Received January 19, 2021, accepted February 21, 2021, date of publication February 24, 2021, date of current version March 4, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3061711

Radio Resource Allocation and Power Control Scheme in V2V Communications Network

YANZHAO HOU[1], (Member, IEEE), XUNCHAO WU[1], (Graduate Student Member, IEEE), XIAOSHENG TANG[1], XIAOQI QIN[1], (Member, IEEE), AND MINGYU ZHOU[2]

[1]National Engineering Laboratory for Mobile Network Technologies, Beijing University of Posts and Telecommunications, Beijing 100876, China
[2]Baicells Technologies, Beijing 100089, China

Corresponding author: Yanzhao Hou (houyanzhao@bupt.edu.cn)

This work was supported in part by the National Key Research and Development Program of China under Grant 2018YFB1800800, in part by the National Natural Science Foundation of China under Grant 61701042, and in part by the 111 Project of China under Grant B16006.

ABSTRACT Reasonable resource management scheme is the premise to ensure system reliability and practicability of vehicle-to-vehicle (V2V) communications network. In this paper, spectrum resource allocation and power control scheme is studied. Firstly, the problem of resource block (RB) sharing is considered. Assuming that each V2V link occupies at most one resource block while multiple links can share the same RB. In this work, a factor graph model is proposed corresponding to the RB allocation problem through function mapping. Therefore, the RB allocation problem is equivalent to studying the message update and belief inference problem on the factor graph model. We propose a Belief Propagation based on Real-time Update of Messages (BPRUM) algorithm, in which the message of each node is calculated based on the new messages of other nodes rather than the messages calculated in the last iteration. Secondly, after the RB allocation is completed, a power control scheme under the maximum power limit is proposed by utilizing the Lagrange dual decomposition. And the total throughput of the system is maximized by using the proposed power control scheme. Simulation results show that the resource allocation and power control scheme can achieve a significant increment in spectrum utilization and throughput of the V2V communications network.

INDEX TERMS Resource allocation, belief propagation, Lagrange dual decomposition, V2V communications.

I. INTRODUCTION

In the three scenarios of long-term evolution-based vehicle-to-anything (LTE-V2X) defined by the Third Generation Partnership (3GPP), vehicle-to-vehicle (V2V) communications has received extensive attention [1]. In the V2V communications scenario, two vehicles communicate directly, and the communication resources are allocated by the cellular base station (BS). Due to the V2V communications mode is similar to the traditional device-to-device (D2D) communications, many technologies in D2D can be applied to V2V communications. In addition, part of the standardization work has been studied by 3GPP [2], [3]. These standards are generally considered as LTE-V2V.

In the LTE-V2V scenario, spectrum resource is separated into resource blocks (RBs) and V2V links share the same RB with cellular users. In order to satisfy the communications requirement of cellular users and V2V links, there are many resource management solutions. In [4], the author proposed a relaying system, called relay assisted enhanced V2V (RA-eV2V), according to the V2V communications mode defined in 3GPP. In this system, the roadside unit can cooperate with vehicle users, and the communication quality of the V2V link has been greatly improved. In [5], Allouch *et al*. studied resource allocation in LTE-V mode 3 scenario under meeting security-related requirements and proposed a novel Priority and guarantEed-bAsed Resource aLlocation approach (PEARL) for cellular V2V communications. Yucel *et al*., in [6], studied resilience, fairness and security issues in the V2V communications network and developed a heuristic algorithm to achieve resource allocation with minimum instability between cellular users and vehicle users. In [7], the author studied the problem of computation offloading and resource allocation in vehicular networks. And two problems, i.e., the vehicular terminal side and the mobile edge computing (MEC) enabled roadside units side optimization problems, were formulated, aim to minimize the averaged cost of vehicular terminals and the MEC enabled

The associate editor coordinating the review of this manuscript and approving it for publication was Kai Li.

roadside units, respectively. Moreover, two algorithms are identified to define benchmarks that provide a clear reference to quantify the performance of the resource allocation algorithms designed for LTE-V2X by Bazzi *et al*. in [8]. In [9], the author proposed a rate-adaptive data dissemination algorithm that derives the optimal transmit rate allocation for vehicular platoons. The study approaches to the resource allocation problem as an end-to-end optimization problem, targeting to minimize the end-to-end latency and investigating the impact of packet and platoon sizes on the latency.

Besides, some literature studies the joint radio spectrum resource management and power control scheme. In [10], consider that vehicle users have the same priority as cellular users, a joint radio resource and power management scheme has been proposed. The author studied the problem of maximizing the secure rate of V2V links under the influence of eavesdroppers. In [11], Mei *et al*. proposed optimizing the radio resource, power allocation and modulation/coding schemes for V2V communications refers to maximizing the minimum SINR among the cellular users subject to the block error ratio (BLER) and packet latency requirements of vehicle users as well as transmit power constraints. In [12], Sun *et al*. proposed a problem formulation that fulfills the different requirements of V2V communication and traditional cellular communication and conduct a Separate resOurce bLock and powEr allocatioN (SOLEN) algorithm to solve this problem. Aslani *et al*. proposed a novel scheme for BS to allocate power and sub-carriers to cellular users and vehicular users under C-V2X networks mode-3 in [13]. This scheme minimizes the number of non-allowed V2V links subject to high data rate requirements for cellular users and high reliability requirements for vehicular users. In [14], two schemes were proposed by Luo *et al*. for vehicle users secrecy capacity optimization problem and user fairness, respectively. The secrecy performance has been improved.

Although some literature studied spectrum resource allocation or/and power control in V2V communications network, few researchers investigate the maximum number of V2V links within one BS while the available spectrum resource is limited. In [15], Zhang *et al*. developed a Minimizing the Increment of Spectral Radius (MISR) RB allocation scheme by converting the quality of service (QoS) requirement of V2V links into the matrix spectrum radius limit. This paper gives one solution to consider maximizing the number of V2V links in V2V communications network.

In this paper, we consider RB allocation and power control scheme in V2V communications network. The RB allocation mechanism refers to the mode 3 resource allocation mechanism defined in [16]. V2V links using dedicated RB resources and there is no interference between V2V links and cellular users. Meanwhile, assume that the QoS of wireless communication is satisfied while the signal to interference plus noise ratio (SINR) is more than a special value [17], [18].

Different from the MISR approaches in other literature, we study the RB allocation scheme under the assumption that all V2V links are configured with the maximum transmission power, which can ensure that the RB resource allocation scheme is feasible. After the RB allocation is completed, we can conduct further study on the power allocation scheme.

Firstly, as shown in [19], we maximize the utilization of RB resources while supposing that each V2V link uses the maximum transmission power. A factor graph model is proposed corresponding to the RB allocation problem through function mapping. Then the belief inference problem based on the factor graph model is solved using the proposed Belief Propagation based on Real-time Update of Messages (BPRUM) algorithm. Compared with other algorithms, the BPRUM algorithm shows better performance. Furthermore, we study the power control problem based on the RB allocation results. By introducing penalty factors and using variable substitution, we adopted the Lagrangian dual decomposition method to solve the optimization problem of maximizing system throughput.

The main contributions of this paper lie in the following aspects:

- We studied a method to convert the RB allocation problem into a belief inference problem. A BPRUM algorithm is proposed based on the derivation of the message passing procedure on the factor graph model. Spectrum utilization has been improved through the scheme of multiple users sharing the same RB.
- A power control scheme is proposed after RB allocation is completed by utilizing the Lagrange dual decomposition. In order to avoid a single V2V link maximizing his power, we introduced a penalty factor and approximated the objective function.
- Regarding the problem that it is difficult to determine the user power configuration using MISR algorithm for RB allocation, the proposed power control scheme can not only meet the maximum power limit but also meet the minimum SINR requirement while improving the system throughput.

The rest of this paper is organized as follows. Section II presents the system model and problem formulation. In section III, the RB allocation method based on belief propagation is introduced. We analyze the message passing procedure on the factor graph and propose the BPRUM algorithm in this section. The Lagrange dual decomposition method for power allocation is proposed in Section IV. Section V presents simulation results and analysis. Finally, Section VI concludes this paper.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. SYSTEM MODEL

As shown in Fig. 1, one V2V link consists of one transmitting vehicular user equipment (VUE) and one receiving VUE. Assume that there are M V2V links within a BS. On the BS side, the BS allocates RBs according to the collected channel state information (CSI) and informs the V2V links. Assume that the maximum number of RBs that a BS can allocate is N. In order to meet the normal communication of more V2V links, the BS can allocate one RB to more than

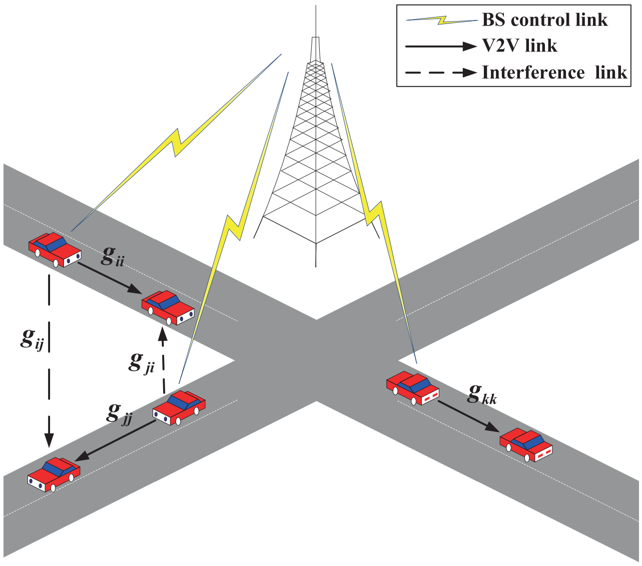


FIGURE 1. An illustration of V2V communications network.

one V2V link, but one V2V link occupies at most one RB. Therefore, interference occurs between V2V links occupying the same RB.

