Joint Allocation of Wireless Resource and Computing Capability in MEC-Enabled Vehicular Network

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Abstract: In MEC-enabled vehicular network with limited wireless resource and computation resource, stringent delay and high reliability requirements are challenging issues. In order to reduce the total delay in the network as well as ensure the reliability of Vehicular UE (VUE), a Joint Allocation of Wireless resource and MEC Computing resource (JAWC) algorithm is proposed. The JAWC algorithm includes two steps: V2X links clustering and MEC computation resource scheduling. In the V2X links clustering, a Spectral Radius based Interference Cancellation scheme (SR-IC) is proposed to obtain the optimal resource allocation matrix. By converting the calculation of SINR into the calculation of matrix maximum row sum, the accumulated interference of VUE can be constrained and the the SINR calculation complexity can be effectively reduced. In the MEC computation resource scheduling, by transforming the original optimization problem into a convex problem, the optimal task offloading proportion of VUE and MEC computation resource allocation can be obtained. The simulation further demonstrates that the JAWC algorithm can significantly reduce the total delay as well as ensure the communication reliability of VUE in the MEC-enabled vehicular network.

Keywords: vehicular network; delay optimization; wireless resource allocation; matrix spectral radius; MEC computation resource allocation

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I. INTRODUCTION

With the rapid growth of smart cars and wireless communication, a number of advanced technologies such as self-driving and video-aided real-time navigation have emerged in vehicular network [1–4]. The implementation of these applications requires strong computational capability to manage various tasks that are computationally-intensive and delay-sensitive [5, 6]. To cope with the problems such as pool terminal computing capability, Mobile Edge Computing (MEC) is considered to be a promising paradigm[7–10]. With MEC, the computation tasks of vehicles can be forwarded to the MEC server through wireless link [11, 12] to reduce the local computing delay. However, with the increasing tasks being forwarded to MEC server, since the wireless and computation resource are limited, the co-channel interference among vehicles will increase dramatically and great pressure will be put on the MEC server [13, 14], which will lead to high delay and low reliability for vehicle. Specifically, the delay in MEC-enabled vehicular network is categorized two types: the communication delay and the computing delay. The communication delay is mainly affected by the accumulated interference which is caused by other vehicles sharing the same wireless resource. The computation delay is not only affected by task offloading proportion, but also by the MEC computation capability scheduling. And the communication reliability of vehicles mainly depends on the co-channel interference.

Some wireless resource allocation mechanisms are proposed to mitigate interference among vehicles, in order to minimize vehicle communication delay [15–17]. In [18], an alternative greedy heuristic resource block (RB) sharing algorithm is introduced to constrain the accumulated interference of vehicle-to-vehicle (V2V) links. However, it ignores that vehicle-to-infrastructure (V2I) links also exist, and resource blocks are shared by V2V links and V2I links. In [19], the interference relations among different vehicle-to-everything (V2X) links are formulated as a novel interference-aware graph. Then a resource sharing algorithm utilizing interference-aware graph is constructed to obtain the near optimal solution for resource allocation. In [20], the delay and reliability requirements of V2V links are transformed into optimization problem which is determined only by the slowly changing channel information, and the authors propose a separate RB and power allocation scheme. A location-dependent resource allocation scheme (LDRAS) is implemented at the expense of spectral performance in [21], which could ensure a certain maximum interference level. In [22], a time dynamic optimization scheme is introduced to reduce communication delay through optimization of the wireless resources and constraining the network switching rate. In [23], a graph-based V2V partitioning algorithm is proposed to separate V2V links with high mutual interference into different clusters. However, it will lead to unstable clustering result due to the first vertex which is randomly selected. At the same time, the complexity of the implementation will increase dramatically as the number of V2V links increases.

In order to cope with the issues such as pool terminal computing capability, computationally-intensive tasks, etc., some task offloading and MEC computation resource scheduling strategies were proposed to enable terminal to utilize the powerful computational capability of MEC server [24–27]. In [28], the problem is conceived as a multiple-user task offloading game to reduce the delay and a distributed algorithm is proposed. However, the local computation resource of VUE would not be effectively utilized if all tasks are offloaded to MEC server. In [29], a task offloading method based on machine learning is proposed to achieve efficient and reliable task offloading under information uncertainty. Aiming to reduce the average delay of task offloading, the authors in [30] proposed a task offloading algorithm using multi-armed bandit (MAB) theory. To decrease the local processing delay of vehicles, the author in [31] proposed a software-defined network architeture (SDN) based on load-balancing algorithm where vehicles could offload the computational tasks partly to MEC server. In [32], a federated offloading algorithm is proposed to improve the computation resource utilization and decrease processing delay. However, the task offloading proportion is only optimized for a vehicle, not the global optimal.

In the MEC-enabled vehicular network, computational tasks of vehicle can be partially offloaded to MEC server via V2I wireless resource which can be shared by V2V vehicles. And MEC server will schedule computing resources for tasks transmitted by V2I links. In order to minimize the total delay as well as ensure the reliability of vehicles at the same time, the wireless resource allocation and MEC computation resource scheduling need to be jointly considered and optimized [33, 34]. In this context, a Joint Allocation of Wireless resource and MEC Computing resource (JAWC) algorithm based on spectral radius estimation theory is proposed. Specifically, there are mainly two steps in the proposed algorithm, V2X links clustering and MEC computation resource scheduling. Firstly, in the V2X links clustering phase, the reliability requirement of V2X links which contain V2I links and V2V links is transformed into a matrix spectral radius constraint to ensure that the interference among vehicles is less than a preset threshold. Then, a Spectral-Radius-based Interference Cancellation (SR-IC) heuristic clustering algorithm is proposed to divide V2X links into different clusters. After the V2X links clustering, the optimal task offloading proportion and MEC computation resource allocation can be calculated in MEC computation resource scheduling step. The main contributions of this work can be summarized as follows:

- Transform the SINR requirements of V2X links into a matrix spectral radius constraint to ensure that the interference among vehicles is less than a preset threshold. By converting the calculation of matrix spectral radius into the calculation of matrix maximum row sum, the calculation complexity can be significantly reduced and the reliability of V2X links can be well ensured.

