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Energy-Efficient Cluster Management in Heterogeneous Vehicular Networks

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Abstract—We consider the problem of energy-efficient cluster management in heterogeneous vehicular networks. In certain vehicular networking applications such as collision avoidance, multiple wireless technologies like Dedicated Short-Range Communication (DSRC) and LTE are combined to make use of both of their advantages. Thus, an optimum cluster management can be used to reduce the power consumption of Inter-Vehicle Communication (IVC) by centrally deciding methods. We first describe the system model and formulate the problem of energy-efficient Cluster Head (CH) selection as the *p*-median problem in graph theory. Then, we describe a direct enumeration method and a heuristic method to solve the problem by minimizing the total transmission power consumed by all the vehicles. Finally, simulation and comparison are performed to show the energy efficiency of our method.

Keywords—*energy; efficient; vehicle; heterogeneous; DSRC*

I. Introduction

The concept of a vehicular network is rapidly becoming a reality. It has attracted extensive attention from both the academia and industry, and is being applied to many different areas including road safety and efficiency. Meanwhile, the standards for Dedicated Short-Range Communication (DSRC) based on IEEE 802.11p are being promoted to achieve Inter-Vehicle Communication (IVC), such as IEEE WAVE in the U.S [1] and ETSI ITS-G5 in Europe [2]. However, the DSRC technologies have some weaknesses due to their distributed nature. For instance, in many safety applications, beaconing messages are used to gather information from vehicles [3]. The frequent broadcast of periodic beaconing messages may overload the 802.11p channels. Thus, a completely decentralized architecture is not appropriate for a vehicular network because it may lead to messages overhead and channel congestion.

Consequently, heterogeneous vehicular networks, which are typically comprised of centralized parts and decentralized parts, have attracted attention [4]. The vehicles in a heterogeneous vehicular network are usually divided into many clusters. On one hand, the vehicles within a cluster communicate with each other in a distributed manner. Usually, a cluster head (CH) is selected to aggregate information locally from cluster members (CMs). On the other hand, an existing cellular infrastructure is chosen as the centralized part of a cluster for making decisions and forwarding information between clusters.

Green networking is a key technology to promote fuel and electricity efficiencies for vehicles, which in turn save the environment. Currently, most of the related researches [5] focus on green communication and routing protocols in distributed Vehicular Ad hoc Networks (VANETs). However, few works consider the power control problem in a heterogeneous vehicular network, which is an important issue for green networking. The current schemes in heterogeneous vehicular networks usually adopt the default transmission power for IVC. However, a lot of energy is wasted in such an unnecessary way. Worse, a higher transmission power leads to a greater possibility of mutual interference, followed by data retransmissions that consume much more energy. Thus, energy efficient cluster management in heterogeneous vehicular networks is still an open issue.

Our goal is to minimize the total power consumed by all the vehicles in a heterogeneous vehicular network. Accordingly, less fuel (or electricity) is consumed and less CO_2 is produced. We achieve this by determining which vehicle(s) should be selected as the optimum CH(s), so that the total transmission distance of all the vehicles is minimized. Accordingly, the transmission power of each vehicle can be adjusted as needed and the total transmission power of vehicles is minimized.

The main contributions of our work are shown as follows.

(1) We describe the system model, and formulate the CH selection and cluster management problems in a heterogeneous vehicular network as the p -median problem in graph theory.

(2) We solve the problem using a direct enumeration method and a heuristic method to minimize the total transmission power of vehicles.

The remainder of this paper is organized as follows. Some related work is shown in Section II. The system description and problem formulation are stated in Section III. The solutions by a direct enumeration method and a heuristic method are presented in Section IV. Performance evaluations are provided in Section V, followed by the conclusion.

II. Related Work

Energy efficient clustering algorithms have been widely discussed in wireless sensor networks [6]. However, a main goal of these algorithms is to balance the energy consumption among all the nodes so as to avoid some nodes die more rapidly than other nodes. Thus, the total energy consumption of all the nodes is not the main concern and can hardly be

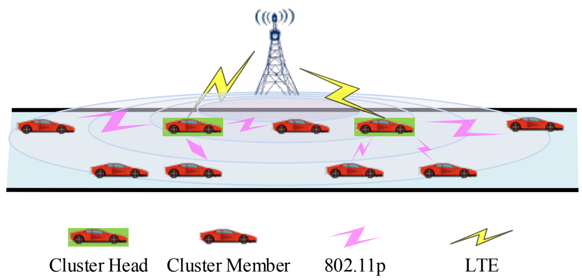

Fig. 1. System topology of a heterogeneous vehicular network.