The interference between V2V links is illustrated in Fig. 1. We have shown two cases respectively, i.e., two V2V links share one RB and one RB is only allocated to one V2V link. If the BS allocates the same RB to the i-th and j-th V2V links, there will be mutual interference between the two V2V links. The k-th V2V link is assigned to other RB. Therefore the k-th V2V link will not be interfered by the i-th and j-th V2V links. The group of V2V links is set as $\mathcal{M} = \{1, 2, \ldots, \mathrm{M}\}$ and the group of RB is set as $\mathcal{N} = \{1, 2, \ldots, \mathrm{N}\}$. Define the resource allocation matrix $\boldsymbol{X} = (x_{mn})_{\mathrm{M}\times\mathrm{N}}$ as

$$\boldsymbol{X}=\begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1\mathrm{N}} \\ x_{21} & x_{22} & \cdots & x_{2\mathrm{N}} \\ \vdots & \vdots & \ddots & \vdots \\ x_{\mathrm{M}1} & x_{\mathrm{M}2} & \cdots & x_{\mathrm{MN}} \end{pmatrix}$$

where binary variable x_{mn} equals to 1 if the m-th V2V link is allocated to the n-th RB, and x_{mn} is set as 0, otherwise.

The channel power gain between the transmitting VUE of the k-th V2V link and the receiving VUE of the m-th V2V link is defined as g_{km}. From this definition, the channel power gain of the k-th V2V link can be defined as g_{kk} and the interference channel power gain between any two V2V links can be expressed as g_{km} and g_{mk}. The CSI matrix is represented by $\boldsymbol{G} = (g_{km})_{\mathrm{M}\times\mathrm{M}}$.

$$\boldsymbol{G}=\begin{pmatrix} g_{11} & g_{12} & \cdots & g_{1\mathrm{M}} \\ g_{21} & g_{22} & \cdots & g_{2\mathrm{M}} \\ \vdots & \vdots & \ddots & \vdots \\ g_{\mathrm{M}1} & g_{\mathrm{M}2} & \cdots & g_{\mathrm{MM}} \end{pmatrix}$$

The diagonal elements represent the channel power gain of V2V links, and the other elements represent the interference channel power gain between any two V2V links. When two V2V links do not share the same RB, the corresponding value is 0.

Let $\boldsymbol{p}$ be a vector indicating the transmit power and $p_{\max}$ represents the maximum transmission power, i.e., $\boldsymbol{p} = [p_1, p_2, \ldots, p_{\mathrm{M}}]$ and $p_m \le p_{\max}$ for $\forall 1 \le m \le \mathrm{M}$. Moreover, suppose that the noise power, denoted by δ^2, is the same for the receiving VUE of all V2V links.

Then, we can calculate the SINR of the receiving VUE by (suppose that BS allocates the n-th RB to the m-th V2V link, i.e., $x_{mn} = 1$)

$$\mathrm{SINR}_m = \frac{g_{mm}p_m}{\sum_{k=1,k\neq m}^{\mathrm{M}} x_{kn}g_{km}p_k + \delta^2} \tag{1}$$

B. PROBLEM FORMULATION FOR RB ALLOCATION

In V2V communications, the number of RBs is limited. A reasonable RB allocation scheme to maximize spectrum efficiency is a problem worthy of study. Since there is no mutual interference between the V2V links allocated with different RB when the inter-spectrum interference is not considered, the RB allocation scheme can be regarded as a problem of maximizing the number of V2V links in an RB. First of all, we select as many V2V links as possible from all M V2V links, while satisfying that any V2V link can communicate normally in the case of mutual interference between them, and assign the first RB to these selected V2V links. Then repeat the above steps to select a group of V2V links that meet the normal communication conditions from the remaining V2V links and assign another RB to these V2V links. Until M V2V links are allocated to the corresponding RB.

Furthermore, due to the limitation of delay and reliability in V2V communications, the QoS of V2V links must be guaranteed during the resource allocation process. Based on the analysis in [15] and [20], the QoS of V2V links can be met by setting strict SINR limitation. Let $\boldsymbol{\gamma}$ be a vector indicating the minimum SINR limitation of V2V links, $\boldsymbol{\gamma} = [\gamma_1, \gamma_2, \ldots, \gamma_{\mathrm{M}}]$. And, suppose that all V2V links use the maximum transmission power, i.e., $p_m = p_{\max}$ for $\forall m \in \mathcal{M}$.

Based on the above analysis, the key to the problem of RB allocation is to find the most V2V links that can share one RB. The n-th RB allocation scheme can be represented by

$$\boldsymbol{x} = \arg\max_{\boldsymbol{x}} \sum_{m\in\mathcal{M}_n} x_{mn} \tag{2}$$

$$\text{s.t. } \mathrm{SINR}_m \ge \gamma_m, \forall\, x_{mn} = 1 \tag{3}$$

where $\mathcal{M}_n$ indicates the set of V2V links to be assigned, and $\boldsymbol{x}$ is a vector related to the n-th RB allocation scheme. SINR restrictions of the receiving VUE is shown by (3).

C. PROBLEM FORMULATION FOR POWER ALLOCATION

The power control scheme of the transmitting VUE is also important in V2V communications. In the procedure of RB allocation, we assume that the transmitting VUE has set the maximum power. There is still some room for optimization of the power configuration. We consider maximizing the total throughput of the V2V communications network to obtain the power optimization result. The problem is formulated as

$$\max_{\boldsymbol{p}} \sum_{n=1}^{\mathrm{N}} \sum_{m=1}^{\mathrm{M}_n} \log_2 (1 + \mathrm{SINR}_m) \tag{4}$$

$$s.t.\ C1: p_m \le p_{\max},\ \forall 1 \le m \le \mathrm{M}_n \tag{5}$$

$$C2: \mathrm{SINR}_m \ge \gamma_m,\ \forall 1 \le m \le \mathrm{M}_n \tag{6}$$

where M_n represents the number of V2V links allocated in the n-th RB. SINR_m of the m-th receiving VUE is calculated by (1) according to the RB allocation result and mutual interference in one RB. Constriction (5) (6) describes the power limitation and the SINR requirement, respectively.

There is no mutual interference between users occupying different RB, so we can separately optimize the power of V2V links assigned to different RB, and the optimization problem can be simplified as

$$\max_{\boldsymbol{p}} \sum_{m=1}^{\mathrm{M}_n} \log_2 (1 + \mathrm{SINR}_m) \tag{7}$$

$$s.t.\ C1: p_m \le p_{\max},\ \forall 1 \le m \le \mathrm{M}_n \tag{8}$$

$$C2: \mathrm{SINR}_m \ge \gamma_m,\ \forall 1 \le m \le \mathrm{M}_n \tag{9}$$

III. RB ALLOCATION SCHEME BASED ON BELIEF PROPAGATION

The problem of RB allocation scheme described in (2) is NP-hard. As a powerful method to solve this problem, the matrix spectral radius theory has attracted the attention of many researchers [15], [20], [21]. Through matrix transformation, the SINR restriction shown in (3) can be transformed into the restriction on the spectral radius related to the resource allocation matrix $\boldsymbol{X}$ and the CSI matrix $\boldsymbol{G}$, and then the matrix spectral radius theory is used to solve the problem. Although this method can obtain an RB allocation scheme, it cannot guarantee the transmit power is within the maximum power limit $p_{\max}$.

In this part, the factor graph model is introduced, which is a bipartite graph that expresses a mathematical relationship [22], to convert the correspondence between RB and V2V links into the correspondence between function nodes and variable nodes. Furthermore, the belief propagation algorithm is used to deduce the message passing process.