- The JAWC algorithm is implemented to minimize the total delay in MEC-enabled vehicular network. In order to maximize the transmission rate of vehicle, the algorithm considers the rational RBs allocation to minimize the accumulated interference among V2X links. And on the basis of full use of local CPU and MEC server computing resources, the optimal task offloading proportion and MEC computation resource allocation are given.
- The JAWC algorithm consists of two steps. In the V2X clustering step, a Spectral-Radius-based Interference Cancellation (SR-IC) heuristic clustering algorithm is proposed. Then in the MEC computation resource scheduling stage, a convex problem is formulated to obtain the optimal solution.

The remainder of this paper is outlined as follows. Section II defines the system model and formulates the optimization problem. Section III presents the JAWC algorithm. Simulation results are described in Section IV. Finally, the paper is concluded in Section V.

II. SYSTEM MODEL

The scenario considering hybrid V2V and V2I transmission is shown in Figure 1, where a total of M V2X links are in the coverage of an RSU equipped with an MEC sever. Specifically, there are J V2I links and K V2V links. The computational tasks of vehicles can be partly fowarded to the MEC server via V2I links. Then the MEC server will schedule computation resource for the task. For illustration purpose,we denote V=$\{v_1, v_2, ...v_M\}$,V_{V2I}=$\{v_{V2I,1}, v_{V2I,2} \cdots v_{V2I,J}\}$ and V_{V2V}=$\{v_{V2V,1}, v_{V2V,2} \cdots v_{V2V,K}\}$ to be the vehicle sets for all V2X links, V2I links, as well as V2V links, respectively. There are a total of N RBs that can be allocated to V2I links and V2V links. We assume that each V2I link occupies a different RB and V2V link can share the RBs occupied by V2I link.

In this paper, we consider that the resource allocation is in a time slot, in which the channel condition remain constant. Due to the mobility of vehicles, we assume that the channel power gain from the *i-th* transmitting VUE to the *j-th* receiving VUE, denoted by h_{ij}, is formulated as h_{ij}=$g_{ij}\varphi_{ij}$, where g_{ij} and φ_{ij} represent the slowly varying large-scale fading and the fast varying small-scale fading, respectively.

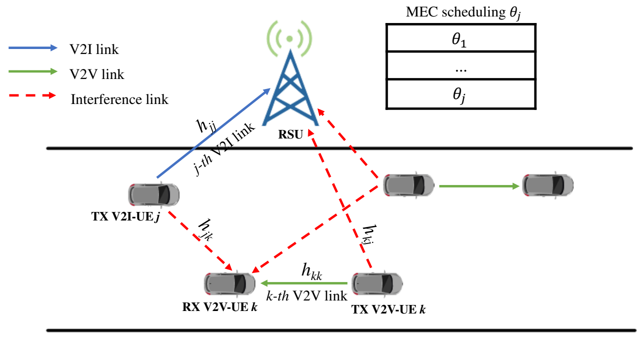

Figure 1. *System model of vehicular network with hybrid V2V and V2I transmission.*

In this work, we consider Rayleigh fast fading for all VUEs[16]. Specifically, h_{ii} denotes effective channel power gain between the transmitter and the receiver in the *i-th* V2X link. We define the transmit power vector of all V2X links as P=$(P_1, P_2, ..., P_M)^T$, where the *i-th* element denotes the transmit power of the *i-th* V2X link. And σ^2 denotes the additive white Gaussian noise power.

2.1 QoS Requirements

In order to guarantee high communication reliability, we define a SINR requirement matrix Γ=diag$(\gamma_1, \gamma_2, ..., \gamma_M)$, where γ_i represents the SINR threshold for the *i-th* V2X link. For illustration purpose, several matrices are defined to concisely describe the SINR constraint in the following.

Definition 1. *RB Allocation Matrix. RB allocation matrix* $X = (x_{mn})_{M\times N}$ *is defined to be*

$$X = \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1N} \\ x_{21} & x_{22} & \cdots & x_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ x_{M1} & x_{M2} & \cdots & x_{MN} \end{pmatrix}. \quad (1)$$

where

$$x_{m,n} = \begin{cases} 1, if\ the\ RB_n\ is\ allocated\ to\ the \\ \quad m_{th}\ V2X\ link, \\ 0, otherwise. \end{cases} \quad (2)$$

for $1 \le m \le M, 1 \le n \le N, M = J + K.$

Definition 2. *RB Sharing Matrix. The wireless resource sharing matrix $R = (r_{ij})_{M\times M}$ is defined to be*

$$R = \begin{pmatrix} 0 & r_{12} & \cdots & r_{1M} \\ r_{21} & 0 & \cdots & r_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ r_{M1} & r_{M2} & \cdots & 0 \end{pmatrix}. \tag{3}$$

where

$$r_{i,j} = \begin{cases} 1, if\ the\ i_{th}\ V2X\ link\ and\ the\ j_{th} \\ \quad V2X\ link\ occupy\ the\ same\ RB, \\ \qquad\qquad 0, otherwise. \end{cases} \tag{4}$$

for $1 \le i, j \le M$.

