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Cluster-Based Radio Resource Management in Dynamic Vehicular Networks

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ABSTRACT With the rapid growth of traffic demand for vehicular data transmissions, the limited cellular band becomes a constraint to meet the needs of all cellular-vehicle-to-everything (C-V2X) users. In this paper, we investigate an efficient clustering-based spectrum resource management scheme for dynamic heterogeneous vehicular networks. Due to the frequent changes of channel state information (CSI) caused by high mobility of vehicles, the traditional radio resource management scheme based on complete CSI is no longer applicable. To solve this problem, we consider different quality of service (QoS) requirements for vehicular communications and propose an optimization problem for C-V2X networks. The proposed dynamic vehicular optimization strategy is carried out on the vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) links, which can construct a more realistic two-way lane in actual communication environments. We also propose a low-complexity vehicle matching algorithm based on large-scale fading to improve the stability of communication links. The desirable performance is confirmed by computer simulations.

INDEX TERMS Cellular-vehicle-to-everything, vehicle-to-vehicle, cluster, vehicle matching.

I. INTRODUCTION

Intelligent transportation system (ITS) is becoming an important part of future wireless heterogeneous networks [1]. Autonomous vehicles may turn out the fastest growing intelligence terminal devices after smartphones and tablets. In recent years, the new generation of information and communication technologies, such as 6G and artificial intelligence, are rapidly integrated into the vehicular networks and the communication demand between vehicle equipment is prolific increasing [2]–[4]. Cellular-vehicle-to-everything (C-V2X) networks, based on long-term evolution (LTE) technology, has the advantages of large transmission coverage and controllable delay. Also, it can reuse the infrastructure and frequency spectrum of current base station (BS) architectures to support safety and non-safety applications [5], [6]. Even in scenarios without BS coverage, it can ensure vehicles to use ITS services adaptively. Therefore, it has obtained great attention in industrial and academic fields.

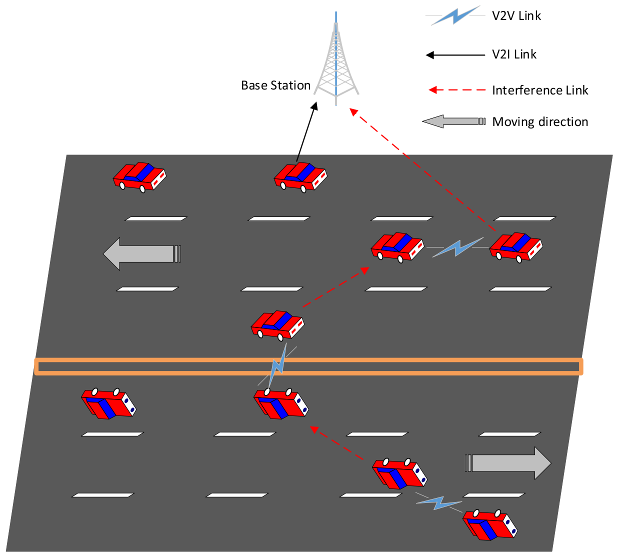

FIGURE 1. System model.

There are two complementary transmission interfaces for C-V2X, LTE-Uu supporting vehicle-to-infrastructure (V2I)

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communications and PC5 for direct transmission between vehicle-to-vehicle (V2V) [7], [8]. In March 2017, Release14 published by 3GPP was based on LTE-V2X, which determined the basic requirements, system architecture, air interface technology, and security services for V2X. Release 15 supports enhancing LTE-V2X with backward compatibility to Release 14. Release16 focuses on the continuation of LTE-V2X and attempts to solve advanced application cases, such as vehicle alignment, enhanced V2I functions, extended sensors, advanced driving, remote driving, and etc [9].

In recent years, the radio resource management for vehicular communications has been the subject of much research endeavor because of the scarcity of spectrum and the underutilization of most licensed frequency bands [10]. The main problem mainly lies in how to properly allocate spectrum for V2V links to improve network performance without causing significant interference to cellular users, i.e., V2I links. In [11], the authors focused on the quality of service (QoS) requirements of two types of vehicular users (i.e., V2I links and V2V links) and one cellular phone user. They proposed a three-dimensional graph-based matching scheme among vehicular users, mobile phone users, and resource blocks to improve spectrum utilization. The authors in [6] considered the LTE-Uu interface in a heterogeneous network. They focused on the different QoS requirements of multiple user equipment and maximized its total channel capacity. In [12], the authors proposed an efficient cluster-based V2X network resource management scheme. The stability of cluster head was measured by speed, connection time, and average distance between transmission vehicles. By reducing interference from V2V to V2I links, they can improve the channel capacity of V2I links. However, their clustering strategy suffers from the two-way lane problem on highway due to its design, in which the V2V link cluster members are selected by geographic location, i.e. within the coverage of the cluster head. And, in fact, the cluster members may have a cross-lane distribution and different driving directions. Its clustering becomes unreasonable once the cross-lane cluster member vehicles leave the coverage of cluster head quickly. The authors in [13] selected the optimum receiver vehicle to determine V2V link and allocated the suitable channels to minimize the total delay. Moreover, a greedy cellular-based V2V link selection algorithm was proposed to solve the maximum weighted independent set (MWIS-AW) problem. At last, the delay, throughput, and packet delivery rate have been greatly improved. In [4], the authors designed an energy sensing-based spectrum sharing scheme, where C-V2X users are able to access the unlicensed channels fairly and reduce the data transmission collisions between C-V2X and vehicular ad hoc network (VANET) users. They also maximized the number of active C-V2X users. In [10], the authors utilized unlicensed spectrum in high-speed wireless networks and investigated spectrum-efficiency (SE)-oriented collaborative transmission. The proposed vehicle pairing, spectrum allocation, and power control algorithm (VP-SA-PCA) can enormously improve the utilization rate and bit error rate of unlicensed spectrum. The authors in [14] enabled C-V2X users to access unlicensed channels fairly and increased the system capacity greatly, where the C-V2X and Wi-Fi coexistence scheme is based on reinforcement learning and the CSI is estimated based on large-scale fading, relative velocity, and communication distance. However, the scheme became poor with the communication demand increasing. Consider that the high mobility and big data characteristics of vehicles will lead to rapid changes in CSI, the channel model in [14]–[17] only used large-scale fading and ignored small-scale fading effect. Therefore, it could not reflect the actual capacity performance and the developed resource allocation scheme was sub-optimal.