A. PROBLEM TRANSFORMATION FOR RB ALLOCATION

In order to realize the transformation from the original problem (2) to the factor graph model, we first define several functions

$$R_n(\boldsymbol{x}) = \sum_{m \in \mathcal{M}_n} x_{mn} \tag{10}$$

$$\eta_n(\boldsymbol{x}) = \exp\left[R_n(\boldsymbol{x})\right] \tag{11}$$

$$G_{kn}(\boldsymbol{x}) = \begin{cases} 0, & \text{if } x_{kn} = 1 \text{ and } \mathrm{SINR}_k < \gamma_k \\ 1, & \text{otherwise} \end{cases} \tag{12}$$

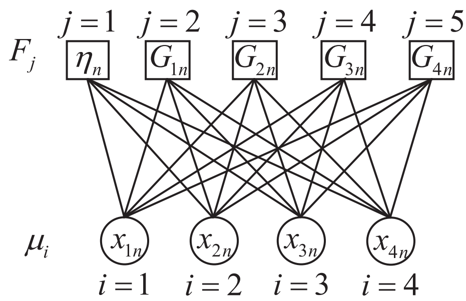


FIGURE 2. The factor graph model for RB allocation ($|\mathcal{M}_n| = 4$).

Theorem 1 : The RB allocation scheme described in (2) can be converted to

$$\boldsymbol{x} = \arg\max_{\boldsymbol{x}} \eta_n(\boldsymbol{x}) \prod_{k \in \mathcal{M}_n} G_{kn}(\boldsymbol{x}) \tag{13}$$

Proof : $\eta_n(\boldsymbol{x})$ is an exponential function, obviously maximizing $R_n(\boldsymbol{x})$ is equivalent to maximize $\eta_n(\boldsymbol{x})$. $G_{kn}(\boldsymbol{x})$, $k \in \mathcal{M}_n$, is a binary function. $G_{kn}(\boldsymbol{x})=0$ if the k-th V2V link is allocated to the n-th RB while the SINR requirement of the receiving VUE is not met, $G_{kn}(\boldsymbol{x}) = 1$ otherwise, which corresponds to the restriction shown in (3). ■

Define the function mapping rule and variable mapping rule as follows

$$F_j(\boldsymbol{x}) \doteq \begin{cases} \eta_n(\boldsymbol{x}), & j = 1 \\ G_{kn}(\boldsymbol{x}), & j = k+1 \end{cases} \tag{14}$$

$$\mu_i \doteq x_{mn},\ i = m \tag{15}$$

Thus, the RB allocation problem is rewritten as

$$\boldsymbol{x} = \arg\max_{\boldsymbol{x}} \prod_j F_j(\boldsymbol{x}) \tag{16}$$

Considering the process of RB allocation, we sequentially allocate RB to all V2V links that can share the same RB in the remaining V2V links. Suppose that the number of remaining V2V links is 4, i.e., $|\mathcal{M}_n| = 4$, the corresponding relationship between the n-th RB and V2V links is shown in Fig. 2.

B. BELIEF PROPAGATION ALGORITHM IN RB ALLOCATION SCHEME

As shown in Fig. 2, there are messages passing on the factor graph model between the function node and variable node. These nodes can make message judgments through the belief propagation algorithm. In this part, we formulate the message form and analyze the message passing process. Then, the BPRUM algorithm is proposed to solve the RB allocation problem.

1) MESSAGE PASSING PROCEDURE ON FACTOR GRAPH

Define $m^t_{\mu_i \to F_j}(x)$ and $m^t_{F_j \to \mu_i}(x)$ represent the message μ_i to F_j and F_j to μ_i, respectively [23]. This message are calculated by

$$m^{t+1}_{\mu_i \to F_j}(x) = \prod_{l \in \Gamma^{\mu}_i \setminus \{j\}} m^t_{F_l \to \mu_i}(x) \tag{17}$$

$$m_{F_j\to\mu_i}^{t+1}(x) = \max_{\Gamma_j^F\setminus\{i\}} \left\{ F_j(\boldsymbol{x}) \prod_{l\in\Gamma_j^F\setminus\{i\}} m_{\mu_l\to F_j}^{t}(x_l) \right\} \tag{18}$$

where Γ_i^μ and Γ_j^F are the set of indicator variables and represent the function nodes F_j connected to μ_i and the variable nodes μ_i connected to F_j, e.g., $\Gamma_i^\mu = \{1, 2, \ldots, |\mathcal{M}_n| + 1\}$ and $\Gamma_j^F = \{1, 2, \ldots, |\mathcal{M}_n|\}$ in Fig. 2.

In order to simplify the calculation, we can use the scalar ratio to transform the defined message [23]. Define $\alpha_{i\to j}^t$ and $\beta_{j\to i}^t$ represent the message from μ_i to F_j and F_j to μ_i, respectively,

$$\alpha_{i\to j}^t = \log\left(\frac{m_{\mu_i\to F_j}^t(1)}{m_{\mu_i\to F_j}^t(0)}\right) \tag{19}$$

$$\beta_{j\to i}^t = \log\left(\frac{m_{F_j\to\mu_i}^t(1)}{m_{F_j\to\mu_i}^t(0)}\right) \tag{20}$$

According to this definition, we can get

$$\alpha_{i\to j}^{t+1} = \sum_{l\in\Gamma_i^\mu\setminus\{j\}} \beta_{l\to i}^t \tag{21}$$

As for the messages from F_j to μ_i $\beta_{j\to i}^{t+1}$, since $m_{F_j\to\mu_i}^{t+1}(x)$ is the most value form defined on the set $\left\{\mu_l | l \in \Gamma_j^F \setminus \{i\}\right\}$, we analyze the calculation of $\beta_{j\to i}^{t+1}$ according to the three cases of the value of j. The detailed derivation process is shown in Appendix A.

2) BELIEF UPDATE

In the message passing process in Fig. 2, the variable nodes and function nodes continuously update the messages they receive. Since the value of variable node μ_i is a binary variable, we determine the value of μ_i by the size of the belief in each iteration.

At first, define the belief of variable node μ_i

$$b_i^{t+1} = \prod_{j\in\Gamma_i^\mu} m_{F_j\to\mu_i}^t(x) \tag{22}$$

Here, similar to (19) and (20), we also convert the belief into a logarithmic domain representation.

$$\widetilde{b}_i^t = \log\left(\frac{b_i^t(1)}{b_i^t(0)}\right) = \sum_{j\in\Gamma_i^\mu} \beta_{j\to i}^t \tag{23}$$

where $\beta_{j\to i}^t$ represents the message from the function node F_j to the variable node μ_i during the t-th iteration. Thus, the value of μ_i is judged by the following conditions

$$\widehat{\mu}_i^t = \begin{cases} 1, & \text{if } \widetilde{b}_i^t > 0 \\ 0, & \text{if } \widetilde{b}_i^t < 0 \end{cases} \tag{24}$$

**Algorithm 1 : ** Belief Propagation Based on Real-Time Update of Messages

Input: M, $\boldsymbol{p}$, $\boldsymbol{\gamma}$, $\boldsymbol{G}$.
Set $n = 1$, $\mathcal{M} = \{1, 2, \ldots, \mathrm{M}\}$ and set $t_{\max}$ as a large enough number.
while $|\mathcal{M}| > 0$ **do**
  Set $t=0$, and set $\boldsymbol{A}^t = \boldsymbol{0}_{|\mathcal{M}|\times(|\mathcal{M}|+1)}$, $\boldsymbol{B}^t = \boldsymbol{0}_{(|\mathcal{M}|+1)\times|\mathcal{M}|}$.
  while not convergent and $t < t_{\max}$ **do**
    for $i \in \mathcal{M}$ **do**
      for $j \in \{1\} \cup \{k+1 | k \in \mathcal{M}\}$ **do**
        Calculate the message $\alpha_{i\to j}^{t+1}$ by (21)
        Update the value of $\alpha_{i\to j}^t$ in matrix $\boldsymbol{A}^t$ with the value of $\alpha_{i\to j}^{t+1}$
        Set $\beta_{1\to i}^{t+1} = 1$
        if $j = i + 1$ **then**
          Calculate the message $\beta_{j\to i}^{t+1}$ by (41)
        end if
        if $j > 1$ and $j \neq i + 1$ **then**
          Calculate the message $\beta_{j\to i}^{t+1}$ by (43)
        end if
      end for
      Calculate the belief $\widetilde{b}_i^t$ by (23)
      Estimate each variable $\widehat{\mu}_i$ by (24)
    end for
    Check the convergence, and set $t = t + 1$
  end while
  Obtain the RB allocation vector $\boldsymbol{x}$, set $index\_x = \{l \in \boldsymbol{x} | \, x_{ln}=1\}$
  Set $\mathcal{M} = \mathcal{M}\setminus index\_x$, $\boldsymbol{p} = \boldsymbol{p}\setminus\{p_l | l \in index\_x\}$, $\boldsymbol{\gamma} = \boldsymbol{\gamma}\setminus\{\gamma_l | l \in index\_x\}$, $\boldsymbol{G} = \boldsymbol{G}\setminus\{g_{km} | k, m \in index\_x\}$.
  $n = n + 1$
end while
Output: $\mathrm{N} = n - 1$, RB allocation matrix $\boldsymbol{X}$.

