme, in which the entire road is divided into road sections with equal length 100 m and vehicles within the same section form a cluster using DSRC transmissions. The third is the K-means clustering scheme, in which vehicles are clustered by using the classic K-means algorithm according to the location information, while the total bandwidth is optimally distributed between DSRC and LTE transmissions.

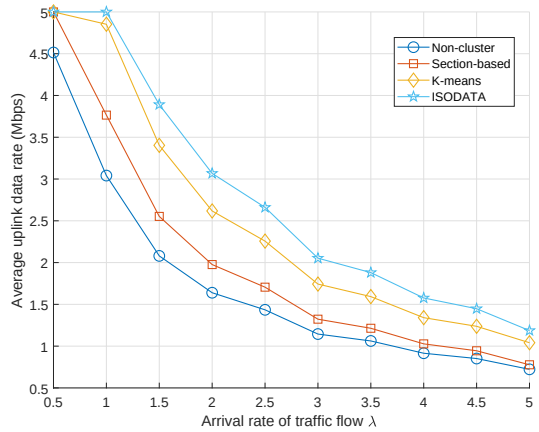


Fig. 2. Average uplink rate as a function of the arrival rate of traffic flow λ with uplink rate requirement $R_{up} = 5$ Mbps.

In Fig. 2, we show the average uplink rate of vehicle users as a function of the arrival rate of traffic flow, in which the uplink rate requirement is given by $R_{up} = 5$ Mbps. The non-cluster scheme achieves the lowest average uplink rate since only LTE transmissions are utilized. The section-based scheme outperforms the non-cluster scheme as DSRC transmissions are utilized to enhance the uplink spectrum efficiency via CH relaying. When the traffic flow becomes dense, i.e., $\lambda >$, the DSRC gain decreases to zero since the DSRC transmissions suffers from the high probability of data collisions within a cluster. The K-means scheme outperforms both the non-cluster scheme and the section-based scheme, because vehicles are clustered more efficiently based on their real-time locations and the total bandwidth are optimally allocated between DSRC and LTE transmissions. The proposed ISODATA scheme outperforms all three schemes since the size of clusters can be dynamically adjusted according to the density of traffic flow, and the corresponding load and bandwidth are optimally distributed between DSRC and LTE.

In Fig. 3, we show the optimal DSRC bandwidth as a function of the arrival rate of traffic flow for the proposed ISODATA scheme, in which the uplink rate requirement is given by $R_{up} = 5$ Mbps. As we can see, the optimal DSRC bandwidth first increases with the traffic density, which exploits the spacial multiplexing gain of DSRC transmissions to enhance uplink transmissions. And then, the optimal DSRC bandwidth decreases as the traffic density becomes extremely high, as the spectrum efficiency of DSRC transmissions decreases dramatically due to frequent data collisions. Therefore, the bandwidth allocation between DSRC and LTE should be dynamically adjusted according to the fluctuation of traffic density.

In Fig. 4, we show the average uplink rate of vehicle users as a function of the uplink data rate requirement R_{up}, in which

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2019.2904036, IEEE Internet of Things Journal

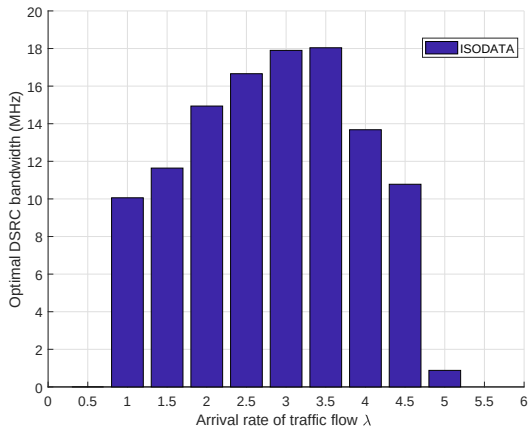


Fig. 3. Optimal DSRC bandwidth as a function of the arrival rate of traffic flow λ with uplink rate requirement $R_{up} = 5$ Mbps.

