Resource Allocation in D2D Enabled Vehicular Communications: A Robust Stackelberg Game Approach Based on Price-Penalty Mechanism

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***Abstract*—This paper studies how to apply game theory to realize a well-function device-to-device enabled vehicular (D2D-V) communication system, where the uplink channel allocated to the cellular user (CU) is reused by multiple D2D-V users. Considering a non-cooperative setting where the CU and D2D-V users are selfish and profit-driven, a novel Stackelberg game framework is proposed to model the single-leader-multiple-follower hierarchical competition, where the CU and D2D-V users act as the leader and the followers, respectively. For the current D2D-V networks, the interference in the dense vehicle scene often leads to extremely poor communication quality. Moreover, a vehicle's mobility leads to an uncertain channel state and further affects the stability of communication. To achieve effective communication, robust Stackelberg game-based resource allocation is developed, and a price-penalty mechanism is further proposed. Unlike previous Stackelberg games, the robust game is highlighted by handling the channel uncertainty which is embedded in the interference probability constraints. Besides, a game equilibrium (GE) is considered to be the solution and its existence and uniqueness are investigated. Also, a distributed robust power control and nonuniform price bargaining algorithm is proposed to approach the GE. Numerical simulations are performed to evaluate the algorithm performances, and the results indicate that the proposed algorithm is effective in high mobility vehicular networks under uncertain channel environments.**

***Index Terms*—Vehicular networks, D2D communication, robust power control, Stackelberg game, channel uncertainty.**

I. Introduction

FUTURE vehicular networks are expected to rapidly develop to satisfy the increasing demand for data traffic [1], especially the quality of service (QoS) of low delay and high reliability [2], [3]. However, the traditional fourth-Generation mobile communication network (4 G) can only provide Mbps communication service and 10ms-level latency, which are tough to meet the harsh requirements of vehicular networks [4]. Compared with 4 G, the fifth-Generation mobile communication network (5 G) has a ten-time transmission rate and one-tenth of the delay. Therefore, 5 G can serve vehicular communications well and is naturally applied to the vehicular cellular network [6]. However,the traditional single cellular architecture has low spectral efficiency, and it is not able to sustain direct vehicle-to-vehicle communication since the packets have to be relayed by the Evolved Node B (eNB). As a key technology of 5 G, device-to-device (D2D) underlay communication can realize direct communication between adjacent vehicles and reduce the dependence on the eNB [7]. Moreover, due to the outstanding performance in low communication delay and high spectrum efficiency, D2D is naturally introduced to the cellular network. The cellular network with D2D underlay communication in vehicular systems constitutes the D2D-enabled vehicular (D2D-V) networks.

Despite the advantages described above, the widespread deployment of existing D2D-V networks still poses some challenges. First, due to the time-varying channel fading and the high-speed movement of vehicles [8], [9], the assumption of certainty channel gain is impractical and fails to apply power control strategy in reality. To achieve a more realistic channel description, complex channel fading and vehicle movement should be considered in the current D2D-V networks. Second, it is more reasonable to consider the high vehicle density scenario where multiple D2D-V pairs reuse the uplink channel of the cellular user (CU), but it is a significant challenge to realize complex interference management, especially when channel uncertainty is considered. Last but not the least, the involved D2D-V networks are hierarchical, and the CU and D2D-V users in the networks are different stakeholders who compete for their benefits. It is a challenging issue to determine the equilibrium point where the interests of all parties are maximized, especially in the high mobility scenario with imperfect channel state information (CSI). It is necessary to establish an accurate channel model to overcome these challenges. Furthermore, we propose a game-based robust resource allocation scheme to realize effective interference management and maximize the benefits of all parties.

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A. Related Works

D2D underlay communication is currently served as an essential solution for vehicular communications. In the D2D-V networks, the authorized vehicular users with spectrum resources can directly communicate without going through the eNB. However, the scarce spectrum resources appear to be inadequate in high-density vehicular networks. To realize D2D underlay communication under the limited spectrum resources, effective channel reusing is crucial [10], [11]. There are mainly two reusing methods in D2D-V communication, namely one-to-one and many-to-one. [12] and [13] studies resource allocation problems under the one-to-one reusing mode, but the spectrum efficiency of the whole system is low. In response to the defects of one to one reusing mode, the authors propose a many-to-one reusing mode where the spectrum utilization is well improved [14]. However, the coexistence of D2D-V and cellular communication in the same frequency band will cause serious co-channel interference, especially in the many-to-one reusing mode. Hence, effective interference management strategy is particularly important. To realize effective interference management, robust power control is a crucial component and widely used in wireless resource optimization schemes [15]. Many existing works have formulated the power control schemes for the sake of coordinating co-channel interference and improving network capacity [16]–[18]. Given that only limited signaling information can be exchanged over the backhaul network, it is always desirable to accomplish such optimization by distributed mechanisms in practice [19]. Besides, due to the optimization scheme requires a real-time power control strategy, frequent information interaction results in a large number of signaling overhead. Compared with the centralized mechanism, the distributed mechanism with low signaling overhead is a better choice.

In recent years, game theory has been used as a unifying framework to study resource allocation and interference management. For wireless two-tier networks, power control games are formulated and analyzed in [20]–[25]. All these works can be divided into noncooperative game and hierarchical game. For the noncooperative game, users act as individual players who aim at selfishly maximizing their own benefits. However, this selfish manner often fails to a good system performance. The hierarchical game outperforms the noncooperative method, where the leaders (eNB) can foresee the response of followers (D2D-V users) before their strategy formulation and maximize their utility in a non-cooperative manner. In the D2D-V networks, the upper network and the lower network compete for their utility in a hierarchical structure and the mathematical modeling fits naturally into the framework of a Stackelberg game. A power control framework based on the Stackelberg game is proposed to maximize the network throughput [22]. The authors propose a distributed power control scheme to mitigate the co-channel interference while meeting the users' QoS. As a bridge between the upper and lower levels, power often plays a key role in balancing the QoS of all parties. However, the single power control is missing in the consideration of the beneficial relationship. References [23], [24], and [25] focus on the pricing mechanism and regard interference as a resource that can be allocated to users. In the existing papers, the price mechanism includes the nonuniform pricing model [23] and the uniform pricing model [22], [24], [25]. Compared with the unified pricing model, the nonuniform pricing model with more flexible price variables can get better target utility and is widely used. Therefore, to realize well-function Stackelberg game, the nonuniform pricing mechanism is acquired which combines the power control scheme.

However, wireless vehicular channel is full of high uncertainty, which is a crucial point for effective vehicle-to-everything communications, but it is ignored by the above works [20]–[25]. Motivated by this weakness, the first-order Gauss-Markov process is used to statistically describe the imperfect CSI in [26]. Due to statistically describe, the co-channel interference is tricky to management. In [27], the interference constraint is constructed as chance constraint, which is a probability form with multiple-variable coupling. To deal with the interference constraint, a approximation transmission is necessary. However, traditional methods are useless to express it in closed form. To obtain the closed form, Nemirovski and Shapiro have proposed a convex approximation approach in [28]. Therein, the Bernstein approximation method has commonly been used to approximate the chance constraint [29].

B. Contributions

In this paper, a distributed robust power control and nonuniform price bargaining algorithm is proposed for the D2D-based vehicular networks with channel uncertainty and co-channel interference. The interference management is effectively realized by the allocation of power and price, and user QoS is also guaranteed in the framework. The main contributions are summarized as follows:

- A more practical communication scenario is considered. Instead of the impractical assumption of the perfect or known CSI, the first-order Gauss-Markov process is introduced to describe the imperfect CSI. In particular, vehicle mobility is highlighted to simulate time-varying fast fading.
- More efficient many-to-one reusing mode is adopted to improve spectrum utilization. From the perspective of robust transmission, the probability constraint is constructed to depress the uncertain co-channel interference. To accommodate the probability constraint with multiple-variable coupling, the Bernstein approximation method is used to transform it into a solvable closed form.
- A price-penalty mechanism is proposed to cooperate with the power control scheme. Outperforming the pure power control, the beneficial relationships are highlighted. By charging for interference, the price-penalty mechanism could limit the selfish behaviors and balance the benefits of all parties.

The rest of this paper is organized as follows: a vehicular communication model based on D2D technology is established in Section II, the channel model and Stackelberg game formulation are also presented. In Section III, the game equilibrium is

TABLE I
NOTATIONS

$\mathcal{I}$	The index set $\mathcal{I}$={$0, 1, \cdots, i, \cdots, N$}
$\mathcal{J}$	The index set $\mathcal{J}$={$0, 1, \cdots, j, \cdots, N$}
Pr{$\cdot$}	Probability function
Υ	Parameter of exponential distribution
$E\{\cdot\}$	Exponential distribution
$\mathbb{R}^N$	Set of N-dimensional real vectors
$\mathcal{R}^N$	Euclidean space
$\mathbb{E}\{\cdot\}$	Mathematical expectation of a random variable

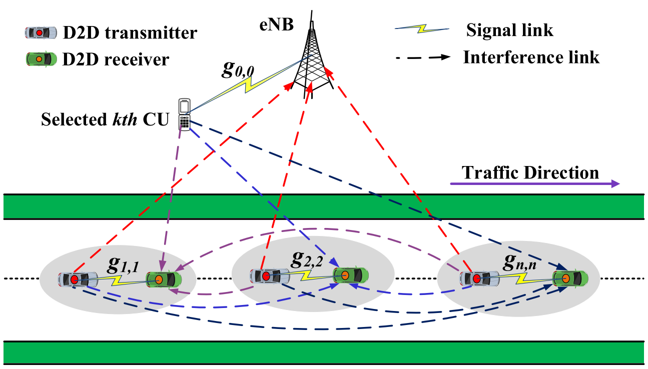

Fig. 1. System model.

defined, and the transformation of the non-convex Stackelberg game is finished. We give the optimal solution of the Stackelberg game and propose a power control and nonuniform price bargaining algorithm in Section IV. In Section V, simulation results and performance analysis are presented. Finally, we draw a conclusion in Section VI.

Notation: In this paper, vectors are typeset by using bold lowercase letters. Some notations are given in Table I.

II. Problem Formulation

A. System and Channel Models

In this paper, we consider the uplink scenario in the D2D-V networks. There is a macrocell and numerous mobile clusters in the networks. Furthermore, the eNB and several CUs are in the macrocell, and each mobile cluster is a D2D pair that can communicate directly. When the distance between two neighbor vehicles exceeds the applicable distance of D2D communication, the mobile clusters are spontaneously formed. Cowans M3 model can well describe the traffic pattern [30]. Cowans M3 model stated that the distances between adjacent clusters follow a truncated exponential distribution. Thus, vehicle speeds are assumed to constant in a small-time interval. As depicted in Fig. 1, the eNB is at the center of the network with the communication range radius R. A straight highway passes through the coverage region of the eNB. Besides, a CU and its reused D2D pairs are shown in this picture, and the CU establishes signal links to its servicing eNB, whereas the data except for the control message of N D2D pairs are communicated directly without passing through the eNB. We assume that the association of a D2D pair is stationary in a small time interval. Without loss of generality, the sets of CU and D2D pairs are $\mathcal{S}_0 := \{0\}$ and $\mathcal{S}_l := \{1, 2, \ldots, n, \ldots, N\}$, respectively. The set of all users is then simply $\mathcal{S} := \mathcal{S}_0 \cup \mathcal{S}_l$.

The CU is the spectrum owner and D2D pairs are spectrum sharers. To realize multiple-user joint communication and improve the spectrum utilization, P D2D pairs are supposed to be allocated to the CU, Q ($Q \leq P$) uplink channels are reused, and it will happen that multiple D2D pairs reuse the same channel. In this approach [14], when a D2D pair is willing to reuse the CU's channel to transform information, it needs to be registered at the eNB, and then one of the Q channels will be assigned to it. For example, supposing that a link is indexed with i, channel index mod$\{i, Q\}$+1 is allocated to the D2D pair. The next D2D pair is indexed with i+1 and is assigned with the channel index, (mod$\{i$+1,$Q\}$+1). In this way, all the D2D pairs can be assigned to different channels. In addition to signal links, Fig. 1 also shows the complex interference links in a specific channel.