3) BELIEF PROPAGATION ALGORITHM IN RESOURCE ALLOCATION PROBLEM

According to the above analysis, each variable node μ_i updates its value by (24) in each iteration. It is worth noting that the value updating only occurs between two iterations. The message update is slow, which affects the performance of the algorithm. However, every time the value of a variable node or function node is updated during the t-th iteration, the subsequent node value can be calculated using the node value that has just been updated instead of the value of the node after the $(t-1)$-th iteration.

Therefore, the BPRUM algorithm is proposed. The message is calculated according to the latest $\alpha_{i\to j}^t$ and $\beta_{j\to i}^t$ rather than $\alpha_{i\to j}^{t-1}$ and $\beta_{j\to i}^{t-1}$ in the t-th iteration.

Define matrices $\boldsymbol{A}^t$ and $\boldsymbol{B}^t$ represent the message $\mu_i \to F_j$ and $F_j \to \mu_i$, respectively. We summarize the BPRUM algorithm in Algorithm 1. In each iteration, we can find a set of V2V links that can share the same RB from the V2V links to be allocated. Here the value of $\beta_{j\to i}^{t+1}$ is updated according to the three cases shown in Appendix A. After allocating these V2V links to one RB, update the value of $\mathcal{M}, \boldsymbol{p}, \boldsymbol{\gamma}, \boldsymbol{G}$. Until all V2V links are allocated to the corresponding RB, the number of RBs N can be obtained.

When it comes to complexity, the main computation of BPRUM algorithm is induced by the updating of $\alpha_{i\to j}^t$ and $\beta_{j\to i}^t$. Note that the updating of $\beta_{j\to i}^t$ needs to adopt the approach shown in [24] (refers to Appendix A), whose complexity is $\mathcal{O}(|\mathcal{M}|)$. Therefore, the complexity of BPRUM algorithm is $\mathcal{O}(|\mathcal{M}|^3)$. In order to allocate all V2V links to corresponding RB, the complexity of the RB allocation scheme is $\sum_n \mathcal{O}(|\mathcal{M}|^2) \approx \mathcal{O}(\mathrm{M}^3)$.

$$\boldsymbol{A}^t = \begin{bmatrix} \alpha_{1\to 1}^t & \alpha_{1\to 2}^t & \cdots & \alpha_{1\to |\mathcal{M}|+1}^t \\ \alpha_{2\to 1}^t & \alpha_{2\to 2}^t & \cdots & \alpha_{2\to |\mathcal{M}|+1}^t \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_{|\mathcal{M}|\to 1}^t & \alpha_{|\mathcal{M}|\to 2}^t & \cdots & \alpha_{|\mathcal{M}|\to |\mathcal{M}|+1}^t \end{bmatrix}$$

$$\boldsymbol{B}^t = \begin{bmatrix} \beta_{1\to 1}^t & \beta_{1\to 2}^t & \cdots & \beta_{1\to |\mathcal{M}|}^t \\ \beta_{2\to 1}^t & \beta_{2\to 2}^t & \cdots & \beta_{2\to |\mathcal{M}|}^t \\ \vdots & \vdots & \ddots & \vdots \\ \beta_{|\mathcal{M}|+1\to 1}^t & \beta_{|\mathcal{M}|+1\to 2}^t & \cdots & \beta_{|\mathcal{M}|+1\to |\mathcal{M}|}^t \end{bmatrix}$$

IV. LAGRANGE DUAL DECOMPOSITION METHOD FOR POWER ALLOCATION

After the RB allocation is completed, we can conduct the power control scheme shown in (7). This optimization problem is non-convex and NP-hard. In [25], the author has studied fast algorithms and performance bounds of this optimization problem.

In this section, we use a dual iterative method to solve the problem (7). Firstly, maximizing the sum rate of V2V links with approximating link rate expression $\log(1+\mathrm{SINR})$ by $\log(\mathrm{SINR})$. Secondly, in order to avoid that a single user maximizes his power during the maximization process, we introduce a penalty term P_m. The original power control problem is rewritten as

$$\max_{\boldsymbol{p}} \sum_{m=1}^{\mathrm{M}_n} \left(\frac{1}{\ln 2} \ln \frac{g_{mm}p_m}{\sum\limits_{k=1,k\neq m}^{\mathrm{M}_n} g_{km}p_k + \delta^2} - P_m p_m \right) \tag{25}$$

$$s.t.\ C1: 0 < p_m \le p_{\max},\ \forall 1 \le m \le \mathrm{M}_n, \tag{26}$$

$$C2: \mathrm{SINR}_m \ge \gamma_m,\ \forall 1 \le m \le \mathrm{M}_n \tag{27}$$

where P_m represents the penalty factor. In order to facilitate calculation, we use variable substitution, i.e., $\hat{p}_m = \ln p_m$, then

$$p_m = e^{\hat{p}_m}$$

Therefore, the problem (25)-(27) can be rewritten as

$$\max_{\boldsymbol{p}} \sum_{m=1}^{\mathrm{M}_n} \left(\frac{1}{\ln 2} \ln \frac{g_{mm}e^{\hat{p}_m}}{\sum\limits_{k=1,k\neq m}^{\mathrm{M}_n} g_{km}e^{\hat{p}_k} + \delta^2} - P_m e^{\hat{p}_m} \right) \tag{28}$$

$$s.t.\ C1: \hat{p}_m \le \ln p_{\max},\ \forall 1 \le m \le \mathrm{M}_n, \tag{29}$$

$$C2: \ln(\mathrm{SINR}_m) \ge \ln \gamma_m,\ \forall 1 \le m \le \mathrm{M}_n \tag{30}$$

We use the Lagrange dual decomposition method to solve this problem, the corresponding Lagrange function is expressed as

$$\begin{aligned} \mathcal{L}(\hat{\boldsymbol{p}},\boldsymbol{\alpha},\boldsymbol{\beta}) = &\sum_{m=1}^{\mathrm{M}_n} \left(\frac{1}{\ln 2} \ln \frac{g_{mm}e^{\hat{p}_m}}{\sum\limits_{k=1,k\neq m}^{\mathrm{M}_n} g_{km}e^{\hat{p}_k} + \delta^2} - P_m e^{\hat{p}_m} \right) \\ &- \sum_{m=1}^{\mathrm{M}_n} \alpha_m \left(\ln p_{\max} - \hat{p}_m \right) \\ &- \sum_{m=1}^{\mathrm{M}_n} \beta_m \left(\ln \frac{g_{mm}e^{\hat{p}_m}}{\sum\limits_{k=1,k\neq m}^{\mathrm{M}_n} g_{km}e^{\hat{p}_k} + \delta^2} - \ln \gamma_m \right) \end{aligned} \tag{31}$$

where $\hat{\boldsymbol{p}} = [\hat{p}_1, \hat{p}_2, \ldots, \hat{p}_{\mathrm{M}_n}]$ is the power of transmitting VUE. $\boldsymbol{\alpha} = [\alpha_1, \alpha_2, \ldots, \alpha_{\mathrm{M}_n}]$ and $\boldsymbol{\beta} = [\beta_1, \beta_2, \ldots, \beta_{\mathrm{M}_n}]$ denote the Lagrange multiplier vector associated with the constraint of the power of transmitting VUE and SINR requirement, respectively.

Based on the formulas (31), we can obtain the derivation with respect to $\hat{p}_m$, α_m and β_m as follws

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial \hat{p}_m} = &\frac{1}{\ln 2} - P_m e^{\hat{p}_m} - \alpha_m + \beta_m \\ &+ \sum_{i\neq m,i=1}^{\mathrm{M}_n} \left(\frac{1}{\ln 2} + \beta_i \right) \bullet \left(- \frac{g_{mi}e^{\hat{p}_m}}{\sum\limits_{j\neq i,j=1}^{\mathrm{M}_n} g_{ji}e^{\hat{p}_j} + \delta^2} \right) \end{aligned} \tag{32}$$

$$\frac{\partial \mathcal{L}}{\partial \alpha_m} = \ln p_{\max} - \hat{p}_m \tag{33}$$

$$\frac{\partial \mathcal{L}}{\partial \beta_m} = \ln \frac{g_{mm}e^{\hat{p}_m}}{\sum\limits_{k=1,k\neq m}^{\mathrm{M}_n} g_{km}e^{\hat{p}_k} + \delta^2} - \ln \gamma_m \tag{34}$$

The Lagrangian dual decomposition method is an iterative process. In the t-th iteration, the Lagrange multipliers are updated as follows

$$\alpha_m^{t+1} = \alpha_m^t + \Delta_1 \cdot \left(\ln p_{\max} - \hat{p}_m^t \right) \tag{35}$$

$$\beta_m^{t+1} = \beta_m^t + \Delta_2 \cdot \left(\ln \frac{g_{mm}e^{\hat{p}_m^t}}{\sum\limits_{k=1,k\neq m}^{\mathrm{M}_n} g_{km}e^{\hat{p}_m^t} + \delta^2} - \ln \gamma_m \right) \tag{36}$$

where Δ_1 and Δ_2 is the step size.