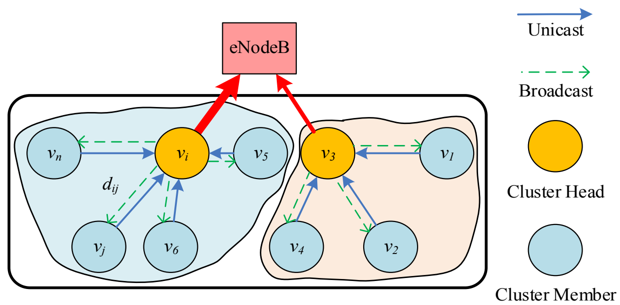

Fig. 2. Simplified view of a heterogeneous vehicular network.

minimized, while our method minimizes the total power consumed by all the vehicles and leads to the least CO_2 emission in a heterogeneous vehicular network.

A standardized beaconing between vehicles is the Cooperative Awareness Message (CAM) defined by ETSI ITS-G5 [2]. The beaconing messages are widely used in vehicular networking applications, e.g., safety application, for awareness of the speeds, directions, and positions of vehicles. LTE4V2X [4] proposes a centralized clustering approach for heterogeneous vehicular networks. In each cluster, a CH is selected by the LTE eNodeB (or the server located behind the eNodeB). Then, the selected CH collects information from the CMs using DSRC beaconing messages, and sends the gathered information to the eNodeB through the LTE channel. However, LTE4V2X does not consider the power control problem. Instead, each vehicle uses the default transmission power when communicating with other vehicles. Thus, interference between vehicles may occur and energy may be wasted in a dense scenario.

M. Torrent-Moreno et al. [7] show that from a sender, there is an optimal transmission power, which is independent of node density, to achieve fair distribution of channel capacity and avoid overload conditions among vehicles. Based on this finding, A. Memedi et al. [8] extend LTE4V2X to allow a centralized transmission power control in VANETs. However, it only gives a brief idea and does not describe a detailed method for cluster management. Instead, it simply selects the vehicle with the minimum distance to the eNodeB as the CH. Although this helps in guaranteeing the quality of the LTE channel for transmitting data between the CH and the base station, the power consumption between the CH and CMs is not optimized.

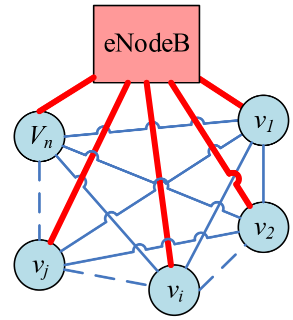

Fig. 3. Graph G for single CH selection.

III. System Description and Problem Formulation

In this section, we first describe the system model. Then we formulate the energy-efficient CH selection problem in heterogeneous vehicular networks as a variant of the *p*-median problem in graph theory.

A. *System description*

The topology of our envisioned heterogeneous vehicular networks is shown in Fig. 1. In the scenario all vehicles utilize two wireless interfaces: one LTE and one IEEE 802.11p. All the vehicles can communicate directly with each other using IEEE 802.11p. In addition, an LTE eNodeB on the roadside serves the passing vehicles. The eNodeB (or the server located behind the eNodeB) manages and maintains the vehicle clusters under its coverage area. The vehicles may be divided into several clusters by the eNodeB. One or more CHs are selected in a cluster. Since our method considers the travelling direction of vehicles when configuring a vehicle cluster, the traffic could be in different directions, although Fig. 1 only shows traffic travelling in a single direction.

The vehicular network in consideration can be simplified, as shown in Fig. 2. Since our goal is to minimize the total power consumption of DSRC communications for all vehicles, two kinds of messages should be taken into account in a decision round for optimizing a cluster. For different applications, the message type and length may be different. Thus, we give them general definitions, and name them Message A and Message B, respectively.

(1) Message A: a CH broadcasts the message to all the CMs to indicate the CH and CMs in a cluster.

(2) Message B: Each CM reports its current parameters to the CH.

Then, the CH gathers the parameters of all the CMs and sends them to the eNodeB using the LTE channel. In the next cycle, the eNodeB updates the clusters based on the information retrieved from the CH.

B. *Problem formulation*

Our goal is to minimize the total transmission power consumed by all the vehicles. This can be achieved by selecting the optimum CH(s) in a heterogeneous vehicular network.