There are five kinds of links in the vehicular two-tier networks: CU-I link (the transmitter is CU and the receiver is the eNB), V2I link (the transmitter is vehicle user and the receiver is the eNB), CU-V link (the transmitter is cellular user and the receiver is the vehicle user), vehicle-to-vehicle (V2V) signal link, and V2V interference link. As shown in Fig. 1, the signal link and interference link are distinguished. The signal link includes the CU-I link and V2V signal link, the interference link includes the V2I link, CU-V link, and V2V interference link. Considering that the mobility characteristics affect the channel state, these links are divided into two channel models: low mobility links and high mobility links. The signal link belongs to low mobility links. However, the relative speed is large in the interference link, so the interference link belongs to high mobility links.

Channel Model I (low mobility links): CU-I link and V2V signal link: Since the mobility characteristics can be neglected in low mobility links, the Doppler effect has little effect on channel model I. The channel power gain of CU-I link and V2V signal link is given as,

$$g_{i,i}^k = S_{i,i}^k F_{i,i}^k, i \in \mathcal{I}, \tag{1}$$

where $S_{i,i}^k$ denotes the large-scale fading effects including shadow-fading and path loss in the channel k,

$$S_{i,i}^k = L_{i,i}^k (d_{i,i}^k)^{-\alpha_i}, i \in \mathcal{I}, \tag{2}$$

where $d_{i,i}^{-\alpha_i}$ denotes the path loss, $d_{i,i}$ is the communication distance and α_i is the path-loss exponent. $L_{i,i}$ is the shadow fading coefficient. $F_{i,i}^k$ denotes the small-scale fast fading and subjects to exponential distribution with the parameter $\Upsilon = 1$, which is given as $F_{i,i}^k \sim E(1)$ [27], [31]. It is noted that $g_{0,0}^k$ denotes the channel gain of CU-I link in the kth channel, and $g_{i,i}^k$ is the channel gain of V2V signal link when $i \geq 1$.

Channel Model II (high mobility links):V2I link, CU-V link and V2V interference link: Different from the low mobility links, channel model II is greatly affected by the Doppler effect. Therefore, the changing and uncertainty of channel will be more. To describe channel gain more accurately, the first-order Markov process is introduced to model the channel fluctuation of high mobility links with the period [32]:

$$\eta = \vartheta\hat{\eta} + \epsilon, \tag{3}$$

where η denotes the channel response in the current time and $\hat{\eta}$ denotes the channel response in the previous time. In the statistical model [32], ϑ is formulated by $\vartheta{=}J_0(2\pi f_d T)$, where $J_0(\cdot)$ is the zero-order Bessel function. T denotes the CSI feedback time interval, we assume that T_1 is the period for vehicles to report their CSI to the eNB regularly. In V2V link and CU-V link, the period for D2D-V transmitters or CU to broadcast their CSI to D2D-V receivers is T_2, both T_1 and T_2 are the specific constant values. The communication distances of the V2I link are longer than that of the V2V link and CU-V link, so $T_1 < T_2$. $f_d{=}\upsilon f_c/c$ is the maximum Doppler frequency with $c{=}3\times 10^8$m/s, υ represents the vehicle speed and f_c is the carrier frequency. The coefficient ϑ $(0<\vartheta<1)$ quantifies the channel correlation between the two consecutive time slots, ϵ is the channel discrepancy term which is with the distribution of $\mathcal{CN}(0,1{-}\vartheta^2)$ and it is independent to $\hat{\eta}$.

The channel model of high mobility links is represented as,

$$g_{i,j}^k = S_{i,j}^k((\vartheta_{i,j}^k\hat{\eta}_{i,j}^k)^2 + (\epsilon_{i,j}^k)^2). \quad i\in\mathcal{I}, j\in\mathcal{J}, i\neq j. \tag{4}$$

Given that $\hat{g}_{i,j}^k = S_{i,j}^k(\vartheta_{i,j}^k\hat{\eta}_{i,j}^k)^2$ and $\tilde{g}_{ij}^k = S_{i,j}^k\vartheta_{i,j}^2$, (4) can be changed to:

$$g_{i,j}^k = \hat{g}_{i,j}^k + \tilde{g}_{i,j}^k, \qquad i\in\mathcal{I}, j\in\mathcal{J}, i\neq j, \tag{5}$$

where $\hat{g}_{i,j}^k$ and $\tilde{g}_{i,j}^k$ are the sampling channel gain of previous time and error channel gain in the kth channel. $\hat{g}_{i,j}^k$ is a measuring constant. $\tilde{g}_{i,j}^k$ is an exponential random variable which is given by $\tilde{g}_{i,j}^k \sim E(\frac{1}{S_{i,j}^k(1-(\vartheta_{i,j}^k)^2)})$ [27].

When $i\neq j$, $g_{0,j}^k$ denotes the CU-V link's channel gain from the CU to the jth D2D-V receiver in the kth channel, $g_{i,0}^k$ is the V2I link's channel gain from the ith D2D-V transmitter to the eNB, and $g_{i,j}^k$ represents the V2V interference link's channel gain from the ith D2D-V transmitter to the jth D2D-V receiver. Thus the channel model can be expressed as,

$$g_{i,j} = \begin{cases} S_{i,i}^k|\eta_{i,i}^k|^2, & i=j, i\in\mathcal{I}, j\in\mathcal{J} \\ S_{i,j}^k(\vartheta_{i,j}^k\hat{\eta}_{i,j}^k)^2 + S_{i,j}^k(\epsilon_{i,j}^k)^2, & i\neq j, \end{cases} \tag{6}$$

B. Problem Formulation

Fig. 2 is a simplified system model. There are n clusters which reuse the uplink channel of the CU, and only three clusters are shown to simplify and represent the communication situations of all clusters. In the Fig. 2, signal links and the interference links are distinguished. The signal links include cellular link and cochannel D2D-V link. V2I link, CU-V link, and V2V interference link belong to the interference links.

According to Fig. 2, the interference of other users to the ith signal link can be expressed as,

$$I_i = \sum_{j=0,j\neq i}^{N} p_j g_{j,i}, \quad i\in\mathcal{I}, j\in\mathcal{J}, \tag{7}$$

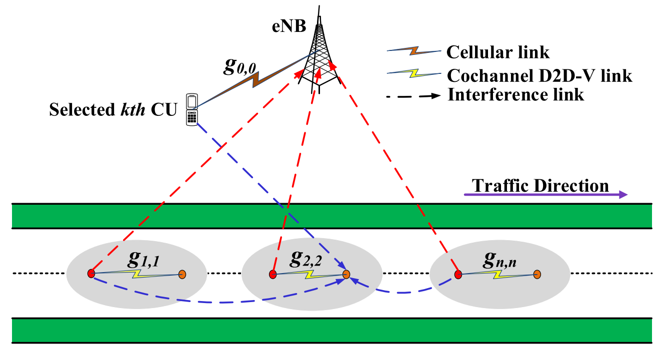

Fig. 2. Simplified system model.

where p_0 denotes the transmission power of the CU when $j=0$, and p_j denotes the D2D-V transmitter's power of the jth cluster when $j\geq 1$.

Furthermore, the real-time SINR in the reused channel can be formulated as,

$$\gamma_i(\mathbf{p}) = \frac{p_i g_{i,i}}{\sum_{j=0,j\neq i}^{N} p_j g_{j,i} + \delta^2}, \quad i\in\mathcal{I}, \tag{8}$$

where δ^2 is the noise interference. When $i=0$, $\gamma_0(\mathbf{p})$ denotes the SINR of the CU-I link. $\gamma_i(\mathbf{p})$ denotes the SINR of the ith cochannel D2D-V link when $i\geq 1$.

However, the real-time SINR is difficult to capture in the actual vehicular communication system. Since vehicles share CSI by broadcasting and the CSI feedback time interval is short, the channel gain is considered constant in the small time interval. The deterministic equivalent SINR is defined as,

$$\bar{\gamma}_i(\mathbf{p}) = \frac{\mathbb{E}\{p_i g_{i,i}\}}{\mathbb{E}\{\sum_{j=0,j\neq i}^{N} p_j g_{j,i}\} + \delta^2}, \tag{9}$$

In wireless networks, the Shannon capacity is used to calculate the transmission rate, which is shown as.

$$R_i = W\log(1+\bar{\gamma}_i(\mathbf{p})), \tag{10}$$

where W is the bandwidth of the reused channel. Therefore, the sum rate of all D2D users can be formulated as,

$$R_{\text{sum}} = \sum_{i=1}^{N} R_i = W\sum_{i=1}^{N}\log(1+\bar{\gamma}_i(\mathbf{p})). \tag{11}$$

The fact that wireless channels affected by vehicle movement will cause channel fading, especially in the 5 G networks, which will undermine the reliability of information transmission. Bit error rate (BER) is a measure of the data transmission accuracy in a specified time. Packet delivery rate is the probability of successful transmission in the signal link. In this paper, the BER is related to the packet delivery rate. To ensure the transmission quality of vehicular communications, the BER is considered and expressed as,

$$\text{BER} = 1 - \Omega_i, \tag{12}$$

where Ω_i denotes the packet delivery rate, it can be determined by the instantaneous SINR γ_i and the target SINR γ_{th}. Among that, the packet delivery rate Ω_i is related to a positive index of

γ_i, which can be expressed as [33],

$$\Omega_i = \exp(-\gamma_{th}/\gamma_i). \tag{13}$$

Communication delay is another significant index that affects the performance of wireless networks. The packets to D2D-V receivers must be in the queue before they transmit at the speed of R_i. It is assumed that the process of a packet arriving at the ith D2D receiver is a Poisson process with parameter ς_i, and the length of the data packet obeys the exponential distribution of parameter τ_i. Under the $M/M/1$ model [34], the relationship between the expected delay and transmission rate of the ith D2D pairs can be expressed as,

$$D_i = \frac{1}{\tau_i R_i - \varsigma_i}. \tag{14}$$

C. Stackelberg Game Formulation

Stackelberg game is a non-cooperative game in which one player is the leader and the other players are followers. The leader declares and implements its action strategy at first. Then, the follower makes a response, and the leader adjusts its action strategy according to the follower's decision. The process repeats until the Nash equilibrium is reached.

In the D2D-V networks, the eNB is the leader and D2D-V transmitters are the followers. After the eNB implements its price strategy, D2D-V transmitters updates their power allocation strategy as a policy corresponding to the eNB. As the primary user served by the mobile operators, the CU responses the followers and aims at maximizing its utility. The game is called the upper subgame, and the game equilibrium (GE) solution is called the upper sub-GE. Among the followers, D2D-V users are cooperatively and compete with the leader to obtain their overall maximum utility. When a participant breaks the balance unilaterally for personal benefit, it will be punished by the price set by the eNB. The game is called the lower subgame, and its equilibrium solution is called the lower sub-GE. The Stackelberg game is defined as,

$$\mathcal{G} = \{\mathcal{S}, \mathcal{P}, \mathcal{U}\}, \tag{15}$$

where $\mathcal{S} = \mathcal{S}_0 \cup \mathcal{S}_l$ represents the set of subscripts for game players. $\mathcal{P} = \{\mathbf{C}, \mathbf{P}\}_{i\in\mathcal{I}}$, the elements in the collection represent the strategy spaces of the eNB and D2D-V users, respectively. The strategy space of the leader (the eNB) is

$$\mathbf{C} = \{c_i : 0 \le c_i \le c_{i,\max}\}, \tag{16}$$

where c_i represents a non-uniform price charged from the eNB to the ith D2D-V user. The strategy space of the followers (D2D-V users) is

$$\mathbf{P} = \{p_i : 0 \le p_i \le p_{i,\max}\}, \tag{17}$$

where p_i represents the power of the ith D2D-V transmitter. Moreover, $\mathcal{U}$ represents the set of upper network utility and lower network utility, that is,

$$\mathcal{U} = \{U_0\} \cup \{U_{\text{sum}}\}. \tag{18}$$

The different service requirements and design objectives motivate us to adopt the framework of the Stackelberg game, which aims at solving the optimization problem of price setting and power distribution.