Algorithm 2 : Power Allocation

Input: RB allocation matrix $\boldsymbol{X}$, the CSI matrix $\boldsymbol{G}$, SINR requirement $\boldsymbol{\gamma}$
Initialization: $\hat{p}_m = p_{\max}$ for $\forall m, \boldsymbol{\alpha} = \mathbf{0}_{1\times \mathrm{M}_n}$, $\boldsymbol{\beta} = \mathbf{0}_{1\times \mathrm{M}_n}$.
Set $t = 0$, and obtain the V2V links allocated in the n-th RB and the CSI matrix $\boldsymbol{G}'$ of these V2V links.
while not convergent and $t < t_{\max}$ **do**
  for $m \in \{1, \ldots, \mathrm{M}_n\}$ **do**
    Update the value of α_m^t, β_m^t according to (35) and (36)
    Update the value of $\hat{p}_m^t$ according to (37).
  end for
  Check the convergence, and set $t = t + 1$
end while
for $m \in \{1, \ldots, \mathrm{M}_n\}$ **do**
  if $\hat{p}_m^t > \ln p_{\max}$ **then**
    Set $p_m = p_{\max}$
  else
    Set $p_m = e^{\hat{p}_m^t}$
  end if
end for
Output: Power allocation vector $\hat{\boldsymbol{p}}$.

Then, let the derivation of function $\mathcal{L}(\hat{\boldsymbol{p}}, \boldsymbol{\alpha}, \boldsymbol{\beta})$ with respect to $\hat{p}_m$ be zero, i.e., $\frac{\partial \mathcal{L}}{\partial \hat{p}_m} = 0$,we have

$$\hat{p}_m^{t+1} = \frac{1 + \ln 2 \cdot (\beta_m^t - \alpha_m^t)}{\ln 2 \cdot P_m + \sum\limits_{i=1, i\neq m}^{\mathrm{M}_n} (1 + \ln 2 \cdot \beta_i^t) \cdot \frac{g_{mi}}{\sum\limits_{j=1, j\neq i}^{\mathrm{M}_n} g_{ji} \cdot \hat{p}_j^t + \delta^2}} \tag{37}$$

From the above discussion, we summarize the power control scheme in Algorithm 2. In this algorithm, we set the penalty term to a fixed penalty factor 0.01, and the update step sizes for α_m and β_m are set to 0.8^t. The initial values of $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ are both set to $\mathbf{0}$, and the transmit power of V2V links is set to the maximum transmission power $p_{\max}$. We first complete the iterative process according to (35)–(37), and then verify the obtained power allocation result. If the obtained power allocation result is greater than the maximum power, set the power of V2V link to the maximum transmission power, i.e., $p_m = p_{\max}$. By executing Algorithm 2, we can derive the power configuration scheme of the V2V links allocated to the n-th RB.

The complexity of Algorithm 2 is $\mathcal{O}(\mathrm{M}_n)$. In order to complete power allocation for all V2V links on N RBs, the complexity of power control scheme is $\sum\limits_{n} \mathcal{O}(\mathrm{M}_n) = \mathcal{O}(\mathrm{M})$.

V. SIMULATION RESULTS AND ANALYSIS

A. SIMULATION CONFIGURATION

In this section, we conduct the simulation of RB allocation and power control scheme in V2V communications network. In particular, the simulation scenario refers to the Manhattan urban environment specified in 3GPP TR 36.885 [3]. The road topology is a 500m × 433m square area.

TABLE 1. Simulation parameters.

Parameters	Value
Number of RBs	50
Carrier frequency	2 GHz
Bandwidth of each RB	180 kHz
SINR threshold $\gamma_m, \forall 1 \leq m \leq \mathrm{M}$	10 dB
Pathloss model	WINNER+B1
Shadowing distribution	Log-normal
Shadowing fading deviation	4 dB
Maximum transmission power, $P_{\max}$	23 dBm
Noise power δ^2	-114 dBm

And the WINNER II micro-cell model is used to calculate the path loss between the transmitting VUE and the receiving VUE [26]. Moreover, the shadow fading of the channels is supposed to be log-normal distributed with a unit deviation of 4dB and the noise power is −114 dBm. On the other hand, assume that the system carrier frequency is 2 GHz and the bandwidth is 180 KHz. The maximum transmission power of transmitting VUE is 23 dBm and the minimum SINR requirement for receiving VUE is 10 dB. More detailed parameters are presented in Table 1.

In our simulation, the reference schemes are Resource Allocation algorithm with a Spectral Radius Feasibility Check (RASRFC) proposed in [21]and Minimizing the Increment of Spectral Radius (MISR) proposed in [15]. First, we analyze the performance of the proposed scheme compared to the above two schemes in RB allocation process. In [21], the RB allocation scheme based on RASRFC algorithm is proposed, where the author determines whether add a new V2V link to the current RB by the value of spectral radius and the feasibility of power distribution (i.e., whether the transmit power meets $p_m \leq p_{\max}$ for $\forall m$). In [15], the author revised the selection process of the following V2V link in the RASRFC algorithm. The following V2V link is selected according to the minimum increment of matrix spectral radius rather than the least inference to the allocated V2V links. Moreover, we simulate the proposed power control scheme. Compared to the equal power distribution scheme, the throughput of V2V links has been improved.

B. RESULTS AND ANALYSIS

We demonstrate the performance of RB allocation algorithm in Fig. 3 and Fig. 4. First, we plot the number of RBs for different numbers of V2V links with the uniform distance $d = 20$m between the transmitting VUE and the receiving VUE of each V2V link. As shown in Fig. 3, when using the RASRFC algorithm, the V2V communications network occupies much more RB than the other two RB allocation schemes. This is because when selecting a subsequent V2V link, if the transmit power requirement of any one of all the V2V links allocated by the current RB exceeds the maximum transmission power $p_{\max}$, the allocation algorithm will select a new RB for resource allocation. On average, each RB can be allocated to more than 4 V2V links. In [15], the subsequent V2V link is selected based on the increment of the matrix

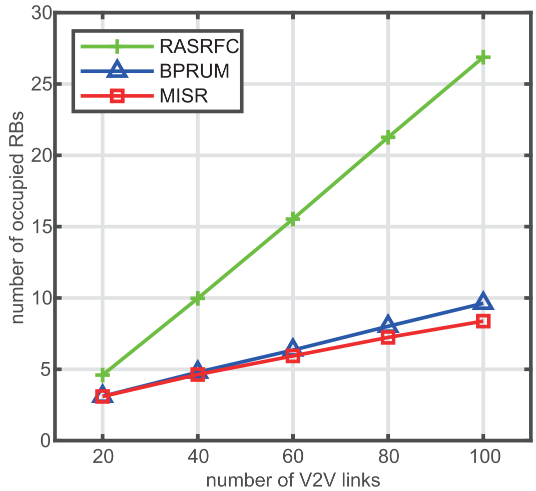


FIGURE 3. Number of occupied RBs for different number of V2V links with $d = 20$m.

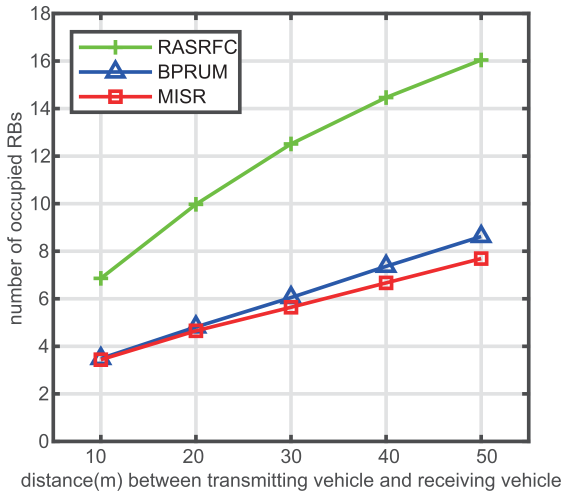


FIGURE 4. Number of occupied RBs for different distance between transmitting and receiving VUE with number of V2V links M = 40.

spectrum radius, which led to an increase in RB utilization. Take 100 V2V links as an example, 8 RB are occupied on average. However, it must be stated that the power of transmitting VUE is limited by $\boldsymbol{p} \geq (I - H)^{-1} \bullet \boldsymbol{q}$ in MISR algorithm. The author does not consider the maximum power limitation of transmitting VUE, i.e., the feasibility of RB allocation results based on MISR algorithm cannot be guaranteed under the limitation of power and receiving SINR. When applying the BPRUM algorithm, the utilization of RB is close to that of MISR algorithm. In Fig. 4, we plot the number of RBs for different distances d between the transmitting VUE and the receiving VUE with the number of V2V links M = 40. As the distance between the transmitting VUE and the receiving VUE increases in each V2V link, the received SINR of the receiving VUE will decrease, i.e., the number of V2V links that can share one RB will decrease. It is observed that the RB utilization has increased by 100% compared to the RASRFC algorithm.