Furthermore, a dedicated short range communication (DSRC) and C-V2X hybrid scheme for vehicle networks was proposed in [18] to make a tradeoff between cellular bandwidth cost and end-to-end delay in which the cluster heads delivered their aggregated data by multi-hop V2V transmissions and cellular networks adaptively. In [8], the authors proposed a D2D-based agile QoS prediction framework based on autonomous vehicle prediction. In [19], the authors proposed a VANET-assisted D2D discovery scheme to reduce the resource consumption of cellular networks. The scheme investigated the delay performance of VANET in highway scenes. However, this method only considered one-way expressway scenario while two-way expressway traffic was more realistic. The same situation is also reflected in [7], [20]. In [20], only the minimum geographic distance was used to measure the link connectivity. The node mobility, which may significantly increase the probability of packet loss for dynamic traffic, was ignored. In addition, network congestion will occur when a large number of vehicles send non-safety-critical services to BS simultaneously. It is difficult to meet the QoS requirements of different services [10]. So, the limited spectrum has become a bottleneck for achieving the needs of all C-V2X users.

As pointed out above, the majority of existing literature on radio resource management in vehicular networks considers full CSI or relatively static one-way scenarios, which are unrealistic in real intelligent transportation systems. The rapid mobility also brings out unreasonable vehicle matching and reduces spectrum reuse efficiency. In this paper, we consider a highly dynamic two-way lane smart vehicular network and propose a novel cluster-based spectrum resource management scheme to improve spectrum efficiency, which can be used in the future ITS. For this aim, we also study a low-complexity vehicle matching algorithm to solve link interruption problem caused by unsuitable matching of communication vehicle pairs. We utilize different QoS requirements of terminal vehicles to address priority for safety-oriented applications. Furthermore, a clustering algorithm based on large-scale fading channels is presented to improve spectrum utilization and total channel capacity. The cluster members are selected by the minimization of inter-cluster interference instead of geographic location, which is more in line with the actual situation.

The rest of the paper is organized as follows. Section II describes the system model and problem formulation. Section III presents the node mobility design of two-way lanes. The resource allocation scheme is discussed in Section IV. Numerical simulation results and discussions are presented in Section V. Finally, Section VI concludes the paper.

II. SYSTEM MODEL AND PROBLEM FORMULATION

Consider a dynamic heterogeneous vehicular network on a two-way highway in the coverage area of BS, as shown in Fig. 1. There are K pairs of V2V links, denoted as VUEs, and C pairs of V2I links, denoted as CUEs (i.e. cellular users), with Rayleigh fading channel. We assume that CUEs access radio channels orthogonally under uplink (UL) spectrum sharing with VUEs and then the interference from spectrum sharing can be mitigated by BS coordination. We categorize VUEs by safety and non-safety applications, denoted as S-VUE and N-VUE, respectively. Denote $\mathcal{C} = \{1, \ldots, i\}$ as CUE set, $\mathcal{K} = \{1, \ldots, k\}$ as VUE set, $\mathcal{S} = \{1, \ldots, j\}$ as S-VUE set, and $\mathcal{N} = \{1, \ldots, l\}$ as N-VUE set, where $\mathcal{K}$ is the union of $\mathcal{S}$ and $\mathcal{N}$. Considering CSI only based on large-scale fading in fast-moving vehicular environments cannot reflect the actual capacity performance of networks in [20]–[22]. Here, we use both small-scale fading caused by multipath effects and large-scale fading caused by shadow fading and path loss.

Based on [20], the channel gain $h_{i,B}$ between the ith CUE and the BS is described as

$$h_{i,B} = \theta_{i,B}\Psi_{i,B} \triangleq \theta_{i,B}\Omega\Gamma_{i,B}L_{i,B}^{-\gamma}, \tag{1}$$

where $\theta_{i,B}$ is the small-scale fast fading gain, $\Psi_{i,B}$ is the large-scale fading gain, $\Gamma_{i,B}$ is a log-normal shadow fading random variable with a standard deviation ξ, Ω is the channel loss constant, γ is the decay exponent, and $L_{i,B}$ is the estimated distance from CUE to BS. From the ith CUE, the received signal-to-interference-plus-noise ratio (SINR) at BS, the jth S-VUE, and the lth N-VUE, can be expressed as