1) Upper subgame construction

In the D2D-V networks, interference is regarded as a resource for D2D-V users [35]. For the upper network, the eNB prices the interference, and charges from D2D-V users as its profit. The utility function is the difference between profit and CU's power payment. Since the CU is the primary user served by mobile operators, its SINR should be guaranteed to be no less than the SINR threshold, even in the communication scenarios with high vehicle density and co-channel interference. Therefore, the upper subproblem is modeled as,

$$P_1 : \max_{\mathbf{c}, p_0} U_0 = \sum_{i=1}^{N} c_i p_i g_{i,0} - z(p_0 - \hat{p}_0)$$
$$s.t. \begin{cases} \gamma_0 \ge \gamma_{th} \\ 0 \le p_0 \le p_{0,\max} \\ 0 \le c_i \le c_{i,\max} \end{cases} \tag{19}$$

where $\gamma_0 = \frac{p_0 g_{0,0}}{\sum_{j=0,j\ne i}^{N} p_j g_{j,0} + \delta^2}$. $p_0 - \hat{p}_0$ represents the additional power consumed by the eNB after spectrum sharing. z is the price factor of the additional power. $\hat{p}_0$ is the power of CU when there is no D2D-V users.

2) Lower subgame construction

In the lower subgame, the utility function is the difference between the D2D-V users' sum transmission rates and the cost of purchasing interference. When the power of a D2D-V user increases, the sum transmission rate will increase. However, more interference will follow, and the lower network needs to spend more interference cost, which is the $punishment$ from the upper network [22]. Therefore, between the revenue and punishment, followers (D2D-V users) need to optimize the power allocation strategy to maximize the sum utility. Moreover, utility maximization should be based on the premise of reliable communication. Interference management is the biggest challenge. The interference constraint of all cochannel D2D-V links is formulated as,

$$\Pr\{I_j \le I_{th}\} \ge 1 - \varepsilon_1, \quad i \in \mathcal{I}, j \in \mathcal{J}, \tag{20}$$

where $I_j = \sum_{i=0,i\ne j}^{N} p_i g_{i,j}$ represents the interference of the jth cochannel D2D-V link, I_{th} is the interference threshold.

Furthermore, delay constraints and packet delivery rate constraints are also considered. Therefore, the lower game subproblem is modeled as follows,

$$P_2 : \max_{\mathbf{p}} U_{\text{sum}} = \sum_{i=1}^{N} [W \log(1 + \bar{\gamma}_i(\mathbf{p})) - c_i p_i g_{i,0}]$$
$$s.t. \begin{cases} \Pr\left\{\sum_{i=0,i\ne j}^{N} p_i g_{i,j} \le I_{th}\right\} \ge 1 - \varepsilon_1 \\ \Pr\{D_i \le D_{i,\max}\} \ge 1 - \varepsilon_2 \\ \Pr\{\Omega_i \ge \Omega_{i,\min}\} \ge 1 - \varepsilon_3 \\ 0 \le p_i \le p_{i,\max} \end{cases} \tag{21}$$

where W is the bandwidth of the reused channel. $\bar{\gamma}_i(\mathbf{p})$ denotes the average SINR of the ith D2D pair when a small CSI feedback time interval is used. $D_{i,\max}$ is the upper delay bound of the ith D2D pair in the process of data transmission. $\Omega_{i,\min}$ is the lower limit of delivery rate. $\varepsilon_1, \varepsilon_2$ and ε_3 are the outage probability thresholds of interference constraint, delay constraint and packet delivery rate constraint, respectively, where $\varepsilon_1, \varepsilon_2, \varepsilon_3 \in (0,1)$. $p_{i,\max}$ is the maximum transmission power of vehicle users.

III. Stackelberg Game Analysis

In the previous sections, the constructed robust optimization problem is non-convex, and the interference constraints of probability form are tricky to deal with. Therefore, this section aims to realize the transformation of uncertain probability constraints and solve the optimal solution.

A. Ge

For the proposed Stackelberg game, the GE is defined as follows [19].

$Definition 1$: Let c_i^* be a solution for upper subgame optimization problem (19) and p_i^* be a solution for (21). Then the point $(\mathbf{c}_i^*, \mathbf{p}_i^*)$ is a GE for the proposed Stackelberg game if for any $(\mathbf{c}_i, \mathbf{p}_i)$, the following conditions are satisfied:

$$U_0(c_i^*, \mathbf{c}_{-i}^*, \mathbf{p}_i^*) \geq U_0(c_i, \mathbf{c}_{-i}^*, \mathbf{p}_i^*), \quad i \geq 1, i \in \mathcal{I}. \tag{22}$$

$$U_{\text{sum}}(p_i^*, \mathbf{p}_{-i}^*, \mathbf{c}_i^*) \geq U_{\text{sum}}(p_i, \mathbf{p}_{-i}^*, \mathbf{c}_i^*) \quad i \geq 1, i \in \mathcal{I}. \tag{23}$$

Generally, the GE for a Stackelberg game can be obtained by finding its subgame's perfect Nash equilibrium (NE). In the proposed Stackelberg game, the eNB and the D2D users compete in a noncooperative game. Each user in the lower network aims to maximize the sum utility by adjusting its power strategy. For a noncooperative game, the NE is defined as the operating point where no player can improve its utility by changing its strategy unilaterally, assuming everyone else continues their current strategy.

Therefore, the process of calculating the GE is described as follows: the leader announces non-uniform prices in the leader-follower game, the best response p_i of the ith follower is calculated first. Then, the leader observes this and adjusts the interference pricing strategy c_i, which aims to maximize the sum utility of the upper network. The followers can also foresee the adjusted price strategy, and carry out the above process repeatedly, until the optimal price strategy c_i^* and the optimal power strategy p_i^* are obtained.

B. Transformation of Upper Subgame

It is obvious that the objective function in P_1 is convex. However, the SINR constraint is deterministic and non-convex. The worst-case method is used, and the SINR constraint can be written as follows,

$$\frac{p_0 g_{0,0}^-}{\sum_{i=1}^{N} p_i g_{i,0}^+ + \delta^2} \geq \gamma_{th}. \tag{24}$$

where $g_{0,0}^-$ represents the worst channel condition of CU-I link, and $g_{i,0}^+$ represents the best channel condition of V2I link sent by the ith D2D-V transmitter and received by the eNB. In the following, it is the same that $g_{i,j}^-$ and $g_{i,j}^+$ represent the worst and best channel condition, respectively, $i \in \mathcal{I}, j \in \mathcal{J}$. The original problem P_1 is transformed into a standard convex maximization problem P_3.

In summary, we can obtain a deterministic optimization problem of robust power allocation by transforming SINR constraints. That is,

$$P_3 : \max_{\mathbf{c}} U_0 = \sum_{i=1}^{N} c_i p_i g_{i,0}^+ - z(p_0 - \hat{g}_0)$$
$$\text{s.t.} \begin{cases} \frac{p_0 g_{0,0}^-}{\sum_{i=1}^{N} p_i g_{i,0}^+ + \delta^2} - \gamma_{th} \geq 0 \\ 0 \leq p_0 \leq p_{0,\max} \\ 0 \leq c_i \leq c_{i,\max} \end{cases} \tag{25}$$

C. Transformation of Lower Subgame

1) Bernstein Approximation of the Interference Constraints: To manage the interference of D2D-V users in the lower optimization problem, the chance constraint is used, which is a kind of uncertain probability constraint. Furthermore, the Bernstein method is adopted to approximate the probability constraint with channel uncertainty.

Theorem 1: The interference constraint of all cochannel D2D-V links $\Pr\{I_j \leq I_{th}\} \geq 1 - \varepsilon_1, \quad i \in \mathcal{I}, j \in \mathcal{J}$ is reformulated as the separable constraints (26) and (27). The auxiliary variables $\mathbf{\Theta}$ is introduced into the new separation structure, which is express as $\Theta_{i,j} = \sigma_{i,j} \alpha_{i,j} p_i$.

$$\sum_{i=0, i \neq j}^{N} \eta_{i,j} p_i + \sqrt{2 \ln\left(\frac{1}{\varepsilon}\right)} \sum_{i=0, i \neq j}^{N} \Theta_{i,j} \leq I_{th}, \tag{26}$$

$$\sqrt{N} \sigma_{i,j} \alpha_{i,j} p_i \leq \sum_{i'=0, i' \neq j}^{N} \Theta_{i',j}, \quad \forall j \in \mathcal{J}, i \in \mathcal{I}. \tag{27}$$

Proof: See Appendix A

2) Transformation of Probability Constraint: The probability constraint can be transformed to the deterministic one according to the following theorem.

Theorem 2: For $\forall i \in \mathcal{I}$, the outage probability $\Pr\{D_i \leq D_{i,\max}\} \geq 1 - \varepsilon_3$ is equivalent to $\frac{(\varsigma_i D_{i,\max} - 1) I_{th}}{\tau_i D_{i,\max} \ln(1-\varepsilon_3)} - p_i \bar{g}_{i,i} \leq 0$.

Proof: See Appendix B

Similar to Theorem 1, the packet delivery rate constraint can be transformed into a deterministic form,

$$\frac{\gamma_{th}(I_{th} + \delta^2)}{\ln \Omega_{i,\min} \ln(1 - \varepsilon_3)} - p_i \bar{g}_{i,i} \leq 0, \quad \forall i \in \mathcal{I}. \tag{28}$$

3) Transformation of the Objective Function: To find the optimal solution of the upper subproblem P_2, we rewrite the original objective function:

$$U_{\text{sum}} = f(p) - h(p) - \sum_{i=1}^{N} c_i p_i g_{i,0}^{+}, \tag{29}$$

$$f(p) = \sum_{i=1}^{N} W \log\left(p_i g_{i,i}^{-} + I_i(p_{-i}) + \delta^2\right), \tag{30}$$

$$h(p) = \sum_{i=1}^{N} W \log\left(I_i(p_{-i}) + \delta^2\right), \tag{31}$$

where $I_i(p_{-i}) = \sum_{j=0, j\neq i}^{N} p_j g_{j,i}$. Therefore,

$$\begin{aligned} U_{\text{sum}} = &\sum_{i=1}^{N} W \log\left(p_i g_{i,i}^{-} + I_i(p_{-i}) + \delta^2\right) \\ &- \sum_{i=1}^{N} W \log\left(I_i(p_{-i}) + \delta^2\right) - \sum_{i=1}^{N} c_i p_i g_{i,0}^{+}. \end{aligned} \tag{32}$$

In summary, we can obtain a deterministic optimization problem of robust power allocation by transforming the objective function, interference constraints, delay constraints, and packet delivery rate constraints. It is expressed as,

$$\begin{aligned} P_4 : \max_{\mathbf{p}} &\sum_{i=1}^{N} W \log\left(p_i g_{i,i}^{-} + I_i(p_{-i}) + \delta^2\right) \\ &- \sum_{i=1}^{N} W \log\left(I_i(p_{-i}) + \delta^2\right) - \sum_{i=1}^{N} c_i p_i g_{i,0}^{+} \\ \text{s.t.} &\begin{cases} \sum\limits_{i=0,i\neq j}^{N} \eta_{i,j} p_i + \sqrt{2\ln(\frac{1}{\varepsilon})} \sum\limits_{i=0,i\neq j}^{N} \Theta_{i,j} \leq I_{th} \\ \sqrt{N}\sigma_{i,j}\alpha_{i,j} p_i \leq \sum\limits_{i'=0,i'\neq j}^{N} \Theta_{i',j} \\ \frac{(1-\varsigma_i D_{i,\max})(I_{th}+\delta^2)}{\tau_i D_{i,\max}\ln(1-\varepsilon_3)} - p_i \bar{g}_{i,i} \leq 0 \\ \frac{\gamma_{th}(I_{th}+\delta^2)}{\ln \Omega_{i,\min}\ln(1-\varepsilon_3)} - p_i \bar{g}_{i,i} \leq 0 \\ 0 \leq p_i \leq p_{i,\max} \end{cases} \end{aligned} \tag{33}$$

IV. Stackelberg Game Solutions

A. Solutions to Lower Subgame

In the lower network, based on the given non-uniform pricing, each D2D-V user in set $\mathcal{S}_l$ is aim at maximizing the sum utility by competitively allocating the optimal power p_i. The cooperating subgame is formulated as $G_l = \{\mathcal{S}_l, \mathbf{P}, U_{\text{sum}}\}_{i\geq 1, i\in\mathcal{I}}$, where $\mathcal{S}_l$ is the D2D-V set, $\{\mathbf{P}\}$ is the power allocation strategy of D2D-V users and $\mathbf{P} = \{p_i : 0 \leq p_i \leq p_{i,\max}\}$, where $i \geq 1$ and $i \in \mathcal{I}$. U_{sum} is the sum utility of the lower network.