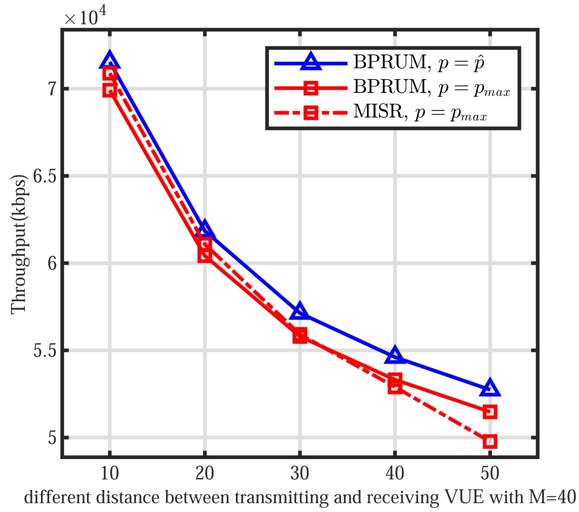


FIGURE 5. Throughput of V2V links versus the distance between transmitting and receiving VUE for M = 40.

On the other hand, we conducted the simulation of the power control algorithm. We have performed the simulation 1000 times. According to Algorithm 2, we can see that for each result of using the BPRUM algorithm to allocate RB, there must be a feasible power allocation scheme that can meet the maximum power limit and the minimum SINR limit, i.e., (5) and (6). However, for the result of using the MISR algorithm, according to [15], the user power should meet $\boldsymbol{p} \geq (I - H)^{-1} \bullet \boldsymbol{q}$. First of all, the power range here is not easy to obtain. Even if we only consider the critical value, the calculated power result cannot be guaranteed to meet (5) and (6). In the simulation process, we adopt a simple configuration method, i.e., each transmitting VUE is configured to the maximum power $p_{\max}$. By verifying whether the restriction conditions (5) and (6) are met, in our simulation, we only compare the feasible situation with our proposed scheme.

Fig. 5 shows the throughput of V2V links with respect to the number of user pairs M = 40 for different RB allocation schemes and power control schemes. Note that for the MISR algorithm, we may not find a power control scheme that not only meets the maximum power limitation (5) but also meets the minimum SINR condition (6). Therefore, we only analyze the feasible situation, i.e., both (5) and (6) conditions can be met. These results show that as the distance between the two vehicles of V2V link increases the throughput of the V2V links gradually decreases. At the same time, the benefit of using power control schemes is gradually becoming larger. When the distance between the two vehicles of V2V link is $d = 20$m, compared to MISR algorithm, the throughput is increased by 6.2%. This is because as the distance between transmitting and receiving VUE increases, the power attenuation of the expected signal received by the receiving VUE is greater, and its anti-interference ability is weakened. The use of power control scheme can reduce the interference between different V2V links, thereby increasing the throughput of V2V links. Fig. 6 shows the throughput with

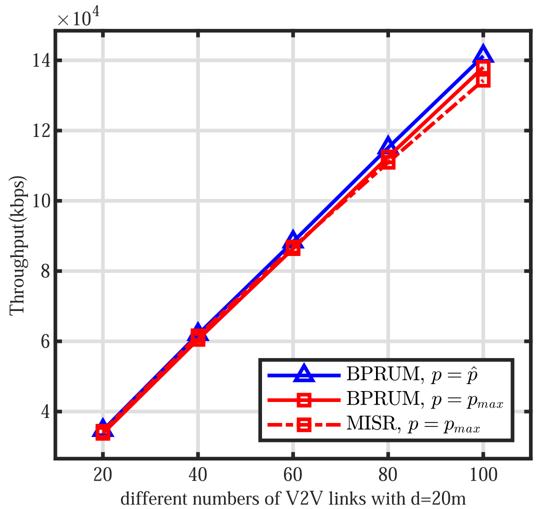


FIGURE 6. Throughput of V2V links versus the number of V2V links for d = 20m.

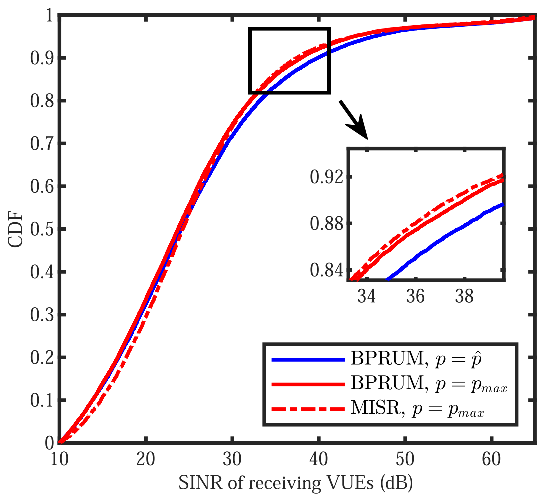


FIGURE 7. CDF of the SINR of V2V links with M = 40, d = 20m.

respect to different numbers of V2V links. The increment in throughput brought by the use of power control schemes gradually increases while the number of V2V links increases.

Fig. 7 shows the CDF of the SINR of receiving VUE for M = 40, d = 20m. Firstly, both schemes can meet the SINR requirement, i.e., $\text{SINR}_m \geq 10, \forall m$. Moreover, after the power control scheme is adopted, the CDF curve is below the curve using the maximum power. This is more obvious in the range of 30-40 dB, which shows that the power control scheme improves the SINR of the receiving VUE. The CDF of the throughput of V2V links is shown in Fig. 8. As can be seen from the CDF curves, the proposed power control scheme exhibits the best throughput increment. Additionally, it can be seen that the CDF curve of the MISR algorithm is not very smooth. The reason is that in our 1000 simulations when the transmitting VUE is configured for maximum power $p_{\max}$, only 230 times are feasible.

Fig. 9 and Fig. 10 depict the CDF of the SINR of receiving VUE and the throughput of V2V links for M = 80, d = 40m,

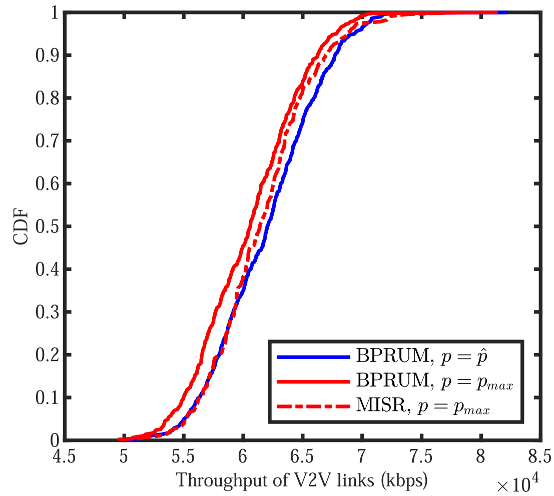


FIGURE 8. CDF of the throughput of receiving VUEs with M = 40, d = 20m.

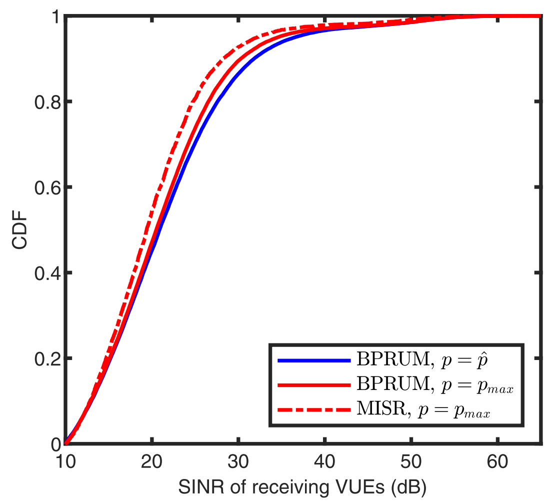


FIGURE 9. CDF of the SINR of V2V links with M = 80, d = 40m.

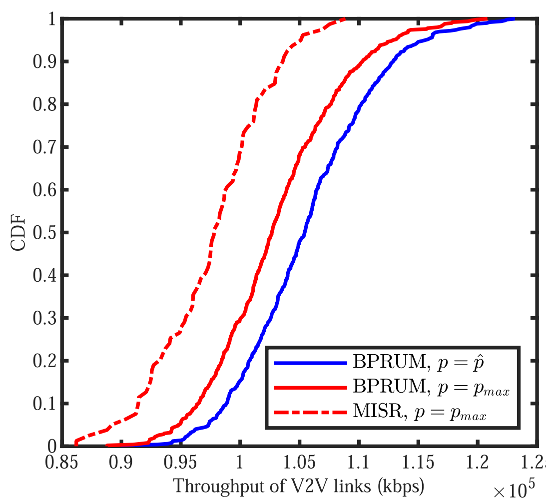


FIGURE 10. CDF of the throughput of receiving VUEs with M = 80, d = 40m.

respectively. Compare with Fig. 7 and Fig. 8, it is revealed that as the number of V2V links and the distance between the two vehicles of V2V link increases, the proposed power control scheme improves the throughput more significantly. This is because as the number of V2V links and communication distances increase, there is more room for optimization to improve system throughput than the maximum transmission power configuration, which is consistent with the conclusion shown in Fig. 5 and Fig. 6. Moreover, when the MISR algorithm is used for 1000 simulations, we only get 92 feasible situations. Compared with MISR algorithm, the advantages of using BPRUM algorithm and power control scheme are more obvious.