$$SINR_i^c = \frac{P_i^c h_{i,B}}{\sigma^2 + \sum_{j\in S} \rho_{i,j}P_j^d h_{j,B} + \sum_{l\in N} \rho_{i,l}P_l^d h_{l,B}}, \tag{2}$$

$$SINR_j^d = \frac{P_j^d h_j}{\sigma^2 + \sum_{i\in C} \rho_{i,j}P_i^c h_{i,j} + \sum_{l\in N} \rho_{i,l}P_l^d h_{l,j}}, \tag{3}$$

and

$$SINR_l^d = \frac{P_l^d h_l}{\sigma^2 + \sum_{i\in C} \rho_{i,l}P_i^c h_{i,l} + \sum_{j\in S} \rho_{i,j}P_j^d h_{j,l}}, \tag{4}$$

respectively, where P_i^c, P_j^d, and P_l^d denote transmission powers of the ith CUE, the jth S-VUE, and the lth N-VUE, respectively. σ^2 is the noise power. $\rho_{i,j}$ and $\rho_{i,l}$ are the spectrum distribution indicators.

Thus, the achieved transmission rates of the ith CUE, the jth S-VUE, and the lth N-VUE can be calculated as

$$R_i^c = \log\left(1 + SINR_i^c\right), \tag{5}$$

$$R_j^d = \log\left(1 + SINR_j^d\right), \tag{6}$$

$$R_l^d = \log\left(1 + SINR_l^d\right), \tag{7}$$

respectively.

We aim to improve the spectrum efficiency through appropriate vehicle matching and resource management, i.e. maximize the total channel capacity of the vehicular network under different QoS requirements of V2V links, especially S-VUEs. To this point, the resource management problem in the vehicular networks can be formulated as

$$\begin{aligned}
\max_{\rho_{i,j},\rho_{i,l},P_i^c,P_j^d,P_l^d} & \Big\{\sum\nolimits_{i\in C,j\in S,l\in N}\left[\log\left(1+SINR_i^c\right)\right] \\
& +\rho_{i,j}[\log(1+SINR_j^d)] \\
& +\rho_{i,l}\left[\log\left(1+SINR_l^d\right)\right]\Big\}\Big\} \qquad (8)\\
\text{s. t. } & SINR_l^d \geq SINR_0^d \qquad (8a)\\
& \Pr\left\{SINR_j^d \leq SINR_0^d\right\} \leq p_0, \quad \forall j \in S \qquad (8b)\\
& \rho_{i,l} \in 0, 1\}, \quad \forall i \in C,\ \forall l \in N \qquad (8c)\\
& \rho_{i,j} \in \{0, 1\}, \quad \forall i \in C,\ \forall j \in S \qquad (8d)\\
& 0 \leq P_i^c \leq P_{max}^c, \quad \forall i \in C \qquad (8e)\\
& \sum\nolimits_{\mathrm{l}\in \mathrm{N}} \rho_{\mathrm{i,l}}\mathrm{P_l^d} \leq \mathrm{P_{max}^d}, \quad \forall \mathrm{i} \in \mathrm{C},\ \forall \mathrm{l} \in N \qquad (8f)\\
& \sum\nolimits_{j\in S} \rho_{i,j}P_j^d \leq P_{max}^d, \quad \forall i \in C,\ \forall j \in S \qquad (8g)\\
& \frac{(-v_{relative}L_{kk'} + /v_{relative}/D_{set})}{/v_{relative}/^2} \geq T_{set} \qquad (8h)
\end{aligned}$$

where $SINR_0^d$ in (8a) is the minimum SINR to establish a reliable V2V link. p_0 in (8b) is the tolerable outage probability limit. P_{max}^c in (8e) and P_{max}^d in (8f)-(8g) are the maximum transmission powers of V2I and V2V transmitters, respectively. T_{set} and D_{set} are the minimal duration time and maximum allowable transmission distance of V2V links, respectively. $v_{relative}$ and $L_{k,k'}$ are the relative speed and distance of the two vehicles k and k' in V2V links, respectively. Constraint (8b) represents the minimum reliability requirement for S-VUE., where the probability is evaluated in terms of the random fast fading of radio channels. Constraints (8c) and (8d) mathematically model our assumption that the spectrum of one CUE can only be shared with a single S-VUE or N-VUE and one S-VUE or N-VUE is only allowed to access the spectrum of one CUE. Constraints (8e), (8f), and (8g) are the transmission power limits for CUEs and VUEs to ensure that they will not exceed the maximum transmission power. Constraint (8h) is the requirement for the sustainable time of V2V links, which can further improve the reliability of V2V links.

The above mathematical optimization problem considers both the particularity of time-varying channels in vehicle networks and the different QoS requirements of terminal vehicles. It is a non-convex optimization problem. In this paper, we can resolve it by dual decomposition method. For the power allocation sub-problem, it can be solved based on different QoS and power constraints for terminal vehicles. Considering the dynamic characteristics of vehicular communications and the imperfect CSI, we will propose a clustering algorithm to divide the V2V links into two clusters, i.e. S-VUE and N-VUE. Finally, we will use graph theory to solve the clustering interference problem for the spectrum sharing V2V links.

III. TWO-WAY VEHICLE MOBILITY DESIGN

In this section, we will develop a robust vehicle matching scheme based on the high mobility characteristics of vehicles on two-way highway scenarios. This design relies on some parameters such as vehicle speed, vehicle distance positioning, vehicle trajectory recognition, and so on.