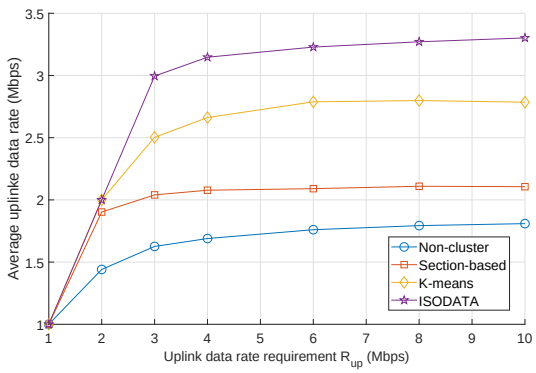


Fig. 4. Average uplink rate as a function of the uplink rate requirement R_{up} with the arrival rate of traffic flow $\lambda = 2$.

the arrival rate of traffic flow is given by $\lambda = 2$. As we can see, the average uplink rate increases with the uplink rate requirement, and our proposed clustering scheme based on ISODATA outperforms the conventional section-based and K-means schemes. When the uplink rate requirement is low, all schemes can satisfy the uplink requirement and the practical data rate increases linearly with the rate requirement. When the rate requirement exceeds the uplink capacity, the average uplink rates of all schemes reach their upper bounds and the curves become flat as R_{up} increases.

In Fig. 5, we show the average uplink rate of vehicle users as a function of the clustering period, in which the uplink rate requirement is given by $R_{up} = 5$ Mbps and the arrival rate of traffic flow is given by $\lambda = 2$. As we can see, the average uplink rate decreases as the clustering period increases, since the uplink performance can be influenced when vehicles join or leave the clusters within a clustering period. Therefore, there exists a tradeoff between average uplink rate of HetVNETs and signaling overhead of cluster formation, which should be fully exploited in practical deployment.

VII. Conclusions

We have considered a HetVNET using both DSRC and LTE for uplink transmissions, for which we have proposed a clustering scheme based on ISODATA and a load-bandwidth management scheme to optimally distribute bandwidth resources to DSRC and LTE transmissions. We have proved that the optimal bandwidth allocation for a given cluster structure can be achieved within linear computational complexity. Simulation results have shown that the proposed scheme outperforms the conventional section-based and K-means clustering methods in terms of average uplink rate, and a tradeoff between uplink throughput and signaling overhead can be achieved.

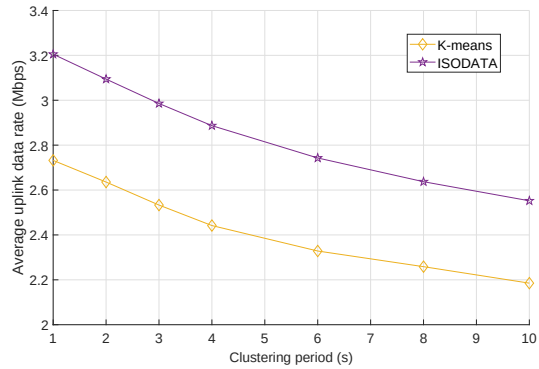


Fig. 5. Average uplink rate as a function of clustering period with the uplink rate requirement $R_{up} = 5$ Mbps and the arrival rate of traffic flow $\lambda = 2$.

References

[1] NHTSA, "Federal Motor Vehicle Safety Standards; V2V Communications," *Federal Register*, Docket No. NHTSA-2016-0126, Jan. 2017.

[2] K. Sjoberg, P. Andres, T. Buburuzan, and A. Brakemeier, "Cooperative Intelligent Transport Systems in Europe: Current Deployment Status and Outlook," *IEEE Veh. Tech. Mag.*, vol. 12, no. 2, pp. 89-97, Jun. 2017.

[3] J. Li, H. Cheng, H. Guo, and S. Qiu, "Survey on Artificial Intelligence for Vehicles," *Auto. Innov.*, vol. 1, no. 1, pp. 2-14, Jan. 2018.