The existence and uniqueness of GE will be discussed in the following work. $Proposition 1$: An NE exists in Stackelberg game $G_l = \{\mathcal{S}_l, \mathbf{P}, U_{\text{sum}}\}$, if for all $i \geq 1$ and $i \in \mathcal{I}$, the following statements hold [36].

(1) $\mathbf{P}$ is a nonempty convex and compact subset of some Euclidean space $\mathcal{R}^N$.

(2) $U_{\text{sum}}(p_i)$ is continuous in $\mathbf{P}$ and concave in p_i.

According to this proposition, the following theorem can be achieved.

Theorem 3: An NE exists in the proposed Stackelberg game $G_l = \{\mathcal{S}_l, \mathbf{P}, U_{\text{sum}}\}$.

Proof: See Appendix C

Since P_4 is a standard convex optimization problem, the Lagrangian function is constructed to seek the optimal powers. The Lagrangian function of (33) is formulated as,

$$\begin{aligned} L(\mathbf{p} : \boldsymbol{\mu}, \boldsymbol{\lambda}, \boldsymbol{\nu}, \boldsymbol{\varphi}) = &\sum_{i=1}^{N} W \log\left(p_i g_{i,i}^{-} + I_i(p_{-i}) + \delta^2\right) \\ &- \sum_{i=1}^{N} W \log\left(I_i(p_{-i}) + \delta^2\right) - \sum_{i=1}^{N} c_i p_i g_{i,0}^{+} \\ &- \sum_{j=1}^{N} \mu_j \left(\sum_{i=0,i\neq j}^{N} \eta_{i,j} p_i + \sqrt{2\ln\left(\frac{1}{\varepsilon_2}\right)} \sum_{i=0,i\neq j}^{N} \Theta_{i,j} - I_{th}\right) \\ &- \sum_{j=1}^{N} \sum_{i=0,i\neq j}^{N} \lambda_{i,j} \left(\sqrt{N}\sigma_{i,j}\alpha_{i,j} p_i - \sum_{i'=0,i'\neq j}^{N} \Theta_{i',j}\right) \\ &- \sum_{i=1}^{N} \nu_i \left(\frac{(1-\varsigma_i D_{i,\max})(I_{th}+\delta^2)}{\tau_i D_{i,\max}\ln(1-\varepsilon_3)} - p_i \bar{g}_{i,i}\right) \\ &- \sum_{i=1}^{N} \varphi_i \left(\frac{\gamma_{th}(I_{th}+\delta^2)}{\ln \Omega_{i,\min}\ln(1-\varepsilon_3)} - p_i \bar{g}_{i,i}\right), \end{aligned} \tag{34}$$

where $\boldsymbol{\mu}, \boldsymbol{\lambda}, \boldsymbol{\nu}$, and $\boldsymbol{\varphi}$ are the Lagrangian multipliers, and $\boldsymbol{\mu} \geq \mathbf{0}$, $\boldsymbol{\lambda} \geq \mathbf{0}$, $\boldsymbol{\nu} \geq \mathbf{0}$, and $\boldsymbol{\varphi} \geq \mathbf{0}$.

Then, the corresponding dual function is formulated as,

$$\begin{aligned} D(\boldsymbol{\mu}, \boldsymbol{\lambda}, \boldsymbol{\nu}, \boldsymbol{\varphi}) = &\max_{0\leq p_i\leq p_{i,max}} L(\mathbf{p} : \boldsymbol{\mu}, \boldsymbol{\lambda}, \boldsymbol{\nu}, \boldsymbol{\varphi}) \\ = &\max_{0\leq p_i\leq p_{i,max}} \sum_{i=1}^{N} W \log\left(p_i g_{i,i}^{-} + I_i(p_{-i}) + \delta^2\right) \\ &- \sum_{i=1}^{N} W \log\left(I_i(p_{-i}) + \delta^2\right) - \sum_{i=1}^{N} c_i p_i g_{i,0}^{+} \\ &- \sum_{j=1}^{N} \sum_{i=0,i\neq j}^{N} \left(\mu_j \eta_{i,j} + \lambda_{i,j}\sqrt{N}\sigma_{i,j}\alpha_{i,j}\right) p_i \\ &- \sum_{j=1}^{N} \sum_{i=0,i\neq j}^{N} \left(\sum_{i'=0,i'\neq j}^{N} \lambda_{i',j} - \mu_j \sqrt{2\ln\left(\frac{1}{\varepsilon_2}\right)}\right) \Theta_{i,j} \\ &- \sum_{i=1}^{N} \nu_i \left(\frac{(1-\varsigma_i D_{i,\max})(I_{th}+\delta^2)}{\tau_i D_{i,\max}\ln(1-\varepsilon_3)} - p_i \bar{g}_{i,i}\right) \\ &- \sum_{i=1}^{N} \varphi_i \left(\frac{\gamma_{th}(I_{th}+\delta^2)}{\ln \Omega_{i,\min}\ln(1-\varepsilon_3)} - p_i \bar{g}_{i,i}\right) + \sum_{j=1}^{N} \mu_j I_{th}, \end{aligned} \tag{35}$$

where

$$\mu_j = (2\ln(\varepsilon_2))^{-\frac{1}{2}} \sum_{i'=1, i'\neq j}^{N} \lambda_{i',j}. \tag{36}$$

Therefore, the dual problem of (35) can be formulated as,

$$\min_{\boldsymbol{\mu}>\mathbf{0},\boldsymbol{\lambda}>\mathbf{0}} D(\boldsymbol{\mu}, \boldsymbol{\lambda}, \boldsymbol{\nu}, \boldsymbol{\varphi}). \tag{37}$$

The Lagrangian multiplier $\boldsymbol{\lambda}$, $\boldsymbol{\nu}$, and $\boldsymbol{\varphi}$ are updated through the sub-gradient method, which are formulated as,

$$\lambda_{i,j}^{(t+1)} = \left[\lambda_{i,j}^{(t)} + K_{\lambda}^{(t)}\left(\sqrt{N}\sigma_{i,j}\alpha_{i,j}e^{\tilde{p}_i} + \frac{\sum_{i=0,i\neq j}^{N}\eta_{i,j}p_i - I_{th}}{\sqrt{-2\ln(\varepsilon_1)}}\right)\right]^{+}, \tag{38}$$

$$\nu_i^{(t+1)} = \left[\nu_i^{(t)} + K_{\nu}^{(t)}\left(\frac{(1-\varsigma_i D_{i,\max})(I_{th}+\delta^2)}{\tau_i D_{i,\max}\ln(1-\varepsilon_2)} - p_i\bar{g}_{i,i}\right)\right]^{+}, \tag{39}$$

$$\varphi_i^{(t+1)} = \left[\varphi_i^{(t)} + K_{\varphi}^{(t)}\left(\frac{\gamma_{th}(I_{th}+\delta^2)}{\ln\Omega_{i,\min}\ln(1-\varepsilon_3)} - p_i\bar{g}_{i,i}\right)\right]^{+}, \tag{40}$$

where K_λ, K_ν, K_φ denote the step-size, and $K_\lambda > 0$, $K_\nu > 0$, $K_\varphi > 0$. t denotes the iteration index. $[X]^+ = \max[0, X]$.

The power vector $\mathbf{p}$'s iteration function is obtained by

$$\frac{\partial L_i(\mathbf{p}:\boldsymbol{\mu},\boldsymbol{\lambda},\boldsymbol{\nu},\boldsymbol{\varphi})}{\partial p_i} = \frac{W g_{i,i}^{-}\epsilon_{i,i}}{p_i g_{i,i}^{-} + I_i(p_{-i}) + \delta^2} - c_i g_{i,0}^{+} - \sum_{j=0,j\neq i}^{N}(\mu_j\eta_{i,j} + \lambda_{i,j}\sqrt{N}\sigma_{i,j}\alpha_{i,j}) + \nu_i\bar{g}_{i,i} + \varphi_i\bar{g}_{i,i} \tag{41}$$

Let $\frac{\partial L_i(\mathbf{p}:\boldsymbol{\mu},\boldsymbol{\lambda},\boldsymbol{\nu},\boldsymbol{\varphi})}{\partial p_i} = 0$, the optimal power is:

$$p_i^* = \frac{W}{c_i g_{i,0}^{+} + \Pi_i^*} - \frac{I_i^*(p_{-i}) + \delta^2}{g_{i,i}^{-}} \tag{42}$$

The iterative expression is as follows,

$$p_i^{(t+1)} = \frac{W}{c_i g_{i,0}^{+} + \Pi_i^{(t)}} - \frac{I_i^{(t)}(p_{-i}) + \delta^2}{g_{i,i}^{-}} \tag{43}$$

where $\Pi_i^{(t)} = \sum_{j=0,j\neq i}^{N}(\mu_j^{(t)}\eta_{i,j} + \lambda_{i,j}^{(t)}\sqrt{N}\sigma_{i,j}\alpha_{i,j}) + \nu_i^{(t)}\bar{g}_{i,i} + \varphi_i^{(t)}\bar{g}_{i,i}$

Theorem 4: When $g_{i,i}^{-} > \sum_{j=0,j\neq i}^{N} g_{j,i}^{+}$, the NE is unique in the proposed Stackelberg game $G_0 = \{\mathcal{S}_0, \mathbf{C}, U_0\}$.

Proof: See Appendix D

According to Theorem 4, it can be confirmed that $p_i(t+1)$ converges to the unique equilibrium point.

B. Solutions to Upper Subgame

In the upper network, based on D2D-V users' optimal transmission power $\mathbf{P}^*$, the CU in set $\mathcal{S}_0$ aims at maximizing the sum utility by setting the price c_i for each D2D-V user. Similar to the analysis of the lower subgame, the upper subgame can be formulated as $G_0 = \{\mathcal{S}_0, \mathbf{C}, U_0\}$, where $\mathcal{S}_0$ is the CU, $\mathbf{C}$ is the price c_i for ith D2D-V user and $\mathbf{C} = \{c_i : 0 \leq c_i \leq c_{i,\max}\}$, where $i \geq 1$ and $i \in \mathcal{I}$. U_0 is the sum utility of the upper network.