The estimated distance, $L_{k,k'}$, between the receiving and transmitting vehicles in V2V links can be expressed as

$$L_{k,k'} = D_{k,k'} + \frac{1}{M} \sum\nolimits_{m=1}^{M} v_{relative} \Delta t_m, \tag{9}$$

where

$$D_{k,k'} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2)}. \tag{10}$$

Denote coordinate origin as BS, (x_1, y_1) and (x_2, y_2) are the vehicular position coordinates of transmitter and receiver, respectively. $1/M(\sum_{m=1}^{M} v_{relative} \Delta t_m)$ is the expectation of the relative displacement value of vehicle matching pair. Thus, the sustainable time of vehicle matching pair can be obtained as

$$T_{k,k'} = \frac{\left(-v_{relative} L_{k,k'} + /v_{relative}/D_{set}\right)}{/v_{relative}/^2}, \tag{11}$$

where $D_{set} \leq D_{max}$, D_{max} is the road length covered by the BS. The communication matching pair is allowed to established only if the sustainable time is not less than the time threshold as

$$\mathrm{T}_{k,k'} \geq T_{set}, \tag{12}$$

where T_{set} is the time threshold. Otherwise, the V2V link cannot complete the communication transmission and match with each other.

From the above presentation, to find the optimal solution for optimization problem in (8a), our proposed vehicle matching algorithm based on terminal node mobility can be summarized in Table 1. From Table 1, the total complexity of the proposed vehicle matching algorithm is O(K), which has linear complexity and is scale linearly with the number of terminal V2V links.

IV. RESOURCE ALLOCATION

In this section, we decompose the resource management optimization problem in (8a) into three sub-problems: clustering algorithm, power allocation, and spectrum sharing.

A. CLUSTERING ALGORITHM

In general, the terminal vehicles will send their status information to their base stations periodically. So, the base stations

TABLE 1. Vehicle matching algorithm.

Algorithm 1 Matching Algorithm Based on Vehicle Mobility

Send: Vehicle status information, number of V2V links: K
Result: Get K pairs V2V link based on filtering conditions
Initialize: The distribution of vehicles on roads obeys Poisson distribution. The set of indVUE1 contains the user index applying for communication transmission, where indVUE1={1,...,K}
for i = 1:numVUE **do**
  if any(abs(i-indVUE1)==0) ||any(abs(i-indVUE2)==0)
    continue;
  end
  Find the shortest distance combination that can be matched by the set of indVUE1 and put it into the set of indVUE2.
end
for j=1:numVUE **do**
  if $L_{j,j'} \leqslant D_{set}$
      Calculate $\mathrm{T}_{j,j'} = \frac{(-v_{relative} L_{j,j'} + /v_{relative}/D_{set})}{/v_{relative}/^2}$
    if $\mathrm{T}_{j,j'} \leqslant \mathrm{T}_{set}$
   Delete the link that does not meet the requirements
   In the remaining points, follow the same criteria as above until a suitable member is found to join the set of indVUE1 and indVUE2.
    end
  end
end

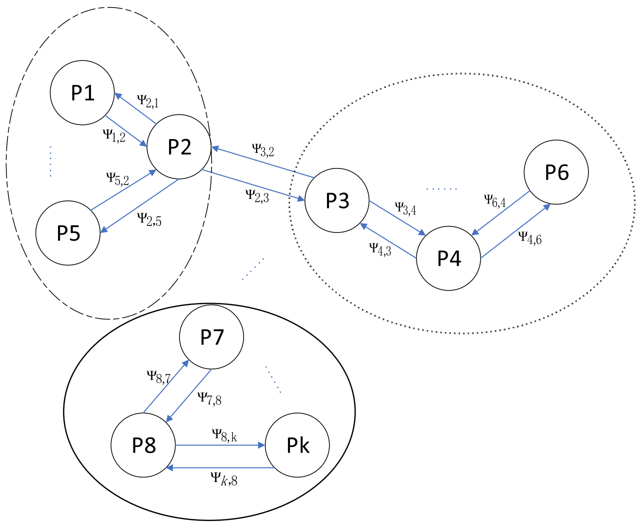

FIGURE 2. Interference connection graph of V2V links.

know the entire vehicle network topologies. According to the clustering strategy, they will reasonably allocate the spectrum resources and forward the relevant information to terminal vehicles to realize the centralized optimal network management. In addition, recognizing the advantage of multiplexing technology for spectrum efficiency, we divide the V2V links into different clusters and all vehicles in the same cluster can reuse the spectrum from one V2I matching link. However, there will bring out lots of mutual interference between V2V links in a same cluster. The corresponding interference relationship graph is shown in Fig. 2, where each V2V link is modeled as a vertex and the interference between two vertices is modeled as an edge. Here, we will allocate V2V links into appropriate clusters so as to share spectrum with minimal mutual interference. The clustering issue can be transformed

TABLE 2. Clustering algorithm.