Within a cluster, a CM sends a message directly to the CH, i.e., communication between a CM and a CH is single-hop. Thus, the graph is a full connected graph, as shown in Fig. 3.

The vehicles under an eNodeB's coverage area can be divided into one or more clusters. Each cluster is assumed with one CH in our study. In the following, we will first discuss a simple scenario where only one cluster exists. Then, we generalize the problem and discuss the scenario of multiple clusters.

(1) Single CH Selection

Considering a heterogeneous vehicular network of $n+1$ nodes, i.e., n vehicles and one eNodeB, the n vehicles can be represented by a vertex weighted full connected graph G. Each vehicle is weighted by a corresponding demand h_i. A vehicle can perform two possible roles: CH or CM. Let i be index of potential CM node, j be index of potential CH node, $d_{i,j}$ be the distance of i - j edge. Note that each node may be a potential CM or a potential CH.

Thus, we have the following problem in mathematical terms. For each pair of nodes i - j, the direct distance $d_{i,j}$ is found. where

$$d_{i,j}=\begin{cases}\infty, & \text{for } d\left(v_i,v_j\right)>L_{802.11p},\ and\ i\neq j\\ d\left(v_i,v_j\right), & \text{for } d\left(v_i,v_j\right)\leq L_{802.11p},\ and\ i\neq j\\ \max\left\{d\left(v_k,v_j\right),j\neq k\right\}, & \text{for } i=j\end{cases}\quad(1)$$

where $L_{801.11p}$ is the maximum transmit range of 802.11p.

As shown in section III.A, a CH broadcasts a message to all its CMs. Consequently, the CH should have the ability to send the message to the CM farthest from it. Thus, in Eq. (1),

$$d_{i,j}=d\left(v_j,v_j\right)=\max\left\{d\left(v_k,v_j\right),j\neq k\right\},\ \text{for } i=j$$

In the vertex weighted full connected graph G, our goal is to find the single vertex median of the graph when a single CH is selected in a cluster.

The distance matrix D can be shown as a $n\times n$ symmetric matrix $d_{i,j}$ between all pairs of nodes v_i, v_j.

$$D=\begin{bmatrix}d_{1,1} & d_{1,2} & \cdots & d_{1,n}\\ d_{2,1} & d_{2,2} & \cdots & d_{2,n}\\ \vdots & \vdots & \ddots & \vdots\\ d_{n,1} & d_{n,2} & \cdots & d_{n,n}\end{bmatrix}$$

Since the message types and lengths shown in section III.A may be different, the vertex weights of graph G are unequal. Let H be the demand matrix with the vertex weights on the diagonal.

$$H=\begin{bmatrix}h_1 & 0 & \cdots & 0\\ 0 & h_2 & \cdots & 0\\ \vdots & \vdots & \ddots & \vdots\\ 0 & 0 & \cdots & h_n\end{bmatrix}$$

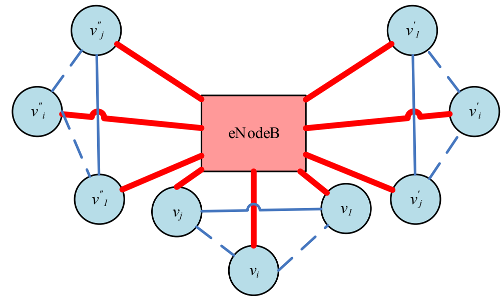

Fig. 4. Graph G for multiple CHs selection.

Then, let R be the weighted distance matrix,

$$\begin{aligned}R&=HD=\left[r_{i,j}\right]=\left[h_i d_{i,j}\right]\\ &=\begin{bmatrix}h_1 & 0 & \cdots & 0\\ 0 & h_2 & \cdots & 0\\ \vdots & \vdots & \ddots & \vdots\\ 0 & 0 & \cdots & h_n\end{bmatrix}\begin{bmatrix}d_{1,1} & d_{1,2} & \cdots & d_{1,n}\\ d_{2,1} & d_{2,2} & \cdots & d_{2,n}\\ \vdots & \vdots & \ddots & \vdots\\ d_{n,1} & d_{n,2} & \cdots & d_{n,n}\end{bmatrix}\\ &=\begin{bmatrix}h_1d_{1,1} & h_1d_{1,2} & \cdots & h_1d_{1,n}\\ h_2d_{2,1} & h_2d_{2,2} & \cdots & h_2d_{2,n}\\ \vdots & \vdots & \ddots & \vdots\\ h_nd_{n,1} & h_nd_{n,2} & \cdots & h_nd_{n,n}\end{bmatrix}\end{aligned}\quad(2)$$