Particularly, $r_{ij} = 0$ if $i = j$. Since there are a total of N RBs available, there are a total of N resource sharing matrices which can be denoted as $R_1, R_2, ..., R_N$.

For a given resource allocation matrix X, when different V2X links occupy the same RB, the co-channel interference will occur inevitably. In this case, to ensure the communication reliability, the SINR requirement at the *i-th* V2X link receiver is modeled as follows:

$$\gamma_i(P) \triangleq \frac{h_{ii}P_i}{\sum_j r_{ij}h_{ji}P_j + \sigma^2} \ge \gamma_i. \tag{5}$$

for $1 \le i, j \le M$. We denote P_i to be the transmit power of the *i-th* V2X link transmitter. The r_{ij} is the element of the resource sharing matrix R corresponding to the RB. According to (5), we can obtain

$$P_i - \gamma_i \sum_{i\neq j} r_{ij}(\frac{h_{ji}}{h_{ii}})P_j \ge \frac{\gamma_i\sigma^2}{h_{ii}}. \tag{6}$$

Then, the matrix form of (6) can be obtained

$$(I - A)P \ge u. \tag{7}$$

where $u_i \triangleq \frac{\gamma_i\sigma^2}{h_{ii}}$,$P$=$(P_1, P_2, ..., P_M)^T$ and I is the identity matrix. Matrix A is defined to be

$$A = \Gamma R \circ Y. \tag{8}$$

where Γ denotes the SINR requirement matrix, R denotes the RB sharing matrix. $R \circ Y$ is the Hadamard product which is obtained by multiplying the corresponding elements of matrix R and matrix Y. The definition of matrix Y is given below.

Definition 3. *Channel Power Gain Ratio Matrix. The channel power gain ratio matrix Y is defined to be*

$$Y = \begin{pmatrix} 0 & y_{12} & \cdots & y_{1M} \\ y_{21} & 0 & \cdots & y_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ y_{M1} & y_{M2} & \cdots & 0 \end{pmatrix}. \tag{9}$$

where

$$y_{i,j} = \begin{cases} h_{ji}/h_{ii}, if\ i \neq j, \\ 0, \quad if\ i = j. \end{cases} \tag{10}$$

for $1 \le i, j \le M$. The element y_{ij} describes the interference level caused by the *j-th* V2X link to the *i-th* V2X link.

For (7), in order to get a positive solution P, the necessary and sufficient condition is that the spectral radius of matrix A is less than 1[35]. It can be denoted as

$$\rho(A) < 1. \tag{11}$$

where $\rho(A)$ is the spectral radius of matrix A. Then when the constraint (11) is satisfied, the SINR requirements of all V2X links sharing this RB can be guaranteed.

Finally, for the *i-th* V2X link using the *n-th* RB, the corresponding transmission rate can be denoted as

$$S_i(R_n) = Blog_2(1 + \frac{h_{ii}P_i}{\sum_j r_{ij}h_{ji}P_j + \sigma^2}). \tag{12}$$

where B represents the bandwidth of one RB.

2.2 Delay Model

We denote by c_j the computational tasks of vehicle in the *j-th* V2I link. And assume that the CPU needs Z_0 computation cycles to calculate one bit. The vehicle can offload a part of computational tasks to the MEC server via V2I link and MEC server can allocate computation resource for the offloaded tasks. The β_j, θ_j denote the task offloading proportion and the computation resource allocated by MEC server, respectively. The β_j and θ_j are determined by MEC server. For illustration purpose, we denote Λ =

$[\beta_1, \beta_2, ..., \beta_J], \Theta = [\theta_1, \theta_2, ..., \theta_J]$ as the task offloading proportion vector for all V2I links and the MEC computation resource scheduling vector, respectively.

The delay of the *j-th* V2I link includes two parts: task offloading delay and local computing delay, which are denoted as t_j^{off} and t_j^{loc}, respectively. Since computational tasks of V2I link can be processed in parallel using the local CPU and MEC server, the delay of V2I link is the maximum of t_j^{loc} and t_j^{off}. Then the delay of the *j-th* V2I link can be denoted as

$$T_j(\beta_j, \theta_j, S_j) = max\{t_j^{loc}, t_j^{off}\}. \tag{13}$$

where $0 \leq \beta_j \leq 1$ and θ_j represents computation resource allocated by MEC server. S_j represents the transmission rate of the *j-th* V2I link. The t_j^{loc} and t_j^{off} can be given as

$$t_j^{loc} = \frac{(1-\beta_j)c_j Z_0}{f_{loc}}. \tag{14}$$

$$t_j^{off} = \frac{\beta_j c_j}{S_j} + \frac{\beta_j c_j Z_0}{\theta_j}. \tag{15}$$

where f_{loc} represents the computational resource of the local CPU.

For the *k-th* V2V link, there is no computational tasks to be offloaded to MEC server, but there are some traffics that need to be transmitted from the transmitter VUE to the receiver VUE. Therefore, the V2V link only has communication delay, which can be given as

$$T_k(S_k) = \frac{c_k}{S_k}. \tag{16}$$

where c_k, S_k represents the transmission task size and the transmission rate, respectively.