Algorithm 2 Clustering Algorithm Based on Large-scale Fading
Send: The vehicle matching result of Algorithm 1, vehicle status information
Result: Sets of S-VUE and N-VUE
1: Initialization
2: **for** i = 1: K **do**
3: **for** j=1:K **do**
4: Calculate the estimated distance $L_{i,j}$ between the transmitter and receiver in all V2V links by (9)
5: **end**
Obtain the value of large-scale fading between all links by (1), i.e., the maximum weight coefficient moment $\sum_{e\in E(V)}\Psi_e$
6: **end**
7: Use the Prim algorithm in [23] to search for the smallest spanning tree in the weighted connected graph and find the connected graph with the least inter-cluster interference
8: Get a K/Q row, K column matrix; each row is the same cluster member.

into a graph partition problem and its brief description is summarized in Table 2.

Denote G as a graph with vertex set $V(G)$ and edge set $E(V)$. We divide the K vertices of graph G into K/Q disjoint clusters, i.e. $P(1),\ldots,P(K/Q)$, and $P1\cup\ldots\cup P(K/Q)=V(G)$, where Q is the vehicle number of each cluster. So, the topological relationship of the graph G can be expressed as

$$\sum\nolimits_{k/q}\left(\sum\nolimits_{k,k'\in P(k/q)}\Psi_{k,k}\right)+\sum\nolimits_{a\in Pi,b\in Pj,i<j}\Psi_{a,b} = \sum\nolimits_{e\in E(V)}\Psi_e \tag{13}$$

where $\Psi_{a,b}$ is the large-scale fading channel gain between transmitters in different clusters, $\Psi_{k,k}$ is the large-scale fading channel gain between transmitters in intra-cluster. Based on the Prim algorithm for graph theory in [23], it can search a tree formed by the subset of graph edges and all vertexes in the connected graph. Furthermore, the sum of weights of all graph edges is the smallest value. Taking the mutual interference as the graph edge in Fig. 2, we further propose an algorithm based on large-scale fading channels to solve the clustering issue for minimizing the inter-cluster interference, as shown in Table 2, which can help to reduce the complexity of the optimization problem in (5). Note that the computational complexity of the proposed clustering algorithm 2 is $O(K^2)$. Because we only need divide two clusters, i.e. safety and non-safety applications for V2V links, $K/Q=2$.

B. POWER ALLOCATION

In this part, we study the optimal power control scheme for the vehicle matching pairs based on QoS and reliability requirements, i.e.

$$\max_{P_i^c,P_j^d,P_l^d}\left\{\sum\nolimits_{i\in C,j\in S,l\in N}\log\left(1+SINR_i^c\right) +\log\left(1+SINR_j^d\right)+\log\left(1+SINR_l^d\right)\right\} \tag{14}$$

$$\text{s. t. } SINR_l^d\geq SINR_0^d \tag{14a}$$

$$\Pr\left\{SINR_j^d\leq SINR_0^d\right\}\leq p_0,\quad \forall j\in S \tag{14b}$$

$$0\leq P_i^c\leq P_{max}^c,\quad \forall i\in C \tag{14c}$$

$$0\leq P_j^d\leq P_{max}^d,\quad \forall j\in S \tag{14d}$$

$$0\leq P_l^d\leq P_{max}^d,\quad \forall l\in N. \tag{14e}$$

In order to guarantee the QoS requirement of S-VUE, the N-VUE will obtain the minimum required SINR. Thus, the constraint in (14a) can get the boundary value as

$$SINR_l^d=SINR_0^d. \tag{15}$$

From (4), taking the maximum transmit power values of CUE and S-VUE in (15), we can obtain the marginal transmit power of N-VUE as follows.

$$P_l^d=\frac{SINR_0^d(P_i^c h_{i,l}+P_j^d h_{j,l})}{h_l} =\frac{SINR_0^d\left(P_{max}^c h_{i,l}+P_{max}^d h_{j,l}\right)}{h_l}. \tag{16}$$

Furthermore, given that the small-scale fading θ obeys an exponential distribution with unit mean and based on [20], the constraint (14b) can be derived into

$$\Pr\left\{SINR_j^d\leq SINR_0^d\right\}=\int_0^\infty d\theta_{i,j}\int_0^\infty d\theta_{l,j} \times\int_0^{\frac{SINR_0^d(\sigma^2+P_i^c\Psi_{i,j}\theta_{i,j}+P_l^d\Psi_{l,j}\theta_{l,j})}{\Psi_j P_j^d}} \times e^{-(\theta_{i,j}+\theta_{l,j}+\theta_j)}d\theta_j\leq p_0. \tag{17}$$

Integrate the above formula into Appendix, we can obtain

$$P_i^c\leq\frac{\Psi_j P_j^d}{SINR_0^d\Psi_{i,j}} \times\left(\frac{\Psi_j P_j^d}{(1-p_0)\left(SINR_0^d P_l^d\Psi_{l,j}+\Psi_j P_j^d\right)}-\frac{\sigma^2}{\Psi_j}-1\right) \triangleq f\left(P_j^d\right), \tag{18}$$

where $f(x)$ denotes a function about variable x. Based on $P_i^c\geq 0$ in [20], we define the minimal value of P_j^d by setting $f\left(P_j^d\right)=0$ as

$$P_{j,min}^d\triangleq\frac{(1-p_0)\left(SINR_0^d P_l^d\Psi_{l,j}\right)}{(\frac{1}{A}+p_0-1)\Psi_j}. \tag{19}$$

where $A=1+\frac{\sigma^2}{\Psi_j}$. And then, the optimal power of P_i^c can be expressed as

$$P_i^{c*}=min(P_{max}^c,f(P_{max}^d)) \tag{20}$$

Considering the inverse function $f^{-1}(P_i^c)$ of $f(P_j^d)$ and $f^{-1}\left(P_i^c\right)=0$, we can obtain $P_{i,min}^c$ and $f^{-1}(P_{max}^c)$ in the range of $(P_{i,min}^c,+\infty)$. The optimal power distribution of P_j^d can be expressed as

$$P_j^{d*}=min\left(P_{max}^d,f^{-1}\left(P_{max}^c\right)\right) \tag{21}$$

TABLE 3. Hall algorithm for spectrum sharing.