Our goal is to find the v_j acting as the optimum CH. For a graph G, it is to find the vertex median v_{med} for which the sum of the elements in the R's corresponding column is minimized, i.e., the sum of weighted distances is minimized. That is,

$$r_{med}=\mathrm{Min}\left\{r_j\,\middle|\,j=1,2,\cdots,n\right\}\quad(3)$$

where $r_j=\sum_{i=1}^{i=n}r_{i,j}$.

Then, v_{med} is selected as the single CH because it has the minimum sum of weighted distances, which means the least total power requirements [7][8] on all the vehicles.

(2) Multiple CH Selection

Generally speaking, the coverage radius of an LTE eNodeB may be more than 1 kilometer, which is far beyond the IEEE 802.11p transmission range, which is typically 300 meters. Thus, it is reasonable to divide the vehicles within an eNodeB's coverage into multiple clusters, as shown in Fig. 4. Correspondingly, multiple CHs should be selected. Without loss of generality, we assume that one CH is selected in one cluster. Note that it is easy to extend our following method to select multiple CHs in a cluster.

Then, a generalization of the CH selection problem follows logically from (2) and (3). Let v_i, $i=1,2,\cdots,n$, denote n vehicles, $v_1,v_2,\cdots,v_p$ denote the p CHs to be selected. Our goal is to find optimum p subsets of vehicles served by the p CHs. The p subsets form an associated partition of the n

vehicles. Thus, the general formulation of multiple CH selection can be formulated as:

$$\text{Minimize } \sum_{i=1}^{n}\sum_{j=1}^{p} r_{i,j} g_{i,j} \quad (4)$$

where

$$g_{i,j} = \begin{cases} 1, \text{if vehicle } v_i \text{ is served by vehicle } v_j \text{ that is a CH} \\ 0, \text{if vehicle } v_i \text{ is NOT served by vehicle } v_j \text{ that is a CH} \end{cases}$$

The formulation is a variant of the p-median problem [10] in graph theory, i.e., looking for a set of p vertex destinations so that the total length from sources to destinations is a minimum.

The next task is to find the optimum CHs.

IV. Finding the Energy-Efficient Cluster Heads

In this section, a direct enumeration method and a heuristic method are described to solve the problem by minimizing the total transmission power of vehicles.

A. Finding the CHs by Direct Enumeration

The optimum CHs may be found by direct enumeration for a vehicular network with only a few vehicles. All the possibilities are evaluated and a decision is made when the direct enumeration method is adopted.

For a heterogeneous vehicular network with n vehicles and one eNodeB, there will be $\binom{n}{p}$ possible subsets containing exactly p vertices if p CHs are to be selected.

Each possible partition $A_p^{\ k}, k = 1,2,\cdots,\binom{p}{n}$, has a $n \times p$ submatrix $R_p^{\ k}$

$$R_p^{\ k} = \left[r_{i,j} \right] = \left[h_i d_{i,j} \right] = \begin{bmatrix} h_1 d_{1,1} & h_1 d_{1,2} & \cdots & h_1 d_{1,p} \\ h_2 d_{2,1} & h_2 d_{2,2} & \cdots & h_2 d_{2,p} \\ \vdots & \vdots & \ddots & \vdots \\ h_n d_{n,1} & h_n d_{n,2} & \cdots & h_n d_{n,p} \end{bmatrix}$$

Thus, for each $A_p^{\ k}$, $r_p^{\ k}$ can be calculated as:

$$r_p^{\ k} = \sum_{i=1}^{n}\sum_{j=1}^{p} r_{i,j} g_{i,j} \quad (5)$$

Then, as the solution of Eq. (4), the minimum $r_p^{\ k}$ can be found by inspection.

Direct enumeration is reasonable so long as the number of vehicles n and the number of selected CHs p are not large. The method is more reasonable when we only select a single CH in a cluster, i.e., $p = 1$. For a simple example, consider a 1200m road covered by an eNodeB, in which four clusters may be appointed to comprise the vehicles in the areas (0, 300m), (300m, 600m), (600m, 900m), (900m, 1200m), respectively. The single CH selection in each cluster is reasonable by the direct enumeration method.