Next, the solution process of the optimal non-uniform prices will be shown. Put the D2D-V users' optimal transmission power $\mathbf{P}^*$ into P_3, the original question can be rewritten as,

$$P_5 : \max_{\mathbf{c}} U_0 = \sum_{i=1}^{N} c_i p_i g_{i,0}^{-} - z(p_0 - \hat{p}_0)$$

$$s.t. \begin{cases} \frac{p_0 g_{0,0}^{-}}{\sum_{i=1}^{N} p_i g_{i,0}^{+} + \delta^2} - \gamma_{th} \geq 0 \\ p_i = \frac{W}{c_i g_{i,0}^{+} + \Pi_i} - \frac{I_i(p_{-i}) + \delta^2}{g_{i,i}^{-}} \\ 0 \leq p_i \leq p_{i,\max} \\ 0 \leq c_i \leq c_{i,\max} \end{cases} \tag{44}$$

The above problem is a convex optimization problem, and the Lagrange function is constructed as follows,

$$L(\mathbf{c}, p_0 : \omega) = \sum_{i=1}^{N}\left(\frac{W c_i g_{i,0}^{-}}{c_i g_{i,0}^{+} + \Pi_i}\right) - \frac{c_i g_{i,0}^{-}}{g_{i,i}^{-}}\left(\sum_{j=0,j\neq i}^{N} p_j g_{j,i}^{+} + \delta^2\right) - z(p_0 - \hat{p}_0) + \omega\left(\frac{p_0 g_{0,0}^{-}}{\sum_{i=1}^{N} p_i g_{i,0}^{+} + \delta^2} - \gamma_{th}\right) \tag{45}$$

The Karush-Kuhn-Tucker (KKT) conditions of P_5 is,

$$\begin{cases} \frac{L(\mathbf{c},p_0:\boldsymbol{\omega})}{\partial p_0} = -\sum_{i=1}^{N}\left(\frac{c_i g_{i,0}^{-} g_{0,i}^{+}}{g_{i,i}^{-}}\right) \\ -z + \frac{\omega g_{0,0}^{-}}{\sum_{i=1}^{N} p_i g_{i,0}^{+} + \delta^2} = 0 \\ \omega\left(\frac{p_0 g_{0,0}^{-}}{\sum_{i=1}^{N} p_i g_{i,0}^{+} + \delta^2} - \gamma_{th}\right) = 0 \\ \omega \geq 0 \end{cases} \tag{46}$$

According to the first condition of KKT, we can see that,

$$\omega = \frac{\sum_{i=1}^{N}\left(\frac{c_i g_{i,0}^{-} g_{0,i}^{+}}{g_{i,i}^{-}}\right) + z}{g_{0,0}^{-}}\left(\sum_{i=1}^{N} p_i g_{i,0}^{+} + \delta^2\right) > 0 \tag{47}$$

Therefore, the power expression of CU is expressed as,

$$p_0(\mathbf{p}) = \frac{\gamma_{th}\left(\sum_{i=1}^{N} p_i g_{i,0}^{+} + \delta^2\right)}{g_{0,0}^{-}} \tag{48}$$

By substituting the obtained optimal power (48) into the formula (42), the expression of p_0 with respect to $\mathbf{c}$ can be derived,

$$p_0(\mathbf{c}) = K\sum_{i=1}^{N}\left(\frac{W}{c_i g_{i,0}^{+} + \Pi_i} - \frac{\sum_{j=1,j\neq i}^{N} p_j g_{j,i}^{+} + \delta^2}{g_{i,i}^{-}}\right) g_{i,0}^{-} + K\delta^2. \tag{49}$$

where $K = \frac{\gamma_{th}}{\gamma_{th}\sum_{i=1}^{N}\frac{g_{0,i}^{+} g_{i,0}^{+}}{g_{i,i}^{-}} + g_{0,0}^{-}}$.

Substituting variable $p_0(\mathbf{c})$ in (49) into formula (42), we can also get the function of p_i with respect of unique variable $\mathbf{c}$ as follows,

$$p_i^*(\mathbf{c}) = \frac{W}{c_i g_{i,0}^+ + \Pi_i} - \frac{\sum\limits_{j=1,j\neq i}^{N} p_j^* g_{j,i}^+ + \delta^2}{g_{i,i}^-} - \frac{K g_{0,0}^-}{g_{i,i}^-} \cdot \sum_{i=1}^{N} \left(\frac{W g_{i,0}^-}{c_i g_{i,0}^+ + \Pi_i} - \frac{g_{i,0}^- \left(\sum\limits_{j=1,j\neq i}^{N} p_j g_{j,i}^+ + \delta^2 \right)}{g_{i,i}^-} + \delta^2 \right) \tag{50}$$

Substituting (50) into the objective function of problem P_5, we can get

$$\max_{\mathbf{c}} U_0(\mathbf{c}) = \sum_{i=1}^{N} \left[\frac{W c_i g_{i,0}^-}{c_i g_{i,0}^+ + \Pi_i} - \frac{c_i g_{i,0}^- \left(\sum\limits_{j=1,j\neq i}^{N} p_j^* g_{j,i}^+ + \delta^2 \right)}{g_{i,i}^-} + c_i g_{i,0}^- \left(\frac{K g_{0,0}^-}{g_{i,i}^-} \right) \sum_{i=1}^{N} \left(\frac{W g_{i,0}^-}{c_i g_{i,0}^+ + \Pi_i} - \frac{g_{i,0}^- \left(\sum\limits_{j=1,j\neq i}^{N} p_j g_{j,i}^+ + \delta^2 \right)}{g_{i,i}^-} + \delta^2 \right) \right] - z \left(K \sum_{i=1}^{N} \left(\frac{W}{c_i g_{i,0}^+ + \Pi_i} - \frac{\sum\limits_{j=1,j\neq i}^{N} p_j g_{j,i}^+ + \delta^2}{g_{i,i}^-} \right) g_{i,0}^- + K\delta^2 - p_0 \right). \tag{51}$$

Theorem 5: The NE is unique in the proposed Stackelberg game $G_0 = \{\mathcal{S}_0, \mathbf{C}, U_0\}$.

Proof: See Appendix E

According to Theorem 5, we can get the unique Nash equilibrium point in the proposed Stackelberg game between the eNB and D2D-V users. Let $\frac{\partial U_0}{\partial c_i} = 0$, the optimal price and the iterative expressions are as follows,

$$c_i^* = \sqrt{\frac{W\left(\Pi_i^* g_{i,i}^- g_{i,0}^- - K\Pi_i^* g_{0,0}^- (g_{i,0}^-)^2 + zK g_{i,i}^- g_{i,0}^+\right)}{K\delta^2 g_{0,0}^- g_{i,0}^- - \varrho_i (\sum_{j=1,j\neq i}^{N} p_j^* g_{i,j}^+ + \delta^2)}} - \frac{\Pi_i^*}{g_{i,0}^+}. \tag{52}$$

where $\varrho_i = \frac{K g_{0,0}^- g_{i,0}^+ g_{i,0}^-}{g_{i,i}^-} - g_{i,0}^-$.

$$c_i^{(t+1)} = \sqrt{\frac{W\left(\Pi_i^{(t)} g_{i,i}^- g_{i,0}^- - K\Pi_i^{(t)} g_{0,0}^- (g_{i,0}^-)^2 + zK g_{i,i}^- g_{i,0}^+\right)}{K\delta^2 g_{0,0}^- g_{i,0}^- - \varrho_i (\sum_{j=1,j\neq i}^{N} p_j^{(t+1)} g_{i,j}^+ + \delta^2)}} - \frac{\Pi_i^{(t)}}{g_{i,0}^+}. \tag{53}$$

C. Iterative Algorithm for the Stackelberg Game

The optimal solution of p_i and c_i can be determined according to (43) and (53). Then, we propose a robust power control and nonuniform price bargaining algorithm, which is shown in **Algorithm 1**.

V. Simulation and Performance Evaluation

In this section, numerical simulations are performed to evaluate the performance of the proposed algorithm. In the vehicular communication system, a simplified mobile-cluster model involving one CU and four clusters is simulated, which is in the coverage of the eNB. The corresponding system parameters are listed in Table II.

Algorithm 1 Robust Power Control and Nonuniform Price Bargaining Algorithm.

```
Initialize the values of p_i(0) and c_i(0).
Initialize
• Set t = 1, T = 20, p_i(0) be any point in the feasible
  region, 0 ≤ p_i(0) ≤ p_{i,max}, i ∈ [1, 2, ..., N].
• Set μ_i > 0, λ_i > 0, ν_i > 0, and φ_i > 0.
• Set K_λ > 0, K_ν > 0, K_φ > 0.
while (p_i and c_i are not converged) and (t < T) do
  for ∀i ∈ I do
    D2D-V user i receives the price from the eNB, and
    then calculates p_i^(t+1) according to (43).
    Update multiplier μ_i^(t+1) according to (36), λ_i^(t+1)
    according to (38), ν_i^(t+1) according to (39), and
    φ_i^(t+1) according to (40).
    The eNB receives the optimal response function
    and feedback information from the D2D-V users,
    and calculates the nonuniform price c_i according
    to (53).
  end for
  Set t = t + 1.
end while
```

TABLE II
Simulation Parameters

Parameter	Value
Communication radius of eNB (R)	500 m
Radius of mobile-clusters r	30 m
Background noise (δ^2)	-30 dBm
Maximal power $(p_{i,\max})$	0.01 W
Interference threshold (I_{th})	10^{-3}
Interruption probability threshold ε_1, ε_2, ε_3	0.1
Bandwidth (W)	10 MHz
Carrier frequency (f_c)	2 GHz
Sampling period of eNB (T_1)	5 ms
Sampling period of vehicles (T_2)	1 ms

Figs. 3 and 4 show the convergence performance of **Algorithm 1**. The transmission powers of the CU and four D2D-V users are expressed by p_0 and $p_1 - p_4$. As depicted in Fig. 3, the powers converge to the optimal values within several steps. According to Fig. 4, the D2D-V users' nonuniform prices gradually stabilize and finally converge to their respective equilibrium points. Therefore, these results in Figs. 3, and 4 demonstrate that the proposed distributed robust power control and nonuniform price bargaining algorithm is effective and shows rapid convergence speed.

To verify the system robustness, the comparison is performed between the target outage probabilities thresholds (i.e., ε_1, ε_2, and ε_3), and actual outage probabilities of all signal links. As shown in Fig. 5, the actual outage probabilities of CU-I link and D2D-V links are always smaller than the target outage probability, when the target outage probability ε_1 varies from 0.1 to 0.4. The graph proves that the proposed algorithm can realize effective interference management. Moreover, delay and packet

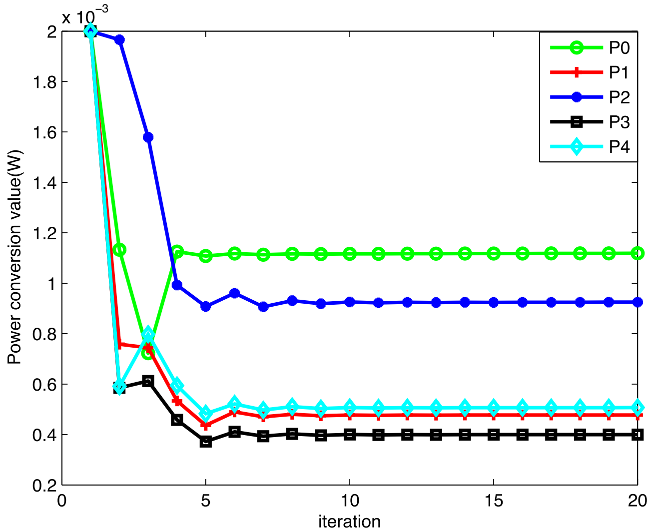

Fig. 3. Power convergence performance of CU and D2D-V users.