2.3 Problem Formulation

The objective of this paper is to minimize the global delay in the MEC-enabled vehicular network as well as guarantee the communication reliability of V2X links, then find the optimal resource block allocation matrix, the optimal task offloading proportion vector and the MEC computation resource allocation vector. Based on the previous definitions, the optimization problem can be formulated as follows:

$$\min_{X,\Lambda,\Theta} \sum_{j=1}^{J} T_j + \sum_{k=1}^{K} T_k. \tag{17}$$

$$
\begin{aligned}
s.t.\quad & C1: \sum_{j=1}^{J} x_{j,n} \leq 1, \forall n \in [1, N], \\
& C2: \sum_{n=1}^{N} x_{m,n} = 1, \forall m \in [1, M], \\
& C3: \rho(A_n) < 1, \forall n \in [1, N], \\
& C4: 0 \leq \beta_j \leq 1, \forall j \in [1, J], \\
& C5: \textstyle\sum_{j=1}^{J} \theta_j = \Theta_{max}.
\end{aligned} \tag{18}
$$

where Λ=$[\beta_1, \beta_2, ..., \beta_J]$, Θ=$[\theta_1, \theta_2, ..., \theta_J]$, $\Lambda, \Theta \in \mathbb{C}^{J\times 1}$, Θ_{max} represents the maximum computation resource that the MEC server can allocate to offloading tasks. Constraint $C1$ guarantees that each V2I link occupies a different RB. Constraint $C2$ ensures that each V2X link can be allocated with one RB. Constraint $C3$ guarantees SINR requirements for all V2X links assigned to the *n-th* RB. Constraint $C4$ guarantees that vehicles can offload part of the computational tasks to the MEC server. And constraint $C5$ ensures that the computation resource of the MEC server can be fully utilized by all V2I links. It can be observed that the problem (17) is a NP-hard problem.

Firstly, characteristics of the problem are analyzed. As can be known from Eq.(16), the delay of V2V link is the inverse function of S_k, which is affected by the accumulated interference caused by the V2X links sharing the same RB. As can be known from Eq.(13), the delay of V2I link is the maximum of t_j^{loc} and t_j^{off}, which is affected by the transmission rate S_j, task offloading proportion β_j and MEC computation resource scheduling θ_j. The task offloading proportion β_j determines how much computational tasks of vehicle can be fowarded to the MEC server, which affects the t_j^{loc} and t_j^{off}. For V2I links, the accumulated interference caused by other V2X links sharing the same RB need to be minimized firstly, then the optimal task offloading proportion β_j and MEC computation resource scheduling θ_j can be calculated.

III. THE PROPOSED JAWC ALGORITHM

Because the problem (17) is NP-hard, we give an alternative Joint Allocation of Wireless and MEC computing resource Algorithm (JAWC) instead. There are two main steps in JAWC. Firstly, in the V2X links clustering step, each vehicle reports the Channel State Information (CSI) to the RSU then the RSU allocates RB for each vehicle. In order to minimize the accumulated interference for V2X links, a Spectral Radius based Interference Cancellation heuristic clustering scheme (SR-IC) is proposed to obtain the optimal RB allocation matrix X, the communication reliability of V2X links can be well guaranteed at the same time. By converting the matrix spectral radius constraint into the matrix maximum row sum constraint, the SINR calculation complexity can also be effectively reduced. Secondly, in the MEC computational resource scheduling step, by transforming the original problem into a convex problem, the optimal task offloading proportion vector Λ and the MEC computational resource allocation vector Θ can be obtained.

3.1 V2X Links Clustering

In V2X links clustering step, a SR-IC scheme is proposed to allocate RBs to VUEs, which can minimize the accumulated interference for V2X links. We first replace the constraint $C3$ with a more stringent constraint. According to Frobenius theory [36], assuming the maximum row sum of matrix A is $E(A)$, we can get

$$\rho(A) \leq E(A). \tag{19}$$

Therefore, if the max row sum of matrix A is less than 1, constraint $C3$ is satisfied. So we can repleace the constraint $C3$ with

$$E(A) < 1. \tag{20}$$

By calculating the maximum row sum of the matrix instead of the SINR value of each VUE, not only the SINR requirement of VUEs can be guaranteed, but the calculation complexity can be effectively reduced. For example, n VUEs are allocated the same RB. When we verify whether the communication reliability of the VUEs meet the requirement, if the SINR value of each VUE is directly calculated, the time complexity required is $O(n)$. By calculating the maximum row sum of the matrix, the time complexity required is $O(1)$.

In MEC-enabled vehicular network illustrated in Section II, orthogonal RBs are occupied by different V2I links, however, the V2V links can share the same RBs with V2I links. In addition, the V2I links contain information such as the computing capability of the vehicles and the computing task size. The MEC server needs to determine the task offloading proportion of each vehicle in V2I link and the MEC computation resource allocation based on these information. We assume that the QoS of V2I should be guaranteed first. Therefore, the SR-IC scheme is further decomposed into two sub-parts. Firstly, in the V2I links matching part, V2Vs link and V2Is link are jointly clustered into several clusters. Secondly, in the V2V links clustering part, if there are any V2V links which are not assigned to any cluster after the V2I links matching, the remaining V2V links can be clustered into new clusters.