Algorithm 3 Hall Algorithm for the Spectrum Sharing of V2I Links

Send: P_i^{c*}, P_j^{d*}, P_l^d

Result: reuse pattern$\{\rho_{i,j}, \rho_{i,l}\}$

1: Initialization

2:**for** C=1,2,…,i **do**

3: **for** S=1,2,…,j **do**

4: Put the obtained power into (5) to obtain the channel capacity R_i^c of cellular user

5: **end**

6:**end**

7: Based on R_i^c, use hall algorithm to find the best reuse pattern $\{\rho_{i,j}, \rho_{i,l}\}$

TABLE 4. Simulation parameters [20], [24].

Parameter	Value
Carrier frequency fc/bandwidth	2 GHz/10 MHz
Transmission range	500 m-2000 m
Cell radius	2000 m
BS receive gain	8 dB*i*
BS receiver noise level	5 dB
Vehicle speed	30 km/h-120 km/h
Number of S-VUE	6-30
Number of N-VUE	6-30
Number of CUE	6-30
P_{max}^d	11,17,23 dB
P_{max}^c	23 dB
T_{set}	3 s
D_{set}	600 m

C. SPECTRUM SHARING

The optimal spectrum sharing problem in (8a), i.e. spectrum reuse between CUEs and VUEs, can be formulated as

$$\max_{\rho_{i,j},\rho_{i,l}} \left\{ \sum\nolimits_{i\in C, j\in S, l\in N} \log\left(1+SINR_i^c\right) + \rho_{i,j}\log\left(1+SINR_j^d\right) + \rho_{i,l}\log\left(1+SINR_l^d\right) \right\}. \quad (22)$$

From the above, P_i^c increases monotonically with P_j^d increasing and it can get a maximum value $f(P_{max}^d)$ under (8c) and (8d). So, the maximum-weight bipartite matching problem can be solved by using the hall method [12], which is detailed in Table 3. From Table 3, the total complexity of our hall algorithm to find the optimal solution for spectrum sharing problem is O(K^3).

V. SIMULATION RESULTS

In this section, computer simulations are presented to confirm the proposed resource management algorithm for dynamic vehicular networks. We consider the network environment with a two-way highway covered by a BS and fix the communication coverage radius of BS at 500 meters. The vehicles are distributed on the road according to spatial random process and the distance between vehicles is determined by the transmission speed and relative distance. We select i pairs of V2I links randomly and use proposed vehicle matching algorithm to generate k matching pairs of V2V links. Other simulation parameters are listed in Table 4 [20], [24].

Fig. 3 shows the total channel capacity of vehicular networks under different vehicle speeds. It is observed that the system capacity has a downward trend as vehicle speed increasing. This is because that the relative distance between vehicles becomes larger as speed increasing. We present our proposed cluster-based resource management scheme under mobility environment and bidirectional lane consideration comparing with some existing algorithms, such as clustering Algorithm 2 with Greedy scheme in [25], vehicle matching scheme based on the minimum distance in [20], and its transforming with our clustering Algorithm 2. According to the simulation result calculation, compared with [20] with our proposed Algorithm 2, our channel capacity performance can be increased more than 25.31%. Obviously, the clustering technology can improve the channel capacity, although there is more and more mutual interference when the transmission speed is high enough. It can also be found that our proposed algorithm with Prim for searching vehicle matching pairs outperforms the one with Greedy scheme and the channel capacity performance is increased by 2.78%. Because our strategy not only considers the closest distance but also requires that the link duration time must be greater than the threshold time requirement. Furthermore, if we increase the requirement of link sustainable time, there are less V2V links which can achieve the QoS for matching pairs.

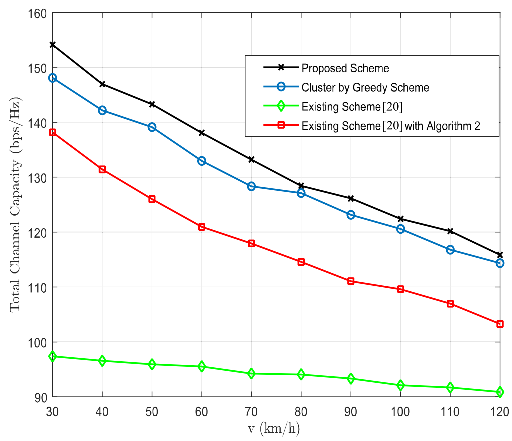

FIGURE 3. Total channel capacity over distinct vehicles speed.