VI. CONCLUSION

In this paper, we studied the problem of radio spectrum resource allocation and power control in V2V communications network. Firstly, through function mapping rules, the RB allocation for V2V links is converted into a belief inference problem based on the factor graph model. Then we performed the BPRUM algorithm to solve this inference problem and maximized the number of V2V links allocated to the same RB. In addition, according to the RB allocation results, we studied the power control scheme and proposed a power optimization scheme to maximize throughput of V2V communications network. Simulation results show that the proposed scheme will make a great contribution to radio spectrum utilization and throughput in V2V communications network.

APPENDIX A

According to the value of j, the calculation of $\beta_{j\to i}^{t+1}$ can be divided into three cases as follows.

Case 1 : For $j = 1$.

Refer to *Theorem* 4 in [23], the value of $\beta_{j\to i}^{t+1}$ equals 1 for $j = 1$.

Case 2 : For $j = i + 1$.

Firstly, we derive the calculation of $m_{F_j\to\mu_i}^{t+1}(x)$ while $x = 0$ and $x = 1$, and then calculate $\beta_{j\to i}^{t+1}$ by substituting them into (20).

For $x = 1$, the message of F_j to μ_i is

$$m_{F_j\to\mu_i}^{t+1}(1) = \max_{\mathrm{E}_i^1}\left\{G_{kn}(\boldsymbol{x}^{(1)})\prod_{l\in\mathrm{E}_i^1}\left(\frac{m_{\mu_l\to F_j}^{t}(1)}{m_{\mu_l\to F_j}^{t}(0)}\right)\right\} \times \prod_{l\in\Gamma_j^F\backslash\{i\}} m_{\mu_l\to F_j}^{t}(0) \quad (38)$$

where $\boldsymbol{x}^{(1)}$ represents $x_{in} = 1$ in RB allocation vector $\mathbf{x}$ of the n-th RB, E_i^1 is a subset of $\Gamma_j^F\backslash\{i\}$ with $\mu_l \doteq x_{ln} = 1$ for all $l \in \mathrm{E}_i^1 \cup \{i\}$, while $\mu_l \doteq x_{ln} = 0$ for all $l \in \Gamma_j^F\backslash\{i\}\backslash\mathrm{E}_i^1$. According to the definition of $G_{kn}(\boldsymbol{x})$ in (12), the value of $G_{kn}(\boldsymbol{x})$ is 0 or 1. In order to ensure that $m_{F_j\to\mu_i}^{t+1}(1)$ can reach the maximum value in (38), the value of $G_{kn}(\boldsymbol{x}^{(1)})$ should be 1 for $\forall\,\boldsymbol{x}^{(1)}$. Moreover, the set E_i^1, refer to (3), should still meet

$$\sum_{l\in\mathrm{E}_i^1} g_{li}p_l \leq \frac{g_{ii}p_i}{\gamma_i} - \delta^2 \quad (39)$$

For $x = 0$, the message of F_j to μ_i is

$$m_{F_j\to\mu_i}^{t+1}(0) = \mathrm{E}_i^2\max\left\{G_{kn}(\boldsymbol{x}^{(0)})\prod_{l\in\mathrm{E}_i^2}\left(\frac{m_{\mu_l\to F_j}^{t}(1)}{m_{\mu_l\to F_j}^{t}(0)}\right)\right\} \times \prod_{l\in\Gamma_j^F\backslash\{i\}} m_{\mu_l\to F_j}^{t}(0) \quad (40)$$

where $\boldsymbol{x}^{(0)}$ represents $x_{in} = 0$ in RB allocation vector $\boldsymbol{x}$ of the n-th RB, E_i^2 is a subset of $\Gamma_j^F\backslash\{i\}$ with $\mu_l \doteq x_{ln} = 1$ for all $l \in \mathrm{E}_i^2$ while $\mu_l \doteq x_{ln} = 0$ for all $l \in \Gamma_j^F \setminus \mathrm{E}_i^2$. Here, $G_{kn}(\boldsymbol{x}^{(0)}) = 1$ for $\forall\,\boldsymbol{x}^{(0)}$.

By substituting (38) and (40) into (20), the message F_j to μ_i can be calculated as follows

$$\begin{aligned}\beta_{j\to i}^{t+1} &= \max_{\mathrm{E}_i^1}\left\{\sum_{l\in\mathrm{E}_i^1}\alpha_{l\to j}^{t}\right\} - \max_{\mathrm{E}_i^2}\left\{\sum_{l\in\mathrm{E}_i^2}\alpha_{l\to j}^{t}\right\}\\ &= \sum_{l\in\overline{\mathrm{E}_i^1}}\alpha_{l\to j}^{t} - \sum_{l\in\overline{\mathrm{E}_i^2}}\alpha_{l\to j}^{t}\end{aligned} \quad (41)$$

where $\overline{\mathrm{E}_i^1} = \arg\max_{\mathrm{E}_i^1}\{\sum_{l\in\mathrm{E}_i^1}\alpha_{l\to j}^{t}\}$, $\overline{\mathrm{E}_i^2} = \arg\max_{\mathrm{E}_i^2}\{\sum_{l\in\mathrm{E}_i^2}\alpha_{l\to j}^{t}\}$. Besides, define $\mathrm{E}_i^+ = \{l \in \Gamma_j^F\backslash\{i\}|\alpha_{l\to j}^{t} > 0\}$, we can get $\overline{\mathrm{E}_i^2} = \mathrm{E}_i^+$.

In addition, we can deduce the set $\overline{\mathrm{E}_i^1}$ according to the method shown in [24]. Define $q_l \triangleq \alpha_{l\to j}^{t}/(g_{li}p_l)$, $l \in \mathrm{E}_i^+$, by sorting q_l in the decreasing order, we can get a sequence $\mathbf{q}$. Let Q_k denote the sum of $g_{li}p_l$ which corresponds with the top k of $\mathbf{q}$. If Q_k satisfies (39) (i.e., $Q_k \leq g_{ii}p_i/\gamma_i - \delta^2$), while $Q_{k+1} > g_{ii}p_i/\gamma_i - \delta^2$, then the set $\overline{\mathrm{E}_i^1}$ is composed of the index values of the first k q_l in sequence $\mathbf{q}$. And $\beta_{j\to i}^{t+1}$ can be calculated by (41).

Case 3 : For $j > 1$ and $j \neq i + 1$.

Based on the derivation in *Case* 2, the message F_j to μ_i can be expressed as

$$\begin{aligned}\beta_{j\to i}^{t+1} &= \max_{\mathrm{E}_i^3}\left\{\sum_{l\in\mathrm{E}_i^3}\alpha_{l\to j}^{t}\right\} - \max_{\mathrm{E}_i^4}\left\{\sum_{l\in\mathrm{E}_i^4}\alpha_{l\to j}^{t}\right\}\\ &= \sum_{l\in\overline{\mathrm{E}_i^3}}\alpha_{l\to j}^{t} - \sum_{l\in\overline{\mathrm{E}_i^4}}\alpha_{l\to j}^{t}\end{aligned} \quad (42)$$

where E_i^3, E_i^4 are subsets of $\Gamma_j^F\backslash\{i\}$. Define $\mathrm{E}_i^+ = \{l \in \Gamma_j^F\backslash\{m\}\backslash\{k\}|\alpha_{l\to j}^{t} > 0\}$, we can get $\overline{\mathrm{E}_i^3} = \overline{\mathrm{E}_i^4} = \mathrm{E}_i^+$ if $\alpha_{k\to j}^{t} \leq 0$.

If $\alpha_{k\to j}^{t} > 0$, define $q_l \triangleq \alpha_{l\to j}^{t}/(g_{lk}p_l)$, $l \in \mathrm{E}_i^+$, by sorting q_l in the decreasing order, we can get the sequence $\mathbf{q}$. Let $Q_{k_1'}$ and $Q_{k_2'}$ denote the sum of $g_{lk}p_l$ which corresponds with the first k'_1 and k'_2 of $\mathbf{q}$, respectively. We can get k'_1 and k'_2, which satisfy $Q_{k'_1} + g_{mk}p_m \leq g_{kk}p_k/\gamma_k - \delta^2$ while $Q_{k'_1+1} + g_{mk}p_m > g_{kk}p_k/\gamma_k - \delta^2$ and $Q_{k'_2} \leq g_{kk}p_k/\gamma_k - \delta^2$ while $Q_{k'_2+1} > g_{kk}p_k/\gamma_k - \delta^2$. Then let $\left(\mathrm{E}_i^1\right)'$ and $\left(\mathrm{E}_i^2\right)'$ denote the index of the first k'_1 and k'_2 q_l in $\mathbf{q}$. Therefore, $\beta_{j\to i}^{t+1}$ can be calculated as follows

$$\beta_{j\to i}^{t+1} = \max\left\{\sum_{l\in \mathrm{E}_i^+}\alpha_{l\to j}^t, \alpha_{k\to j}^t + \sum_{l\in\left(\mathrm{E}_i^1\right)'}\alpha_{l\to j}^t\right\} - \max\left\{\sum_{l\in \mathrm{E}_i^+}\alpha_{l\to j}^t, \sum_{l\in\left(\mathrm{E}_i^2\right)'}\alpha_{l\to j}^t\right\} \quad (43)$$

REFERENCES

[1] Y. Park, T. Kim, and D. Hong, "Resource size control for reliability improvement in cellular-based V2 V communication," *IEEE Trans. Veh. Technol.*, vol. 68, no. 1, pp. 379–392, Jan. 2019.