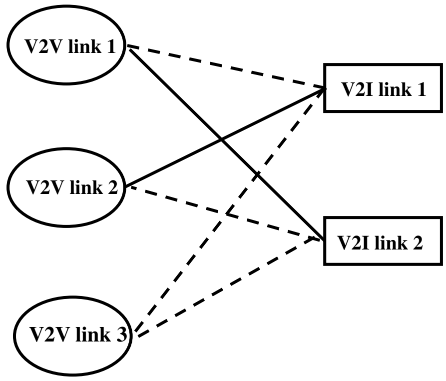

Figure 2. *Bipartite graph representation for mutual interference between V2I links and V2V links.*

3.1.1 V2I Links Matching

In the V2I links matching step, we construct a bipartite graph as illustrated in Figure 2. For the bipartite graph, vertices represent V2I links and V2V links which can be denoted as V_{V2I}=$\{v_{V2I,1}, v_{V2I,2} \dots v_{V2I,J}\}$ and V_{V2V}=$\{v_{V2V,1}, v_{V2V,2} \dots v_{V2V,K}\}$, respectively. The edge between V2I and V2V link represents the mutual interference, which can be denoted as $w_{j,k}$. The weight matrix W of bipartite graph is composed of $w_{j,k}$, where $W \in \mathbb{C}^{J\times K}$.

$$w_{j,k} = h_{jk} + h_{kj}, 1 \leq j \leq J, 1 \leq k \leq K. \tag{21}$$

where h_{jk} is the channel power gain from the *j-th* V2I link to the *k-th* V2V link and h_{kj} is the channel power gain from the *k-th* V2V link to the *j-th* V2I link.

Then in order to divide V2X links into several clusters, a Spectral-Radius-based Interference Cancellation (SR-IC) heuristic clustering algorithm is proposed. There is not a specified clustering threshold in the proposed heuristic algorithm, which is more flexible than other clustering algorithms [37]. And the spectral radius estimation is utilized to ensure the reliability of V2X links at the same time.

Algorithm 1 shows the process of proposed heuristic clustering algorithm.

Algorithm 1. *V2I links matching.*

1: **Input**: W, V_{V2I}, V_{V2V}
2: **while** $V_{V2I} \neq \varnothing$ **do**
3: Select $v_{V2I,j} \in V_{V2I}, v_{V2V,k} \in V_{V2V}$ that correspond to the minimum element in W
4: **if** $E(A_n) < 1$ when add $v_{V2I,j}, v_{V2V,k}$ into cluster C_n **then**
5: Add $v_{V2I,j}, v_{V2V,k}$ into cluster C_n and remove $v_{V2I,j}, v_{V2V,k}$ from V_{V2I}, V_{V2V}
6: Select $v_{V2V,p} \in V_{V2V}$ that will lead to the minimum $H_{Inter,n}$ by traversing all V2V links in V_{V2V}
7: Select the minimum element in W of current bipartite graph as the clustering interference threshold H_{Thre}
8: **while** $H_{Thre} > H_{Inter,n}$ and $E(A_n) < 1$ when add $v_{V2V,p}$ into cluster C_n **do**
9: Add $v_{V2V,p}$ into cluster C_n and remove $v_{V2V,p}$ from V_{V2V}
10: Repeat Step 6 and 7 to update H_{Thre} and $H_{Inter,n}$
11: **end while**
12: $n = n + 1$
13: **else**
14: Add $v_{V2I,j}$ into cluster C_n and remove $v_{V2I,j}$ from V_{V2I}
15: $n = n + 1$
16: **end if**
17: **end while**
18: **Output**: C_n

- Firstly, select a minimum element w_{jk} in W. If the maximum row sum of matrix A_n is greater than 1 when add $v_{V2I,j}$ and $v_{V2V,k}$ into cluster C_n, it indicates that the SINR requirements of all V2X links assigned in this RB can't be guaranteed. Then add only $v_{V2I,j}$ into cluster C_n and delete $v_{V2I,j}$ from the bipartite graph. After that, a new cluster is created.
- If the maximum row sum of matrix A_n is less than 1, add $v_{V2I,j}$ and $v_{V2V,k}$ into cluster C_n, and delete $v_{V2I,j}$ and $v_{V2V,k}$ from the bipartite graph. Select $v_{V2V,p}$ from V_{V2V} that will lead to the minimum $H_{Inter,n}$ by traversing all V2V links. The $H_{Inter,n}$ represents the sum interference introduced by $v_{V2V,p}$ to all V2X links in cluster C_n. The $H_{Inter,n}$ for C_n can be denoted as:

$$H_{Inter,n} = \sum_{v_i \in C_n} h_{pi}. \tag{22}$$

where v_i is the V2I links or V2V links added in cluster C_n, h_{pi} is the interference caused by $v_{V2V,p}$ in V_{V2V} to v_i.

- Then select the minimum element in weight matrix of current bipartite graph as the adaptive clustering interference threshold H_{Thre}. If $H_{Thre} > H_{Inter,n}$ and the maximum row sum of matrix A_n is less than 1 when add the $v_{V2V,p}$ into cluster C_n, add $v_{V2V,p}$ into cluster C_n. Otherwise, a new cluster is created.

3.1.2 V2V Links Clustering

After V2I links matching, all V2I links have been divided into different clusters. If there are any V2V links which are not added into any clusters, we construct the V2V interference graph as shown in Figure 3.