[4] J. Kenney, "Dedicated Short-Range Communications (DSRC) Standards in the United States," *Proc. IEEE*, vol. 99, no. 7, pp. 1162-182, Jul. 2011.

[5] S. Chen, J. Hu, Y. Shi, Y. Peng, J. Fang, R. Zhao, and L. Zhao, "Vehicle-to-Everything (V2X) Services Supported by LTE-Based Systems and 5G," *IEEE Commun. Stand. Mag.*, vol. 1, no. 2, pp. 70-76, Jul. 2017.

[6] J. C. Lin, C. S. Lin, C. N. Liang, and B. C. Chen, "Wireless Communication Performance Based on IEEE 802.11p R2V Field Trials," *IEEE Commun. Mag.*, vol. 50, no. 5, pp. 184-191, May 2012.

[7] S. H. Sun, J. L. Hu, Y. Peng, X. M. Pan, L. Zhao, and J. Y. Fang, "Support for Vehicle-to-Everything Services Based on LTE," *IEEE Wireless Commun.*, vol. 23, no. 3, pp. 4-8, Jun. 2016.

[8] K. Zheng, Q. Zheng, P. Chatzimisios, W. Xiang, and Y. Zhou, "Heterogeneous Vehicular Networking: A Survey on Architecture, Challenges, and Solutions," *IEEE Commun. Surv. Tut.*, vol. 17, no. 4, pp. 2377-2394, Fourthquarter 2015.

[9] H. Zhang, X. Chu, W. Guo, and S. Wang, "Coexistence of Wi-Fi and Heterogeneous Small Cell Networks Sharing Unlicensed Spectrum," *IEEE Commun. Mag.*, vol. 53, no. 3, pp. 158-164, Mar. 2015.

[10] Q. Zheng, K. Zheng, H. Zhang, V. C. Leung, "Delay-Optimal Virtualized Radio Resource Scheduling in Software-Defined Vehicular Networks via Stochastic Learning," *IEEE Trans. Veh. Tech.*, vol. 65, no. 10, pp. 7857-7867, Oct. 2016.

[11] Y. Hui, S. Zhou, and T. H. Luan, "Optimal Access Control in Heterogeneous Vehicular Networks: A Game Theoretic Approach," in *Proc. IEEE GLOBECOM'17*, Singapore, Singapore, Dec. 2017.

[12] T. Zhang, Q. Zhu, G. Liang, J. Xin, and Z. Pan, "A TDMA-Based Hybrid Transmission MAC Protocol for Heterogeneous Vehicular Network," *IEICE Trans. Commun.*, vol. e101-b, no. 4, pp. 1142-1151, Apr. 2018.

[13] B. Di, L. Song, Y. Li, and G. Y. Li, "Non-Orthogonal Multiple Access for High-Reliable and Low-Latency V2X Communications in 5G Systems," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 10, pp. 2383-2397, Oct. 2017.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2019.2904036, IEEE Internet of Things Journal

[14] P. Wang, B. Di, H. Zhang, K. Bian, and L. Song, "Cellular V2X Communications in Unlicensed Spectrum: Harmonious Coexistence with VANET in 5G systems," *IEEE Trans. Wireless Commun.*, vol. 17, no. 8, pp. 5212-5224, Aug. 2018.

[15] S. Wang, T. Wang, and S. Wang, "Effective gateway association schemes for performance improvement of V2I communications in heterogeneous vehicular networks," in *Proc. IEEE ICCC'17*, Qingdao, China, Oct. 2017.

[16] M. Ren, J. Zhang, L. Khoukhi, H. Labiod, and V. Véque, "A Unified Framework of Clustering Approach in Vehicular Ad Hoc Networks," *IEEE Trans. Intell. Transp. Sys.*, vol. 19, no. 5, pp. 1401-1414, May 2018.

[17] A. Khan, M. Abolhasan, and W. Ni, "An Evolutionary Game Theoretic Approach for Stable and Optimized Clustering in VANETs," *IEEE Trans. Veh. Tech.*, vol. 67, no. 5, pp. 4501-4513, May 2018.