In Fig. 4, we shows the relationship between traffic density and network total channel capacity. The traffic density is defined as the number of vehicles in a unit length lane at a certain instant. The number of vehicles in a lane is mainly determined by the factor of speed. The higher the speed, the greater the relative distance between vehicles, and the sparser the vehicles in the lane. This means that the smaller abscissa, the faster vehicular speed. Compared with the algorithms based on the minimum distance links, our algorithm achieves more than 5.75% improvement under different traffic densities. Compared with the greedy algorithm in [21], our algorithm achieves a performance improvement about 4.01% in terms of channel capacity. In the case of high traffic density, our performance is especially better, which profits from the rationality of the vehicle matching algorithm and clustering algorithm.

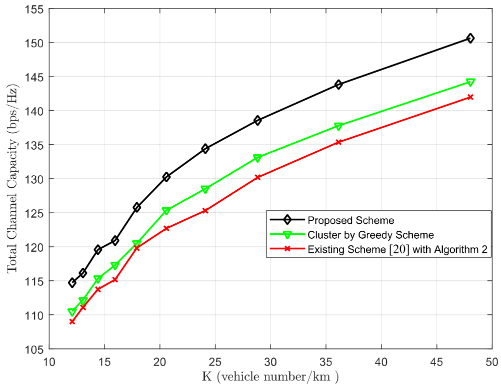

FIGURE 4. Total channel capacity over distinct traffic density.

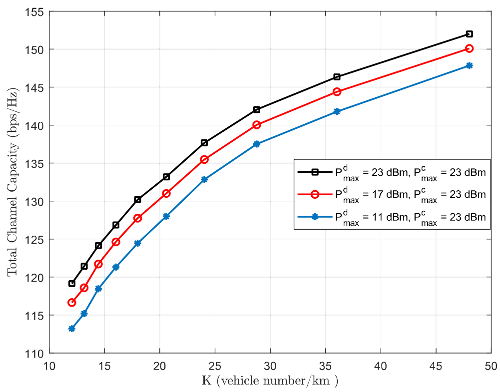

FIGURE 5. Total channel capacity over distinct traffic density with distinct P^d_{max}.

Fig. 5 shows the relationship between the traffic density and the total system capacity under the maximum power of V2V links. We can observe that the total channel capacity will drop as the maximal transmission power decreasing, i.e. the received interference reducing. However, the decreasing rate of system capacity of V2V links is greater than the ones of V2I links and the overall trend of total channel capacity is downward.

Fig. 6 shows the total system capacity over different vehicle speed and maximum allowable transmission distance of V2V links. It can be observed that the smaller the maximum effective distance, the larger the total channel capacity. This is because that the smaller the maximum effective distance, the smaller the relative displacement, and its channel gain becomes larger. So, the channel capacity is improved.

In Fig. 7, it can be seen that increasing transmission power of V2V links can increase the system capacity. Although the received mutual interference of V2I links becomes greater at this time, the channel capacity still becomes better. This is because the number of V2V links is more than the ones of V2I links and the channel capacity growth rate of V2V link is greater than the decline rate of cellular V2I channel capacity. Thus, the channel capacity is showing an upward trend. Similarly, in Fig. 8, we can observe that reducing the minimum communication distance between vehicles can increase the network channel capacity. This is because the distance affects the channel gain, which in turn affects the channel capacity. The shorter the communication distance, the greater the channel gain.

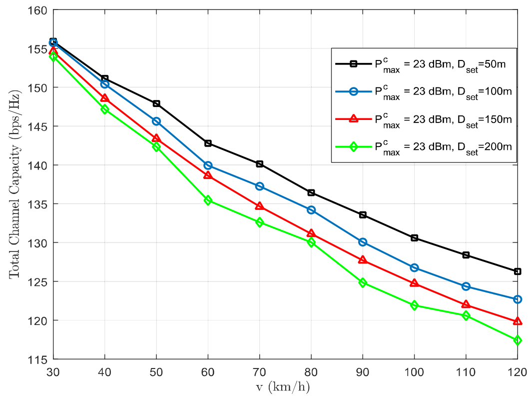

FIGURE 6. Total channel capacity over distinct vehicle speed with different D_{set}.

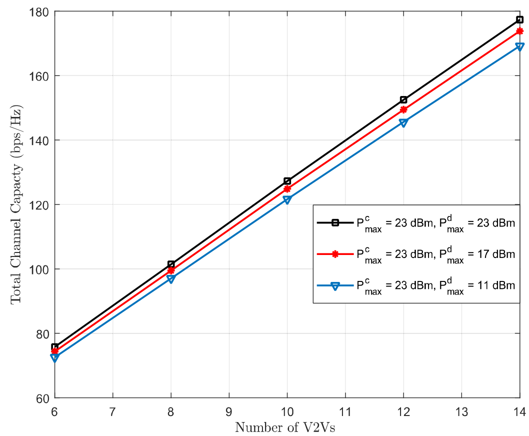

FIGURE 7. Total channel capacity over different number of V2V links with distinct P^d_{max}.

VI. CONCLUSION

This paper studies the resource management problem for vehicular communication networks. Based on the rapid variability of channel state from the high mobility vehicles, we propose a clustering algorithm based on large-scale fading to improve spectrum utilization and construct a more realistic two-way lane model for actual vehicular environments. Considering the complexity of two-way lanes, we further propose a low-complexity vehicle matching algorithm to solve the link interference in high-speed vehicles. The simulation results show that our resource allocation algorithm has better performance compared with the existing schemes.