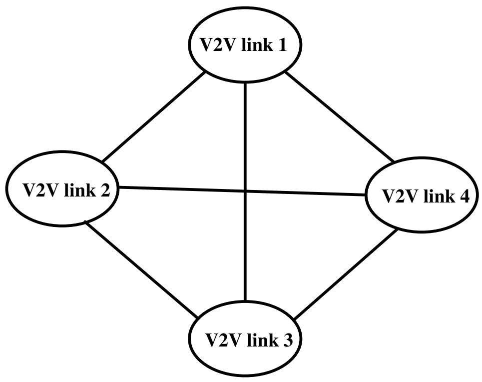

Figure 3. *Graph representation for mutual interference between V2V links.*

The Figure 3 describes the mutual interference between V2V links, which are not assigned to any cluster after the V2I links matching step. The vertices in the graph are denoted as V'_{V2V}=$\{v'_{V2V,1}, v'_{V2V,2} \ldots v'_{V2V,D}\}$, each element of which represents an unassigned V2V link. The edge between two V2V links in the graph represents the mutual interference, which can be denoted as $w_{d,d'}$. The weight matrix W_{v2v} of the graph is composed of $w_{d,d'}$, where $W_{v2v} \in \mathbb{C}^{D\times D}$. D is the number of V2V links in V'_{V2V}. $w_{d,d'}$ can be given by

$$w_{d,d'} = h_{d,d'} + h_{d',d}, \forall d, d' \in V'_{v2v}, d \neq d'. \tag{23}$$

Algorithm 2. *V2V links clustering.*

1: **Input**: V'_{V2V}, W_{V2V}
2: **while** $V'_{V2V} \neq \varnothing$ **do**
3: Select $v'_{V2V,d}, v'_{V2V,d'} \in V'_{V2V}$ that correspond to the minimum element in W_{v2v}
4: **if** $E(A_{n'}) < 1$ when add $v'_{V2V,d}, v'_{V2V,d'}$ into cluster $C_{n'}$ **then**
5: Add $v'_{V2V,d}, v'_{V2V,d'}$ into cluster $C_{n'}$ and remove $v'_{V2V,d}, v'_{V2V,d'}$ from V'_{V2V}
6: Select $v'_{V2V,p} \in V'_{V2V}$ that will lead to the minimum $H_{Inter,n'}$ by traversing all V2V links in V'_{V2V}
7: Select the minimum element in W_{v2v} as the adaptive clustering interference threshold $H_{Thre'}$
8: **while** $H_{Thre'} > H_{Inter,n'}$ and $E(A_{n'}) < 1$ when add $v'_{V2V,p}$ into cluster $C_{n'}$ **do**
9: Add $v'_{V2V,p}$ into cluster $C_{n'}$ and remove $v'_{V2V,p}$ from V'_{V2V}
10: Repeat Step 6 and 7 to update $H_{Thre'}$ and $H_{Inter,n'}$
11: **end while**
12: $n' = n' + 1$
13: **else**
14: Add $v'_{V2V,d}$ into cluster $C_{n'}$ and remove $v'_{V2V,d}$ from V'_{V2V}
15: $n' = n' + 1$
16: **end if**
17: **end while**
18: **Output**: $C_{n'}$

Then the heuristic clustering algorithm proposed in V2I links matching step is used to divide V2V links into several new clusters. Algorithm 2 shows the specific process.

In this section, the spectral-radius-based interference cancellation heuristic clustering algorithm is proposed. In the V2I links matching part, a bipartite graph is constructed to match the V2I links and V2V links for minimal accumulated interference. Then in the V2V links clustering part, the V2V links which are not assigned to any clusters in V2I links matching part are divided into new clusters for minimal accumulated interference among V2V links occupying the same RB.

3.2 MEC Computational Resource Scheduling

After the V2X links clustering step, the problem (17) can be transformed into problem (24),

$$\begin{aligned} &\min_{\Lambda,\Theta} \sum_{j=1}^{J} T_j, \\ &s.t. C4, C5. \end{aligned} \tag{24}$$

As can be known from Eq.(13), the delay of the *j-th* V2I link T_j is the maximum of t_j^{loc} and t_j^{off}. If task offloading delay t_j^{off} is greater than local computing delay t_j^{loc}, VUE will wait for the task computing result from the MEC server, resulting in waste of VUE local computing resources. If t_j^{loc} is greater than t_j^{off}, VUE will wait for the task computing result from local CPU. In order not to bring additional delay to VUE waiting for the computing result from MEC or local CPU, t_j^{loc} should be equal to t_j^{off}. Then we can get the correlation of task offloading ratio β_j and MEC computation resource scheduling θ_j, which can be described as:

$$\theta_j(\beta_j) = \frac{S_j Z_0 f_{loc} \beta_j}{S_j Z_0 - (S_j Z_0 + f_{loc})\beta_j}, \forall j \in [1, J]. \tag{25}$$

In order to calculate the optimal solution for problem (24), we first give the Lagrangian function which is denoted as

$$L(\beta_j, \alpha) = \sum_{j=1}^{J} \frac{(1-\beta_j)c_j Z_0}{f_{loc}} + \alpha(\sum_{j=1}^{J} \theta_j(\beta_j) - \Theta_{max}). \tag{26}$$

where α is the Lagrange multiplier. Based on the Karush-Kuhn-Tucker conditions, Eq.(27) and Eq.(28) can be given

$$\frac{\partial L}{\partial \beta_j} = -\frac{c_j Z_0}{f_{loc}} + \frac{\alpha S_j^2 Z_0^2 f_{loc}}{\left[S_j Z_0 - (S_j Z_0 + f_{loc})\beta_j\right]^2} = 0. \tag{27}$$

$$\frac{\partial L}{\partial \alpha} = \sum_{j}^{J} \theta_j(\beta_j) - \Theta_{max} = 0. \tag{28}$$

The problem(24) is convex for variable β_j, then the optimal β_j^* can be obtained by

$$\beta_j^* = \frac{S_j Z_0 - \sqrt{\alpha Z_0 / c_j} S_j f_{loc}}{S_j Z_0 + f_{loc}}. \tag{29}$$

The β_j is a number between 0 and 1, so it can be calculated that the Lagrange multiplier α is a number between 0 and $Z_0 c_j / f_{loc}^2$. Finally, based on the Karush-Kuhn-Tucker conditions, the β_j^* and θ_j^* can be calculated.