[2] *Release Description; Release 14*, document GT 36.885, 2018. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3179

[3] *Study on LTE-Based V2X Services*, document GT 36.885, 2016. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2934

[4] S. Park, B. Kim, H. Yoon, and S. Choi, "RA-eV2 V: Relaying systems for LTE-V2 V communications," *J. Commun. Netw.*, vol. 20, no. 4, pp. 396–405, Aug. 2018.

[5] M. Allouch, S. Kallel, A. Soua, and S. Tohme, "PEARL: A novel priority and guaranteed-based resource allocation approach for V2 V communications in LTE-V mode 3," in *Proc. 8th Int. Conf. Wireless Netw. Mobile Commun. (WINCOM)*, Oct. 2020, pp. 1–6.

[6] F. Yucel, A. Bhuyan, and E. Bulut, "Secure, resilient and stable resource allocation for D2D-based V2X communication," in *Proc. Resilience Week (RWS)*, Oct. 2020, pp. 71–77.

[7] J. Du, F. R. Yu, X. Chu, J. Feng, and G. Lu, "Computation offloading and resource allocation in vehicular networks based on dual-side cost minimization," *IEEE Trans. Veh. Technol.*, vol. 68, no. 2, pp. 1079–1092, Feb. 2019.

[8] A. Bazzi, A. Zanella, G. Cecchini, and B. M. Masini, "Analytical investigation of two benchmark resource allocation algorithms for LTE-V2 V," *IEEE Trans. Veh. Technol.*, vol. 68, no. 6, pp. 5904–5916, Jun. 2019.

[9] K. Li, W. Ni, E. Tovar, and M. Guizani, "Optimal rate-adaptive data dissemination in vehicular platoons," *IEEE Trans. Intell. Transp. Syst.*, vol. 21, no. 10, pp. 4241–4251, Oct. 2020.

[10] Y. Liu, W. Wang, H.-H. Chen, L. Wang, N. Cheng, W. Meng, and X. Shen, "Secrecy rate maximization via radio resource allocation in cellular underlaying V2 V communications," *IEEE Trans. Veh. Technol.*, vol. 69, no. 7, pp. 7281–7294, Jul. 2020.

[11] J. Mei, K. Zheng, L. Zhao, Y. Teng, and X. Wang, "A latency and reliability guaranteed resource allocation scheme for LTE V2 V communication systems," *IEEE Trans. Wireless Commun.*, vol. 17, no. 6, pp. 3850–3860, Jun. 2018.

[12] W. Sun, E. G. Strom, F. Brannstrom, K. C. Sou, and Y. Sui, "Radio resource management for D2D-based V2 V communication," *IEEE Trans. Veh. Technol.*, vol. 65, no. 8, pp. 6636–6650, Aug. 2016.

[13] R. Aslani, E. Saberinia, and M. Rasti, "Resource allocation for cellular V2X networks Mode-3 with underlay approach in LTE-V standard," *IEEE Trans. Veh. Technol.*, vol. 69, no. 8, pp. 8601–8612, Aug. 2020.

[14] X. Luo, H.-H. Chen, and W. Meng, "How much can radio resource allocation help to improve secrecy capacity of V2 V underlay cellular networks?" *IEEE Trans. Veh. Technol.*, vol. 69, no. 12, pp. 14932–14944, Dec. 2020.

[15] S. Zhang, Y. Hou, X. Xu, and X. Tao, "Resource allocation in D2D-based V2 V communication for maximizing the number of concurrent transmissions," in *Proc. IEEE 27th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Sep. 2016, pp. 1–6.

[16] G. T. 36.213. (2020). *Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Layer Procedures*. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2427

[17] S. Stanczak, M. Wiczanowski, and H. Boche, *Fundamentals of Resource Allocation in Wireless Networks, Theory and Algorithms*, vol. 3. Springer, 2009.

[18] Q. Cui, Z. Gong, W. Ni, Y. Hou, X. Chen, X. Tao, and P. Zhang, "Stochastic online learning for mobile edge computing: Learning from changes," *IEEE Commun. Mag.*, vol. 57, no. 3, pp. 63–69, Mar. 2019.

[19] X. Wu, Y. Hou, X. Tao, and X. Tang, "Maximization of concurrent links in V2 V communications based on belief propagation," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, May 2020, pp. 1–6.

[20] W. Sun, D. Yuan, E. G. Strom, and F. Brannstrom, "Resource sharing and power allocation for D2D-based safety-critical V2X communications," in *Proc. IEEE Int. Conf. Commun. Workshop (ICCW)*, Jun. 2015, pp. 2399–2405.

[21] M. Botsov, S. Stanczak, and P. Fertl, "Comparison of location-based and CSI-based resource allocation in D2D-enabled cellular networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2015, pp. 2529–2534.

[22] F. R. Kschischang, B. J. Frey, and H.-A. Loeliger, "Factor graphs and the sum-product algorithm," *IEEE Trans. Inf. Theory*, vol. 47, no. 2, pp. 498–519, Feb. 2001.

[23] J. Liu, B. Bai, J. Zhang, and K. B. Letaief, "Cache placement in fog-RANs: From centralized to distributed algorithms," *IEEE Trans. Wireless Commun.*, vol. 16, no. 11, pp. 7039–7051, Nov. 2017.

[24] S. Cao, X. Tao, Y. Hou, and Q. Cui, "An energy-optimal offloading algorithm of mobile computing based on HetNets," in *Proc. Int. Conf. Connected Vehicles Expo. (ICCVE)*, Oct. 2015, pp. 254–258.

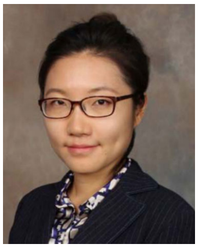
[25] C. W. Tan, M. Chiang, and R. Srikant, "Fast algorithms and performance bounds for sum rate maximization in wireless networks," *IEEE/ACM Trans. Netw.*, vol. 21, no. 3, pp. 706–719, Jun. 2013.

[26] P. Kyösti, J. Meinilä, L. Hentila, X. Zhao, T. Jämsä, C. Schneider, M. Narandzic, M. Milojević, A. Hong, J. Ylitalo, V.-M. Holappa, M. Alatossava, R. Bultitude, Y. Jong, and T. Rautiainen, *WINNER II channel models*, document IST-4-027756 WINNER II D1.1.2 V1.2, Feb. 2008.

YANZHAO HOU (Member, IEEE) received the Ph.D. degree from the Beijing University of Posts and Telecommunications (BUPT), Beijing, China, in 2014. He is currently with the National Engineering Laboratory for Mobile Internet, BUPT. His current research interests include next-generation wireless networks, software-defined radio, vehicular networks, and trial systems. He received the Best Demo Award from the IEEE APCC 2018.

XUNCHAO WU (Graduate Student Member, IEEE) was born in Henan, China, in 1996. He received the B.E. degree in communication engineering from Shandong University, Shandong, China, in 2018. He is currently pursuing the M.E. degree in electronic and communication engineering with the Beijing University of Posts and Telecommunications (BUPT). His current research interests include wireless communications and vehicle-to-vehicle (V2V) communication.

XIAOSHENG TANG is currently a Research Staff with the Wireless Technology Innovation (WTI) Institute, Beijing University of Posts and Telecommunications (BUPT), China. His research interest includes computer communications.



XIAOQI QIN (Member, IEEE) received the B.S., M.S., and Ph.D. degrees from the Virginia Polytechnic Institute and State University, Blacksburg, VA, USA, in 2011, 2013, and 2016, respectively. She is currently a Lecturer with the School of Information and Communication Engineering, Beijing University of Posts and Telecommunications, Beijing, China. Her research interests include algorithm design and cross-layer optimization in wireless networks, coexistence and spectrum sharing in cognitive radio networks, and intelligent Internet of Things.

MINGYU ZHOU received the Ph.D. degree from the Beijing University of Posts and Telecommunications (BUPT), in 2008. After his graduation, he became a Senior Engineer at Huawei Technologies, dedicated in 3GPP standardization and patent application. As the Research Director, he focuses on innovation related work, including standardization, patent, and innovative product (e.g., tethered Drone). Until now, he has applied more than 100 patents (tens of them are PCTs), published more than ten academic papers, and finished more than 100 standardization proposals.