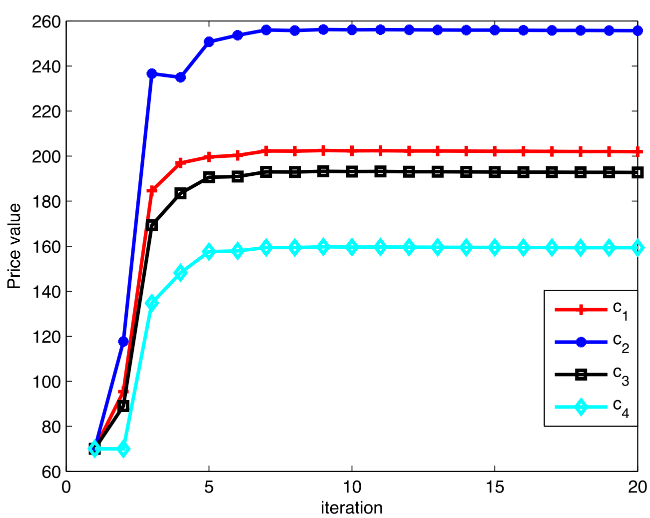

Fig. 4. Price convergence performance of D2D-V users.

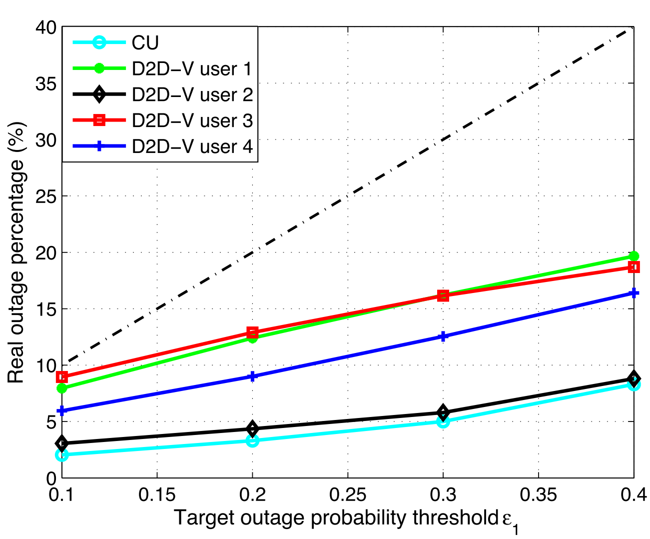

Fig. 5. Outage probability comparison of interference constraints.

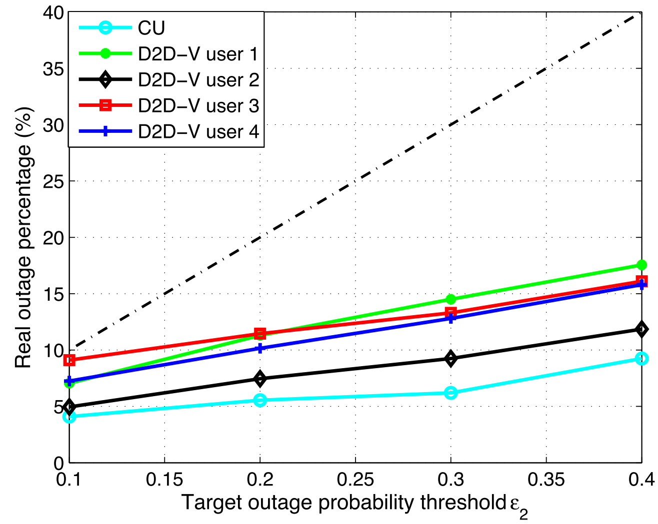

Fig. 6. Outage probability comparison of delay constraints.

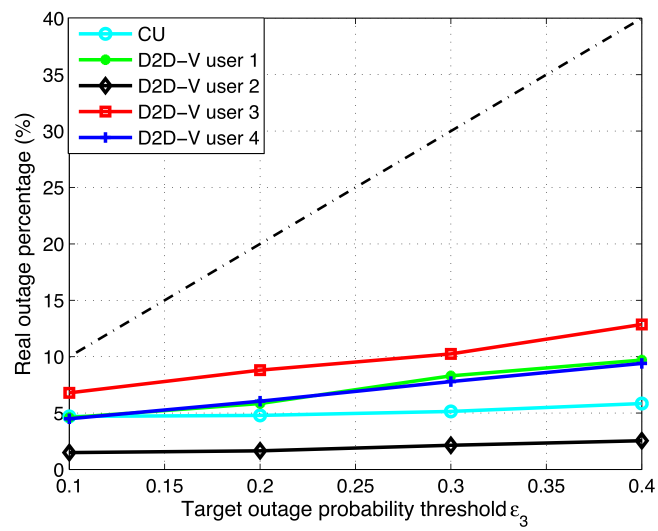

Fig. 7. Outage probability comparison of delivery rate constraints.

delivery rate constraints are also strictly implemented, which are shown in Fig. 6 and Fig. 7. To sum up, the proposed distributed robust power control and nonuniform price bargaining algorithm can guarantee QoS requirements and ensure the network stability in the high-speed D2D-V communication scenarios.

Fig. 8 shows the impact of the outage probability threshold on the utility value of the lower network. The increase of target outage probability thresholds ε_1, ε_2, and ε_3 represents the relaxation of constraints. With the expansion of the boundary, the optimal solutions will change to obtain a larger value of the objective function, so the utility value of the lower network increases. Since these three outage probability thresholds have different degrees of effect on the objective function, the growth trends are different.

In this paper, Stackelberg game theory is used to describe the robust resource optimization problem with channel uncertainty. Furthermore, we do a comparative simulation with [14], [27] and the perfect channel condition of this paper. The successive

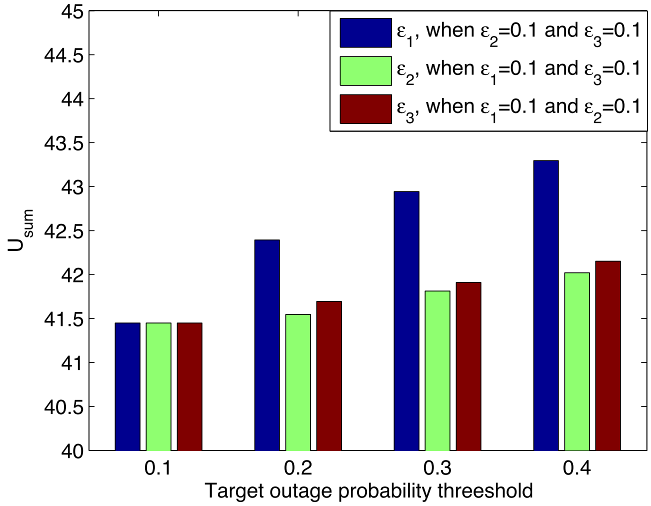

Fig. 8. Utility value of the lower network versus target outage probability threshold ε_1, ε_2, or ε_3.

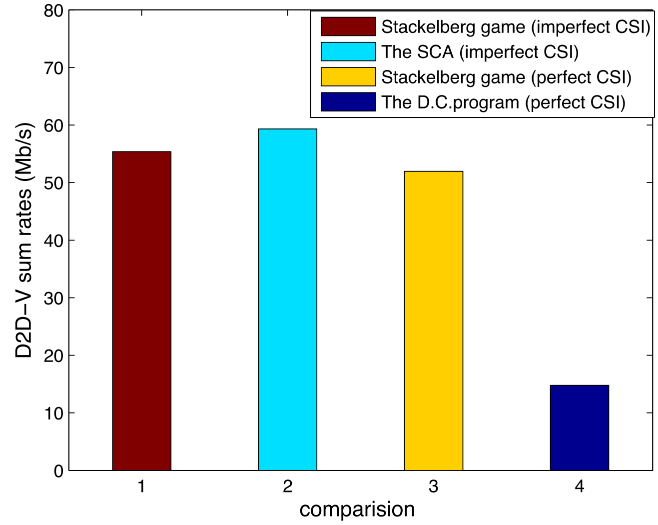

Fig. 10. Utility comparisons.

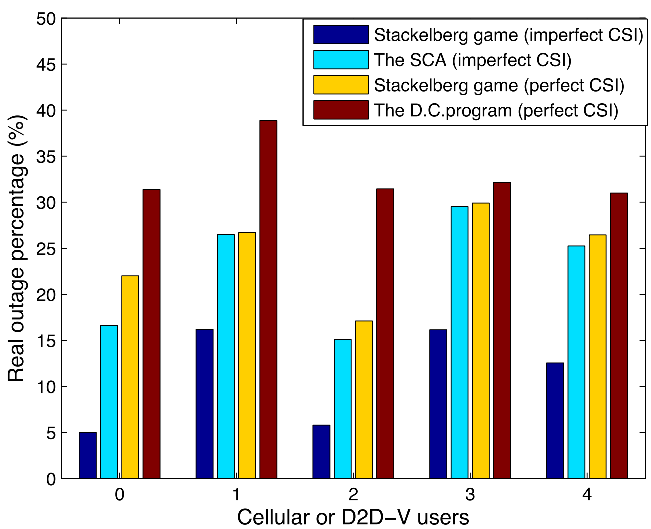

Fig. 9. Comparison of actual outage probability.

convex approximation (SCA) method is used, and imperfect CSI is considered in [14]. It is assumed in [27] that the perfect CSI is available and a D.C. programming algorithm is developed to solve the convex optimization problem. We intend to examine if the consideration of channel uncertainty under the Stackelberg game theory has a promotion on system performance, which makes the four resource allocation schemes comparable.

Fig. 9 shows the comparison of actual outage probability of different papers. As a representative, the conclusion is shown when the parameters $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = 0.1$. It is emphasized that when this parameter is selected as other values, the following conclusions are still coincident. In the abscissa, 0 represents cellular user, 1, 2, 3, 4 represent four D2D-V users respectively. It should be emphasized that the following conclusions are consistent, and these parameters are just one representative. As shown in Fig. 9, the actual outage probability of this paper is less than the perfect CSI assumption, which shows the necessity of channel uncertainty analysis. And it is also less than [27], which means that the algorithm proposed in this paper is more effective in interference management, and the robustness of the D2D-V system is improved. Furthermore, the Bernstein approximation method is also used in this paper and ref. [27] to realize the transformation of uncertain interference constraints. Different from ref. [27], the Stackelberg game approach with price-penalty mechanism is used, which can achieve better interference management.

Under the same parameter setting as Fig. 9, the utility comparison is given in Fig. 10. In the abscissa, "1, 2, 3, 4" represent the four methods "Stackelberg game with imperfect CSI," "The SCA [27]," "Stackelberg game with perfect CSI" and "The D.C. program [14]," respectively. As shown in Fig. 10, the D2D-V sum rates of this paper are less than [27], and more than the other two methods. It shows that higher system stability is obtained at the cost of losing part of the transmission rates by comparing with [27]. However, comparing with "Stackelberg game with perfect CSI" and [14], this paper obtains higher transmission rates and stronger system robustness simultaneously.

Fig. 11 demonstrates the impacts on system performance when different vehicle speeds are simulated in a high mobility vehicular environment. In this simulation, all vehicle velocities are identical, and network topologies are the same. The vehicle speed on the road is set to 0 m/s, 10 m/s, 20 m/s, 30 m/s and 40 m/s, respectively. Since the relative speed in the CU-I link and V2V link is zero, there is no Doppler effect. However, the system performance is mainly affected by users' relative speed on the V2I link and CU-V link. It can be seen from Fig. 11 that with the increase of vehicle speed, the utility value of the lower network decreases, whereas the utility value of the upper network increases. This is because the higher speed will cause a greater Doppler frequency shift in the lower network, increase channel uncertainty, and make the signal link suffer more interference. Therefore, the utility of the lower network reduces, and the upper network that charges for the interference will obtain a better utility.