IV. SIMULATION RESULTS

In this section, simulation results are presented to validate the proposed JAWC algorithm. The simulation parameters are listed in Table 1. In term of the total delay, the proposed algorithm is compared and analyzed with some baseline algorithms, as follows:

1. *Optimization Wireless resource Allocation algorithm (OWA)*: The RSU allocates RBs for V2X links based on the proposed SR-IC scheme, and the β_j, θ_j are determined by MEC server randomly.
2. *Optimization MEC Computation capability Allocation algorithm (OCA)*: The RSU allocates RBs for V2X links randomly, and the β_j, θ_j are determined by MEC server based on the MEC computation resource allocation scheme proposed in Section 3.2.
3. *Federated Offloading Algorithm (FOS)*: The federated task offloading algorithm proposed in [32] is revised as a comparison, where the RSU allocates RBs randomly, task offloading proportion β_j is optimal and MEC computational resource scheduling θ_j are determined by MEC server randomly.

Then, considering the average spectral efficiency, the proposed SR-IC scheme is compared and analyzed with the RB random allocation scheme (RAS). In order to evaluate the performance of the proposed MEC computation resource allocation scheme, the optimal task offloading proportion β_j[32], the optimal MEC computational resource allocation θ_j are compared in terms of V2I delay, respectively. And to be fair, the SR-IC scheme is adopted by all schemes. Finally, the SINR performance of the SR-IC scheme is evaluated and compared with the RAS scheme.

4.1 Simulation Results

Figure 4 shows the total delay in MEC-enabled vehicular network for different data length in different algorithms, where the V2V transmission power is 26 dBm. We can see that with the increase of the data length, the proposed JAWC algorithm can significantly reduce the total delay. For instance, the achieved performance gain of JAWC algorithm is 34.1%, 51.2% and 53.3% compared with OWA, OCA and FOS when the data length is 200 Kbits, respectively. In OCA, the RBs are allocated randomly, which leads to high interference among V2X links in the same cluster, resulting in low transmission rate and high transmission delay. In OWA, the task offloading proportion β_j and the MEC computational resource allocation θ_j are determined by MEC server randomly, which increases the V2I delay. The improper MEC computation resource allocation increases computing delay and severe co-channel interference limits the transmission rate in FOS. In the proposed JAWC algorithm, the accumulated interference in the same cluster can be limited by spectral radius estimation, which leads to high transmission rate and low transmission delay. Furthermore, the optimal offloading ratio β_j and MEC scheduling θ_j minimize the delay of V2I link.

Figure 5 shows the average spectral efficiency under different V2V transmission power in different schemes. It can be observed that, the proposed SR-IC scheme has higher average spectral efficiency compared with RAS. It indicates that the accumulated interference among V2X links is significantly reduced. With the increasing of V2V transmission power, compared with RAS, the average V2I spectral efficiency in SR-IC decreases more slowly. The reason is as the transmission power of V2V is higher, there are fewer

Table 1. *Simulation parameters.*

Parameters	Values
Total bandwidth	10 MHz
Channel model	Large-scale fading and small-scale Rayleigh fast fading
Number of RB N	50
Transmission power of V2I link	26 dBm
Length of lanes	800 m
Noise power σ^2	-80 dBm
Local CPU computing frequency f_{loc}	1×10^9 cycle/s
MEC computing frequency Θ_{max}	2.5×10^{10} cycle/s
SINR threshold for vehicle	10 dB
Number of V2V links	80
Number of V2I links	20

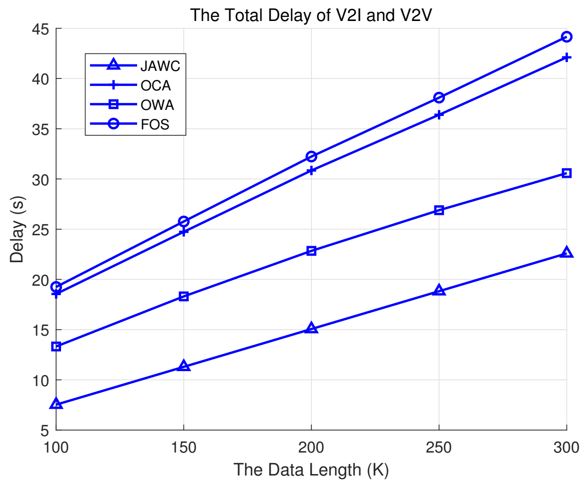

Figure 4. *The global delay for different data lengths.*

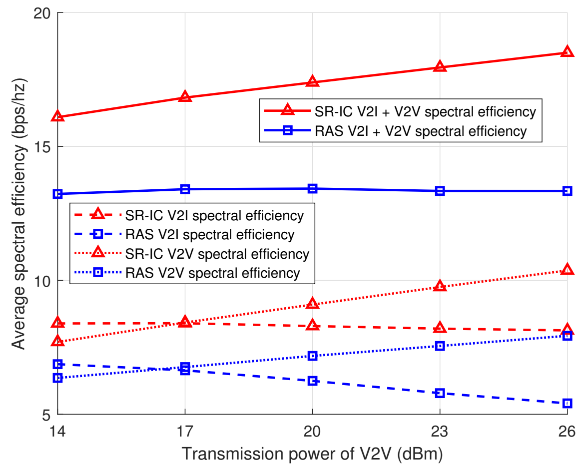

Figure 5. *Average spectral efficiency for different V2V transmission power.*

V2V links that can be assigned to the same cluster with V2I links in V2I links matching part due to the spectral radius constraint. Therefore, the interference caused by V2V links to V2I links will be limited.