For a network with multiple potential CHs, the computational time of direct enumeration grows rapidly. For example, more efficient methods are necessary if multiple CHs are to be selected in a 1200m road, and the CMs of each cluster are NOT restricted in a designated area.

Thus, we present a heuristic method in the next subsection.

B. Finding the CHs by Heuristic Method

An iterative procedure is described to approach the optimum CHs by producing successively improved selections. We extend the algorithm described by [9] to make it suitable for heterogeneous vehicular networks.

Step 1. Deciding the number of CHs.

The eNodeB decide the number of CHs to be selected, i.e., p, based on the eNodeB's coverage radius L_{eNodeB}, the max transmit range of 802.11p $L_{802.11p}$, and the travelling direction of vehicles. Typically, let $p \geq L_{eNodeB}/L_{802.11p}$ for each direction to ensure every vehicle can communicate directly to at least one CH.

Step 2. Deciding the zones where the CHs should be located.

In each travelling direction, the eNodeB's coverage area is divided into p zones. The vehicles in each zone are a subset of graph G denoted by Z^k, $k = 1,2,\cdots,p$. The coverage range of each zone $L_z^{\ k}, \left[L_z^{\ k} \leq L_{802.11p}, k = 1,2,\cdots,p \right]$ is decided by the density of the vehicles and not necessarily the same. For avoiding channel collision due to too many vehicles in a zone, the number of vehicles $N_z^{\ k}$, $k = 1,2,\cdots,p$, in each zone is substantially the same.

Step 3. Selecting the initial subset E_1 of CHs.

In this step, p vehicles are selected to construct the initial subset of CHs. Different from [9], the initial subset is not selected arbitrarily. Instead, the vehicle $v_j^{\ k}$ nearest to the eNodeB is selected as the initial CH in each zone, i.e.,

$$E_1 = \left\{ v_j^{\ k} \left| r_{eNodeB,j}^{\ \ k} \leq r_{eNodeB,i}^{\ \ k} \right., \text{for all } v_j^{\ k}, v_i^k \in Z^k,\ k = 1,2,\cdots,p \right\}$$

where $r_{eNodeB,j}^{\ \ k}$ and $r_{eNodeB,i}^{\ \ k}$ denote the weighted distance from vehicle $v_j^{\ k}$ and v_i^k to the eNodeB, respectively.

Step 4. Deciding the nodes in each cluster $C_p^{\ k}$

For a CH $v_j^{\ k}$, the vehicles that are closer to it than to other CHs are selected as its corresponding CMs. For a higher efficiency, the corresponding CMs of a CH $v_j^{\ k}$ need not be located in the same zone as the CH. Thus, the subset of nodes in each cluster $C_p^{\ k}$ is defined as follows

$$M^k = \left\{ v_i \left| r_{i,j}^{\ k} \leq r_{i,j}^{\ y} \right. \text{ for } y = 1,2,\cdots,p \right\}$$

where $r_{i,j}^{\ k}$ and $r_{i,j}^{\ y}$ denote the weighted distance from vehicle

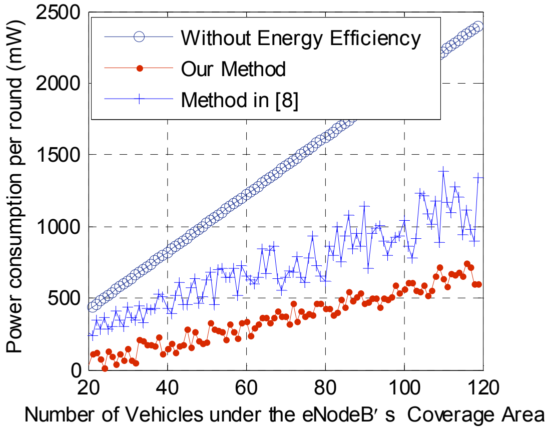

Fig. 5. Comparison between our method, the method not considering energy consumption, and the method proposed by [8].

v_i to CH v_j^k and v_j^y, respectively. Note that the CH v_j^k must be in the subset M^k because v_j^k is the CH in M^k.

Step 5. Deciding the median v_{med}^k of each cluster M^k

v_{med}^k is the median of cluster M^k, if

$$\sum_{i=1}^{n} r_{i,med}^k \le \sum_{i=1}^{n} r_{i,j}^k,\ for\ all\ v_i^k, v_j^k \in M^k,\ k = 1,2,\cdots,p$$

If $v_{med}^k = v_j^k$ for all cluster M^k, computation is stopped and the current CHs v_j^k and clusters M^k, $k = 1,2,\cdots,p,$ constitute the desired solution. Note that v_j^k is first defined as an initial CH in *Step* 3, then may be updated as follows.