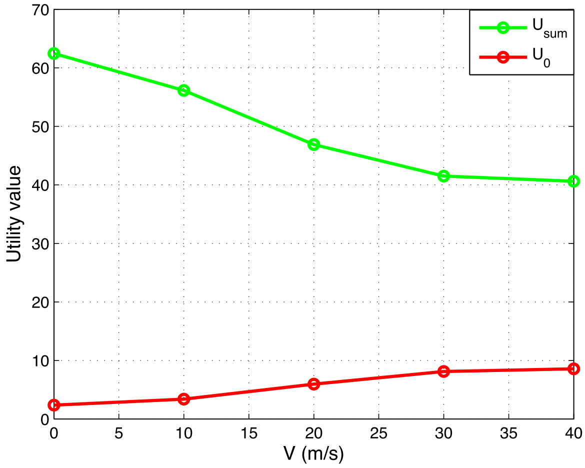

Fig. 11. Utility value versus vehicle speed.

VI. Conclusion

This paper focuses on the optimal power allocation based on game and pricing in vehicular communication networks with channel uncertainty and co-channel interference. To improve the reliability and stability of the D2D-V system, the distributed robust power control and nonuniform price bargaining algorithm is proposed to realize a novel optimization scheme, which is based on the Stackelberg game. The optimization scheme attempt to guarantees users' QoS when there exists a maximized utility requirement. Due to the existence of channel uncertainty, the probability forms of interference, delay, and delivery rate constraints are performed. Due to the original probability constraints are non-convex and intractable, the Bernstein approximation and exponential integral methods are introduced in the convex optimization process. The power allocation algorithm is developed to achieve practical execution scheme. Simulation results validate the converges of the proposed algorithm under dynamic communication environment. It also demonstrates that the proposed power control scheme has better robustness, and the D2D-V transmission rates also get a promotion. It is validated that the proposed algorithm is effective under the complex vehicular scenarios with channel uncertainty and co-channel interference.

Appendix A

Proof: The probability constraint (20) is reformulated as,

$$\Pr\left\{ f_0(\mathbf{p}) + \sum_{n=1}^{N} \eta_n f_n(\mathbf{p}) \le 0 \right\} \ge 1-\varepsilon, \tag{54}$$

where $\mathbf{p}$ is a deterministic variable vector, and $\{\eta_n\}$ are random variables with marginal distributions $\{\xi_n\}$. When the following conditions hold, (54) is potentially satisfied for a given family of $\{\eta_n\}$ distributions,

a) $\{f_n(\mathbf{p})\}$ are affine in $\mathbf{p}$;

b) $\{\eta_n\}$ are independent of each other;

c) $\{\xi_n\}$ share the bounded support of [-1,1], which is in the range of $-1 \le \xi_n \le 1, \forall n = 1, 2, \cdots, N$.

Under these assumptions, a conservative approximation substitute for (54) is as follows [38],

$$\inf_{\rho>0} \left[f_0(\mathbf{p}) + \rho \sum_{n=1}^{N} \Omega_n(\rho^{-1} f_n(\mathbf{p})) + \rho \ln(\frac{1}{\varepsilon}) \right] \le 0, \tag{55}$$

where $\Omega_n(y) = \max_{\xi_n} \ln(\int \exp(xy) d\xi_n(x))$. According to [38], ρ is the conservative approximate parameter. And the calculation can be performed by the upper bound of $\Omega_n(y)$ generally, which is formulated as $\Omega_n(y) \le \max\{\phi_n^- y, \phi_n^+ y\} + \frac{\sigma_n^2}{2} y^2, n = 0, \cdots, N,$, where ϕ_n^-, ϕ_n^+ and σ_n are constants which are determined by the given families of the probability distributions. $-1 \le \phi_n^- \le \phi_n^+ \le 1$, $\sigma_n \ge 0$.

When $\Omega_n(\cdot)$ in (55) is substituted with this upper bound and the arithmetic-geometric inequality, a convex conservative surrogate for (55) can be formulated as,

$$f_0(\mathbf{p}) + \sum_{n=0}^{N} \max\{\phi_n^- f_n(\mathbf{p}), \phi_n^+ f_n(\mathbf{p})\} + \sqrt{2\ln\left(\frac{1}{\varepsilon}\right)} \left(\sum_{n=0}^{N} \sigma_n^2 f_n(\mathbf{p})^2 \right)^{\frac{1}{2}} \le 0. \tag{56}$$

Here the distributions of $\tilde{g}_{i,j}$ are assumed to be bounded by $[a_{i,j}, b_{i,j}]$, and the constants $\alpha_{i,j} = \frac{1}{2}(b_{i,j} - a_{i,j}) \ne 0$ and $\beta_{i,j} = \frac{1}{2}(b_{i,j} + a_{i,j})$ are used to normalize the supports within the range of $[-1, 1]$, where the supports are given as $\xi_{i,j} = \frac{\tilde{g}_{i,j} - \beta_{i,j}}{\alpha_{i,j}} \in [-1, 1]$.

Let $f_{0,j}(\mathbf{p}) = -I_{th} + \sum_{i=0}^{N} (\hat{g}_{i,j} + \beta_{i,j}) p_i$, $f_{i,j}(\mathbf{p}) = \alpha_{i,j} p_i$, (56) is equivalent to the constraint in (20). Hence, substituting $f_{0,j}(\mathbf{p})$ and $f_{i,j}(\mathbf{p})$ into (56), the constraint is rewritten as,

$$-I_{th} + \sum_{i=0, i\ne j}^{N} (\hat{g}_{i,j} + \beta_{i,j}) p_i + \sum_{i=0, i\ne j}^{N} \phi_{i,j}^+ \alpha_{i,j} p_i + \sqrt{2\ln\left(\frac{1}{\varepsilon}\right)} \left(\sum_{i=0, i\ne j}^{N} (\sigma_{i,j}\alpha_{i,j}p_i)^2 \right)^{\frac{1}{2}} \le 0. \tag{57}$$

In the formula (57), the variables p_i with nonlinear coupling structure cause a high computational complexity. To reduce the computational overhead, the ℓ_2-approximation problem of (57) is further formulated as a $\ell_\infty-$approximation structure by $\|\mathbf{z}\|_2 \le \sqrt{N} \|\mathbf{z}\|_\infty$ ($\mathbf{z} \in \mathbb{R}^N$), which is as follows,

$$\sum_{i=0, i\ne j}^{N} \eta_{i,j} p_i + \sqrt{2N\ln\left(\frac{1}{\varepsilon_1}\right)} \max_{i\in\mathcal{I}, i\ne j} \sigma_{i,j}\alpha_{i,j}p_i \le I_{th}, \tag{58}$$

where $\eta_{i,j} = \hat{g}_{i,j} + \phi_{i,j}^+ \alpha_{i,j} + \beta_{i,j}, \quad \forall j \in \mathcal{J}$.

Later, the interference constraint (58) is formulated as the separable constraints $\sum_{i=0, i\ne j}^{N} \eta_{i,j} p_i + \sqrt{2\ln(\frac{1}{\varepsilon})} \sum_{i=0, i\ne j}^{N} \Theta_{i,j} \le I_{th}$ and $\sqrt{N} \sigma_{i,j} \alpha_{i,j} p_i \le \sum_{i'=0, i'\ne j}^{N} \Theta_{i',j}, \quad \forall j \in \mathcal{J}, i \in \mathcal{I}$. The auxiliary variables $\mathbf{\Theta}$ is introduced into the new separation structure, which is express as $\Theta_{i,j} = \sigma_{i,j}\alpha_{i,j}p_i$. ∎

Appendix B

Proof: It can be seen from (14) that the outage probability constraint can be expressed as,

$$\mathbf{Pr}\left\{\frac{1}{\tau_i R_i - \varsigma_i} \leq D_{i,\max}\right\} \geq 1 - \varepsilon_3. \tag{59}$$

According to the constraint $\sum_{j=0,j\neq i}^{N} p_j g_{j,i} \leq I_{th}$, we have

$$\mathbf{Pr}\left\{G \leq \frac{(1-\varsigma_i D_{i,\max})(I_{th}+\delta^2)}{p_i \bar{g}_{i,i}\tau_i D_{i,\max}}\right\} \leq \varepsilon_3. \tag{60}$$

It can be obtained by variable integral that,

$$\int_0^{\frac{(1-\varsigma_i D_{i,\max})(I_{th}+\delta^2)}{p_i \bar{g}_{i,i}\tau_i D_{i,\max}}} e^{-x}\,dx \leq \varepsilon_3. \tag{61}$$

Therefore, the deterministic expression of outage probability constraint can be obtained as follows,

$$\frac{(1-\varsigma_i D_{i,\max})(I_{th}+\delta^2)}{\tau_i D_{i,\max}\ln(1-\varepsilon_3)} - p_i \bar{g}_{i,i} \leq 0, \quad \forall i \in \mathcal{I}. \tag{62}$$

■

Appendix C

Proof: 1) Strategy space is defined to be $\mathbf{P} = \{p_i : 0 \leq p_i \leq p_{i,\max}\}$, which is a nonempty, convex and compact subset of Euclidean space $\mathcal{R}^N$.

(2) It can be shown in (39) that $U_{\text{sum}}(p_i)$ is continuous in $\mathbf{P}_l$. Moreover, in order to prove the concavity of P_4, the second-order derivative with respect to p_i is taken.

The first-order derivative with respect to p_i is obtained,

$$\frac{\partial U_i}{\partial p_i} = \frac{W g_{i,i}^-}{p_i g_{i,i}^- + I_i(p_{-i}) + \delta^2} - c_i g_{i,0}^+. \tag{63}$$

The second-order derivative with respect to p_i is obtained,

$$\frac{\partial^2 U_i}{\partial p_i^2} = -\frac{W (g_{i,i}^-)^2}{\left(p_i g_{i,i}^- + I_i(p_{-i}) + \delta^2\right)^2} < 0. \tag{64}$$

Since the second-order derivative of $U_{\text{sum}}(p_i)$ with respect to p_i is always less than 0, $U_{\text{sum}}(p_i)$ is concave in p_i. Hence, an NE exists in the proposed Stackelberg game $G_l = \{\mathcal{S}_l, \mathbf{P}, U_{\text{sum}}\}$

Appendix D

Proof: Let $p_{-i}(t) = p_j(t), G_{-i} = g_{j,i}^+,\ j \in \mathcal{J}, j \neq i$, then, we get $G_{-i}p_{-i}(t) = \sum_{j=1,j\neq i}^{N} g_{j,i}^+ p_j(t)$. Define that $\Delta p_i(t) = p_i(t) - p_i^*$, we obtain

$$\begin{aligned}|\Delta p_i(t+1)| &= \left|\frac{\sum_{j=0,j\neq i}^{N} g_{j,i}^+ (p_j^{(t)} - p_j^*)}{g_{i,i}^-}\right| \\ &= \left\|\frac{\sum_{j=0,j\neq i}^{N} g_{j,i}^+}{g_{i,i}^-}\right\|_\infty \left\|\sum_{j=0,j\neq i}^{N} \Delta p_j(t)\right\|_\infty \end{aligned} \tag{65}$$

Since the assumption $g_{i,i}^- > \sum_{j=0,j\neq i}^{N} g_{j,i}^+$, we can acquire that $\|\frac{G_{-i}}{g_{i,i}^-}\| < 1$. Based on the definition of the $l_\infty-$norm, we know that $\left\|\sum_{j=0,j\neq i}^{N} \Delta p_j(t)\right\|_\infty = \max[\Delta p_j(t)]_{j\in\mathcal{J},j\neq i}$. Therefore, $\Delta p_i(t+1)$ can converge to zero after some iterations [37], and $p_i(t+1)$ can converge to the unique optimal point p_i^*. Generally, the channel gain of a D2D-V link dominates over that of the interference links. Therefore, the assume $g_{i,i}^- > \sum_{j=0,j\neq i}^{N} g_{j,i}^+$ is tenable, and it can be confirmed that $p_i(t+1)$ converges to the unique equilibrium point.