Figure 6 illustrates the total delay of V2I with the increase of data length, where V2V transmission power is 26 dBm. We can observe that the joint optimal task offloading proportion β_j and MEC computation resource allocation θ_j can significantly reduce the total delay of V2I. The reason is that the computation resource of local CPU and MEC server can be effectively utilized when β_j and θ_j are optimal.

Figure 7 shows the total number of V2X links meeting SINR requirement under different transmission power of V2V in SR-IC and RAS scheme. When the V2V transmission power is small, the interference

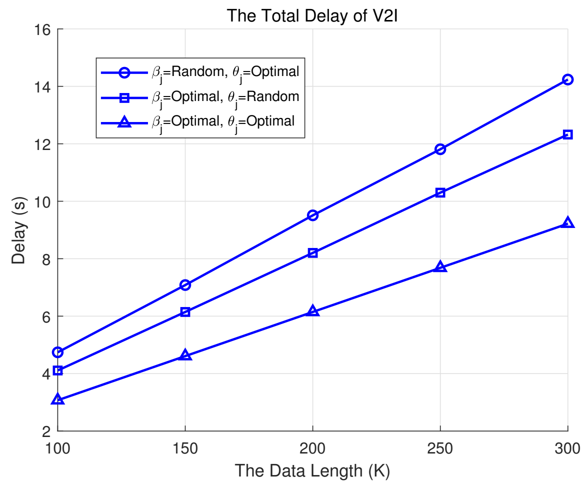

Figure 6. *Total delay of V2I for different data length.*

from V2I link to V2V link is relatively high, so there will be several V2V links that cannot meet the SINR requirement in SR-IC scheme. Compared with RAS scheme, the SR-IC scheme can ensure that more V2X links meet the SINR requirements. For instance, when the transmission power of V2V is 17 dBm, all the V2X links meet the SINR requirement. The reason is that in the V2X clustering step, the spectral radius estimation constraint can limit the accumulated interference in the same cluster, thereby ensuring the SINR requirement of V2X links.

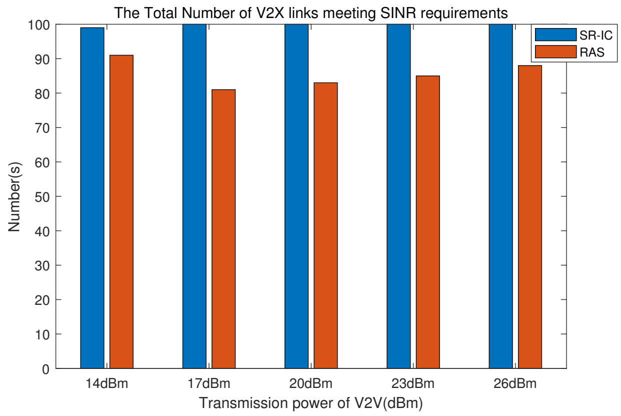

Figure 7. *The total number of V2X links meeting SINR requirements for different V2V transmission power.*

Figure 8 shows the total number of V2X links meeting SINR requirement with the increase of distance between the transmitting vehicle and the receiving vehicle in SR-IC and RAS scheme, respectively. When the distance increases, the number of V2X links that meet the SINR requirement will decrease. The reason is that the channel power gain of V2V links becomes smaller as the distance increases. Compared with RAS scheme, the SR-IC scheme can ensure that more V2X links meet the SINR requirements. For instance, when the distance between the transmitting vehicle and the receiving vehicle is 30 m, the number of V2X links meeting the SINR requirement in SR-IC and RAS are 99 and 85, respectively.

V. CONCLUSION

In this paper, we focused on the problem of minimizing the total delay in MEC-enabled Vehicular Network. To cope with this, a JAWC algorithm including the V2X clustering step and the MEC computation resource scheduling step is introduced. In the V2X

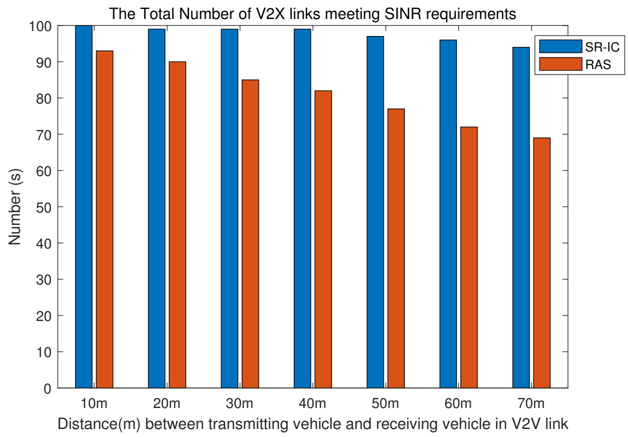

Figure 8. *The total number of V2X links meeting SINR requirements for different distance between the transmitting vehicle and the receiving vehicle of V2V link.*

clustering step, the SINR requirement of vehicles is transformed into matrix spectral radius constraint to ensure the reliability, and a heuristic clustering algorithm is proposed to divide V2X links into different clusters. In the MEC computation resource scheduling step, the original optimization problem is transformed into a convex problem to get the optimal solution. Finally, simulation results validated the effectiveness of the proposed JAWC algorithm.

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