Otherwise, set $v_j^k = v_{med}^k$ and return to S*tep* 4.

V. Performance Evaluation

We performed some simulations in MATLAB. The network topology comprised an eNodeB and a 1200m road on which a random number of vehicles travelled in one direction. The maximum density of vehicles is 100 vehicles/km. Vehicles are evenly distributed on the road.

The traffic could be in different directions because our method considers the vehicles' travelling direction when configuring a cluster, although the vehicles travelled in one direction in the simulations.

For methods not considering energy efficiency, a fixed transmission power of 20mW is adopted for sending a message [8]. The clustering range is less than 300m that is the typical transmit range of IEEE 802.11p.

For methods considering energy efficiency, a vehicle is instructed to use 5mW, 7.5mW, and 10mW as DSRC transmit power for the distance up to 100m, 200m, and 300m between vehicles, respectively, instead of the full 20mW.

Comparisons between our method, the method not considering energy consumption, and the method proposed in [8], were performed. From Fig. 5 we can observe that, since every vehicle adopts a default transmission power, the total

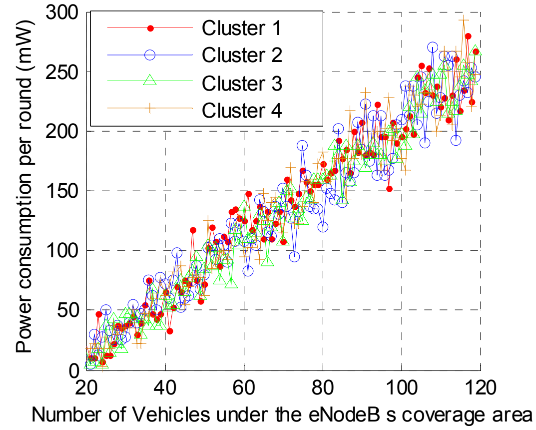

Fig. 6. Power consumption of different clusters

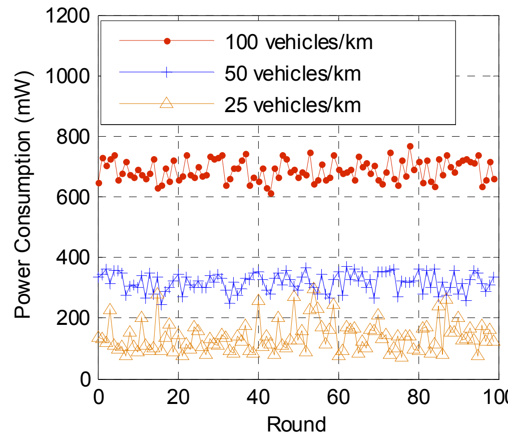

Fig. 7. Power consumption when vehicles are moving.

power consumption increases linearly with the number of vehicles for the method not considering energy efficiency. In contrast, both our method and the method proposed in [8] can reduce the total power consumption for all the vehicles. Furthermore, our method has a better performance than the method in [8]. This is because the method in [8] simply chooses the vehicle nearest to the eNodeB as the CH in a cluster, while our method minimizes the sum of weighted distances between CMs and CH by choosing the optimum vehicles as the CHs based on the *p*-median issue in graph theory.

Fig. 6 shows the total power consumption in different clusters. We can observe that the energy consumption of different clusters is substantially the same. This is because we considered the vehicle density in different zones when selecting CHs and CMs. In this way, channel conflict can be avoided as much as possible in each cluster.

Fig. 7 illustrates the dynamic power consumption when the vehicles are moving. The clusters are updated and the CHs may be reselected in each round because the positions of vehicles are changing. We can conclude that the power consumption keeps stable when the vehicle density does not change. We also observe that the power consumption does not decrease linearly with the vehicle density, which might because of the longer distance between vehicles when the vehicle density is lower.

VI. Conclusion

In this paper, the problem of energy-efficient cluster management is formulated as the *p*-median problem in graph theory. A centralized approach is designed to minimize the total transmission power of vehicles in a heterogeneous vehicular network. Furthermore, a direct enumeration method and a heuristic method are presented to find the solution. Simulation and comparison are performed to show the efficiency of our method.

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