Appendix E

Proof: (1) Strategy space is defined to be $\mathbf{C} = \{c_i : 0 \leq c_i \leq c_i^{\max}\}$, which is a nonempty, convex and compact subset of Euclidean space $\mathcal{R}^N$.

(2) In order to prove the concavity of P_5, the following research is taken.

The first-order derivative of $U_0(\mathbf{c})$ with respect to c_i is,

$$\begin{aligned}\frac{\partial U_0}{\partial c_i} &= \sum_{i=1}^{N} \frac{W g_{i,0}^-}{(c_i g_{i,0}^+ + \Pi_i)^2}\left(\Pi_i - \frac{K g_{0,0}^- g_{i,0}^- \Pi_i}{g_{i,i}^-}\right) \\ &+ \sum_{i=1}^{N} \frac{W(g_{i,0}^+ \epsilon_{i,0})}{(c_i g_{i,0}^+ + \Pi_i)^2} zK + \sum_{i=1}^{N}\left(\frac{\sum_{j=1,j\neq i}^{N} p_j g_{j,i}^+ + \delta^2}{g_{i,i}^-}\right. \\ &\left. \cdot \left(\frac{K g_{0,0}^- g_{i,0}^+ g_{i,0}^-}{g_{i,i}^-} - g_{i,0}^-\right) - \frac{K g_{0,0}^- g_{i,0}^-}{g_{i,i}^-}\delta^2\right)\end{aligned} \tag{66}$$

The second-order derivative of is obtained further as,

$$\begin{aligned}&\frac{\partial^2 U_0}{\partial c_i^2} = \\ &-2\sum_{i=1}^{N} \frac{W g_{i,0}^+ g_{i,0}^-}{(c_i g_{i,0}^+ + \Pi_i)^3}\left(\Pi_i - \frac{K g_{0,0}^- g_{i,0}^- \Pi_i}{g_{i,i}^-}\right) - 2\sum_{i=1}^{N} \frac{W(g_{i,0}^+)^2}{(c_i g_{i,0}^+ + \Pi_i)^3} zK < 0\end{aligned} \tag{67}$$

Since the channel gain of the signal link is much larger than that of interference link, it is obvious that $1 - \frac{K g_{0,0} g_{i,0}}{g_{i,i}} > 0$. The second-order derivative of $U_0(\mathbf{c})$ with respect to c_i is always less than 0. Therefore, $U_0(\mathbf{c})$ is a concave function about c_i, and An NE exists in the proposed Stackelberg game $G_0 = \{\mathcal{S}_0, \mathbf{C}, U_0\}$. Similar to the proof in **Theorem3**, the interference prices can converge to a unique fixed point. ■

References

[1] N. Lu, N. Cheng, N. Zhang, X. Shen, and J. Mark, "Connected vehicles: Solutions and challenges," *IEEE Internet Things J.*, vol. 1, no. 4, pp. 289–299, Aug. 2014.

[2] Q. Gao, S. Lin, and G. Zhu. "Joint vehicular and static users multiplexing transmission with hierarchical modulation for throughput maximization in vehicular networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 21, no. 9, pp. 3835–3847, Sep. 2020.

[3] X. Ma, H. Dong, X. Liu, L. Jia, G. Xie, and Z. Bian, "An optimal communications protocol for maximizing lifetime of railway infrastructure wireless monitoring network," *IEEE Trans. Ind. Inform.*, vol. 14, no. 8, pp. 3347–3357, Aug. 2018.

[4] H. Wymeersch, G. Seco-Granados, G. Destino, D. Dardari, and F. Tufvesson, "5G mmwave positioning for vehicular networks," *IEEE Wireless Commun.*, vol. 24, no. 6, pp. 80–86, Dec. 2017.

[5] Y. Xu, G. Gui, H. Gacanin, and F. Adachi, "A survey on resource allocation for 5G heterogeneous networks: Current research, future trends and challenges," *IEEE Commun. Surv. Tut.*, vol. 23, no. 2, pp. 668–695, Feb. 2021.

[6] M. Garcia *et al.*, "A tutorial on 5 G NR V2X communications," *IEEE Commun. Surv. Tut.*, to be published, doi: 10.1109/COMST.2021.3057017.
[7] Z. Zhou, M. Dong, K. Ota, G. Wang, and L. Yang, "Energy-efficient resource allocation for D2D communications underlaying Cloud-RAN-Based LTE-A networks," *IEEE Internet Things J.*, vol. 3, no. 3, pp. 428–438, Jun. 2016.
[8] J. Pan, H. Shan, R. Li, Y. Wu, W. Wu, and T. Q. S. Quek, "Channel estimation based on deep learning in vehicle-to-everything environments," *IEEE Commun. Lett.*, vol. 25, no. 6, pp. 1891–1895, Jun. 2021.
[9] H. Cheng, H. Shan, and W. Zhuang, "Infotainment and road safety service support in vehicular networking: From a communication perspective," *Mech. Syst. Signal Process.*, vol. 25, no. 6, pp. 2020–2038, Aug. 2011.
[10] Y. Jiao and I. Joe, "Energy-efficient resource allocation for heterogeneous cognitive radio network based on two-tier crossover genetic algorithm," *IEEE J. Commun. Netw.*, vol. 18, no. 1, pp. 112–122, Mar. 2016.
[11] Z. Liu, C. Liang, Y. Yuan, K. Y. Chan, and X. Guan, "Resource allocation based on user pairing and subcarrier matching for downlink non-orthogonal multiple access networks," *IEEE/CAA J. Automatica Sinica* vol. 8, no. 3, pp. 679–689, Mar. 2021.
[12] L. Liang, G. Y. Li, and W. Xu, "Resource allocation for D2D-enabled vehicular communications," *IEEE Trans. Commun.*, vol. 65, no. 7, pp. 3186–3197, Jul. 2017.
[13] C. Yu, K. Doppler, C. Ribeiro, and O. Tirkkonen, "Resource sharing optimization for device-to-device communication underlaying cellular networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 8, pp. 2752–2763, Aug. 2011.
[14] Y. Ren, F. Liu, Z. Liu, C. Wang, and Y. Ji, "Power control in D2D-based vehicular communication networks," *IEEE Trans. Veh. Technol.*, vol. 64, no. 12, pp. 5547–5562, Oct. 2015.
[15] C. Saraydar, N. Mandayam, and D. Goodman, "Effficient power control via pricing in wireless data networks," *IEEE Trans. Commun.*, vol. 50, no. 2, pp. 291–303, Feb. 2002.
[16] S. Guruacharya, D. Niyato, D. Kim, and E. Hossain, "Hierarchical competition for downlink power allocation in OFDMA femtocell networks," *IEEE Trans. Wireless Commun.*, vol. 12, no. 4, pp. 1543–1553, Apr. 2013.
[17] Y. Xu, Z. Liu, C. Huang, and C. Yuen, "Robust resource allocation algorithm for energy harvesting-based D2D communication underlaying UAV-assisted networks," *IEEE Internet Things J.*, to be published, doi:10.1109/JIOT.2021.3078264.
[18] Z. Liu, L. Gao, Y. Liu, X. Guan, K. Ma, and Y. Wang, "Efficient QoS support for robust resource allocation in blockchain-based femtocell networks," *IEEE Trans. Ind. Inform.*, vol. 16, no. 11, pp. 7070–7080, Nov. 2020.
[19] Q. Han, B. Yang, and X. Wang, "Hierarchical-game-based uplink power control in femtocell networks," *IEEE Trans. Veh. Technol.*, vol. 63, no. 6, pp. 2819–2835, Jul. 2014.
[20] H. Ji and C. Huang, "Non-cooperative uplink power control in cellular radio systems," *Wireless Netw.*, vol. 4, no. 3, pp. 233–240, Mar. 1998.
[21] Z. Han and K. Liu, "Noncooperative power-control game and throughput game over wireless networks," *IEEE Trans. Commun.*, vol. 53, no. 10, pp. 1625–1629, Oct. 2005.
[22] K. Xin, Z. Rui, and M. Motani, "Price-based resource allocation for spectrum-sharing femtocell networks: A stackelberg game approach," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 3, pp. 538–549, Mar. 2012.
[23] L. Li, M. Wei, C. Xu, and Z. Zhou, "Rate-based pricing framework in hybrid access femtocell networks," *IEEE Commun. Lett.*, vol. 19, no. 9, pp. 1560–1563, Sep. 2015.
[24] Z. Liu, S. Li, K. Ma, X. Guan, and X. Li, "Robust power allocation based on hierarchical game with consideration of different user requirements in two-tier femtocell networks," *Comput. Netw.*, vol. 12, no. 20, pp. 179–190, Jul. 2017.
[25] Z. Liu, W. Wang, K. Chan, K. Ma, and X. Guan, "Rate maximization for hybrid access femtocell networks with outage constraints based on pricing incentive mechanism," *IEEE Trans. Veh. Technol.*, vol. 69, no. 6, pp. 6699–6708, Apr. 2020.
[26] Y. Liu and E. Song, "Distributionally robust joint power and admission control via SOCP deflation," in *Proc. IEEE 14th Workshop Signal Process. Adv. Wireless Commun.*, Sep. 2013, pp. 11–15.
[27] Z. Liu, Y. Xie, K. Y. Chan, K. Ma, and X. Guan, "Chance-constrained optimization in D2D-based vehicular communication network," *IEEE Trans. Veh. Technol.*, vol. 68, no. 5, pp. 5045–5058, Mar. 2019.
[28] A. Nemirovski and A. Shapiro, "Convex approximations of chance constrained programs," *SIAM J. Optim.*, vol. 17, no. 4, pp. 969–996, 2006.
[29] S. Wang, W. Shi, and C. Wang, "Energy-efficient resource management in OFDM-based cognitive radio networks under channel uncertainty," *IEEE Trans. Commun.*, vol. 63, no. 9, pp. 3092–3102, Sep. 2015.
[30] L. Vasconcelos, A. S. Seco, and J. Silva, "Estimating the parameters of cowan's M3 headway distribution for roundabout capacity analyses," *Baltic J. Road Bridge Eng.*, vol. 7, no. 4, pp. 261–268, 2012.
[31] L. Liang, J. Kim, S. Jha, K. Sivanesan, and G. Li, "Spectrum and power allocation for vehicular communications with delayed CSI feedback," *IEEE Wireless Commun. Lett.*, vol. 6, no. 4, pp. 458–461, Aug. 2017.
[32] T. Kim, D. Love, and B. Clerckx, "Does frequent low resolution feedback outperform infrequent high resolution feedback for multiple antenna beamforming systems?" *IEEE Trans. Signal Process.*, vol. 59, no. 4, pp. 1654–1669, Apr. 2011.
[33] Y. Li, D. Quevedo, V. Lau, and L. Shi, "Optimal periodic transmission power schedules for remote estimation of ARMA processes," *IEEE Trans. Signal Process.*, vol. 61, no. 24, pp. 6164–6174, Sep. 2013.
[34] S. Ross, *Introduction to Probability Models*. New York, NY, USA: Academic, 2014.
[35] Y. Xie, Z. Liu, K. Chan, and X. Guan, "Energy-spectral efficiency optimization in vehicular communications: Joint clustering and pricing-based robust power control approach," *IEEE Trans. Veh. Technol.*, vol. 69, no. 11, pp. 13673–13685, Nov. 2020.
[36] G. Owen, *Game Theory*. New York, NY, USA: Academic, 2005.
[37] D. Ngo, B. Long, and T. Lengoc, "Distributed interference management in two-tier CDMA femtocell networks," *IEEE Trans. Wireless Commun.*, vol. 11, no. 3, pp. 979–989, Feb. 2012.
[38] A. Nemirovski and A. Shapiro, "Convex approximations of chance constrained programs," *SIAM J. Optim.*, vol. 17, no. 4, pp. 969–996, 2006.

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