APPENDIX

According to the definition of link reliability requirement in (14b) and based on [20], the constraint (14b) can

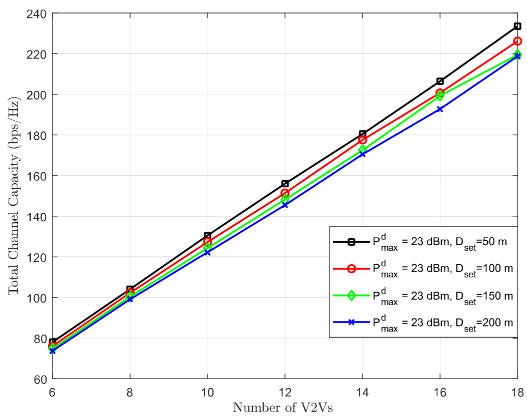

FIGURE 8. Total channel capacity over different number of V2V links with different D_{set}.

be derived into

$$\begin{aligned}
&\Pr\left\{SINR_j^d \le SINR_0^d\right\} \\
&= \Pr\{SINR_j^d = \frac{P_j^d h_j}{\sigma^2 + \sum_{i\in C}\rho_{i,j}P_i^c h_{i,j} + \sum_{l\in N}\rho_{i,l}P_l^d h_{l,j}} \\
&\quad \le SINR_0^d\} \\
&= \int_0^\infty d\theta_{i,j}\int_0^\infty d\theta_{l,j}\int_0^{\frac{SINR_0^d\left(\sigma^2+P_i^c\Psi_{i,j}\theta_{i,j}+P_l^d\Psi_{l,j}\theta_{l,j}\right)}{\Psi_j P_j^d}} \\
&\quad \times e^{-(\theta_{i,j}+\theta_{l,j}+\theta_j)}d\theta_j.
\end{aligned}$$

Using stepwise integration and giving that the small-scale fading θ obeys an exponential distribution with unit mean, we continue to deduce as

$$\begin{aligned}
&= \int_0^\infty d\theta_{i,j}\int_0^\infty e^{-(\theta_{i,j}+\theta_{l,j})}d\theta_{l,j} \\
&\quad \times \int_0^{\frac{SINR_0^d(\sigma^2+P_i^c\Psi_{i,j}\theta_{i,j}+P_l^d\Psi_{l,j}\theta_{l,j})}{\Psi_j P_j^d}} e^{-\theta_j}d\theta_j \\
&= \int_0^\infty d\theta_{i,j}\int_0^\infty e^{-(\theta_{i,j}+\theta_{l,j})} \\
&\quad \times e^{\frac{-SINR_0^d(\sigma^2+P_i^c\Psi_{i,j}\theta_{i,j}+P_l^d\Psi_{l,j}\theta_{l,j})}{\Psi_j P_j^d}-\theta_{i,j}-\theta_{l,j}} d\theta_{l,j} \\
&= \int_0^\infty e^{\theta_{i,j}}d\theta_{i,j}\int_0^\infty e^{-\theta_{l,j}}d\theta_{l,j} \\
&\quad - \int_0^\infty e^{\frac{-SINR_0^d(\sigma^2+P_i^c\Psi_{i,j}\theta_{i,j})}{\Psi_j P_j^d}-\theta_{i,j}} d\theta_{i,j} \\
&\quad \times \int_0^\infty e^{\frac{-SINR_0^d\Psi_{l,j}\theta_{l,j}}{\Psi_j P_j^d}-\theta_{l,j}} d\theta_{l,j} \\
&= 1 - \frac{(\Psi_j P_j^d)^2}{(SINR_0^d P_l^d\Psi_{l,j}+\Psi_j P_j^d)[SINR_0^d\left(\sigma^2+P_i^c\Psi_{i,j}\right)+\Psi_j P_j^d]}.
\end{aligned} \tag{23}$$

Therefore, from the above process, parameter θ has be counteracted by integrating and the transmit power of CUE and S-VUE mainly are affected by the large-scale fading gain Ψ. According to (17), we can simplify the inequality as

$$1 - \frac{(\Psi_j P_j^d)^2}{\left(SINR_0^d P_l^d\Psi_{l,j}+\Psi_j P_j^d\right)\left[SINR_0^d\left(\sigma^2+P_i^c\Psi_{i,j}\right)+\Psi_j P_j^d\right]} \le p_0, \tag{24}$$

that is,

$$\begin{aligned}
&\frac{(\Psi_j P_j^d)^2}{(1-p_0)(SINR_0^d P_l^d\Psi_{l,j}+\Psi_j P_j^d)} \le SINR_0^d\left(\sigma^2+P_i^c\Psi_{i,j}\right) \\
&\quad +\Psi_j P_j^d
\end{aligned} \tag{25}$$

$$\begin{aligned}
&\frac{(\Psi_j P_j^d)^2}{SINR_0^d(1-p_0)(SINR_0^d P_l^d\Psi_{l,j}+\Psi_j P_j^d)} - \frac{\Psi_j P_j^d}{SINR_0^d} - \sigma^2 \\
&\ge P_i^c\Psi_{i,j}.
\end{aligned} \tag{26}$$

Then we can obtain the following conclusion

$$\frac{\Psi_j P_j^d}{SINR_0^d\Psi_{i,j}}\left(\frac{\Psi_j P_j^d}{(1-p_0)\left(SINR_0^d P_l^d\Psi_{l,j}+\Psi_j P_j^d\right)} - \frac{\sigma^2}{\Psi_j} - 1\right) \ge P_i^c. \tag{27}$$

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