[18] G. El Mouna 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. Tech.*, vol. 64, no. 2, pp. 804-817, Feb. 2015.

[19] Q. Zheng, K.Zheng, L. Sun, and V. C. Leung, "Dynamic Performance Analysis of Uplink Transmission in Cluster-Based Heterogeneous Vehicular Networks," *IEEE Trans. Veh. Tech.*, vol. 64, no. 12, pp. 5584-5595, Dec. 2015.

[20] C. Shi, Y. Zhou, W. Li, H. Li, N. Lu, N. Cheng, and T. Yang, "A Centralized Clustering Based Hybrid Vehicular Networking Architecture for Safety Data Delivery," in *Proc. GLOBECOM'17*, Singapore, Singapore, Dec. 2017.

[21] S. Eichler, "Performance Evaluation of the IEEE 802.11p WAVE Communication Standard," in *Proc. IEEE VTC'07-Fall*, Baltimore, MD, USA, Oct. 2007.

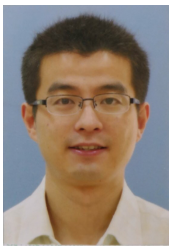
[22] H. A. David, H. N. Nagaraja, *Order Statistics*. Hoboken, New Jersey, USA: John Wiley & Sons, 2004.

[23] J. Dai and S. Wang, "Clustering-Based Spectrum Sharing Strategy for Cognitive Radio Networks," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 1, pp. 228-237, Jan. 2017.

[24] J. Dai and S. Wang, "Clustering-based interference management in densely deployed femtocell networks," *Digital Commun. Netw.*, vol. 2, no. 4, pp. 175-183, Nov. 2016.

[25] G. H. Ball and D. J. Hall, *ISODATA, a novel method of data analysis and pattern classification*. Stanford Research Institute, Menlo Park CA, 1965.

Tianyu Wang (S'11-M'16) received the PhD degree from Peking University, Beijing, China, in 2011. He is currently an associate researcher with the School of Electronic Science and Engineering, Nanjing University, China. He has published more than 40 IEEE journal and conference papers, and received the Best Paper Award from the IEEE ICC'15, IEEE GLOBECOM'14, and ICST ChinaCom'12. His current research interest includes network slicing, load balancing and machine learning in wireless networks.



Xun Cao (S'10-M'12) received the BS degree from Nanjing University, Nanjing, China, in 2006, and the PhD degree from the Department of Automation, Tsinghua University, Beijing, China, in 2012. He held visiting positions with Philips Research, Aachen, Germany, in 2008, and Microsoft Research Asia, Beijing, from 2009 to 2010. He was a Visiting Scholar with the University of Texas at Austin, Austin, TX, USA, from 2010 to 2011. He is currently a full professor with the School of Electronic Science and Engineering, Nanjing University. His research interests include computational photography, image-based modeling and rendering, and VR/AR systems.

Shaowei Wang (S'06-M'07-SM'13) received the PhD degree from Wuhan University, Wuhan, China, in 2006. He is currently a full professor with the School of Electronic Science and Engineering, Nanjing University, Nanjing, China. From 2012 to 2013, he was a visiting scholar/professor with Stanford University, Stanford, CA, USA, and The University of British Columbia, Vancouver, BC, Canada. His research interests include telecommunication system, operations research and machine learning. He organized the Special Issue on Enhancing Spectral Efficiency for LTE-Advanced and Beyond Cellular Networks for IEEE Wireless Communications, and the Feature Topic on Energy-Efficient Cognitive Radio Networks for IEEE Communications Magazine. He is on the editorial board of IEEE Communications Magazine, IEEE Transactions on Wireless Communications, and Springer Journal of Wireless Networks. He serves/served on the technical or executive committee of reputable conferences including IEEE ICC, IEEE GLOBECOM, IEEE INFOCOM, IEEE WCNC etc.