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Distributed Resource Allocation for D2D-Assisted Small Cell Networks With Heterogeneous Spectrum

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ABSTRACT Device-to-device (D2D) communication with increased spectral efficiency and reduced communication delay has undoubtedly become a general trend in future wireless networks. However, when D2D communication is incorporated into small cell networks (SCNs) with large number of randomly overlapped small cells, the co-channel interference between small cell users (SUEs) and D2D users is an inevitable challenge, especially with the heterogeneous spectrum, i.e., licensed spectrum bands and unlicensed spectrum bands. In this paper, we study the downlink channel allocation in D2D-assisted small cell networks with heterogeneous spectrum bands. By taking the required data rate of users and the interference constraint of SUEs into account, we formulate a channel allocation problem integrating channel selection and channel sharing to maximize the network utility, which is the service satisfaction of all users. To derive the solution, we decompose the optimization problem into two games: a potential game and a coalition game. Then, a potential game-based scheme using an interference graph and a coalition scheme with D2D user transferring is proposed to solve these two games, respectively. Based on these schemes, a two-stage distributed channel allocation algorithm is proposed and can converge with low computational complexity. Moreover, the simulation results reveal that the proposed algorithm could achieve high system throughput and network utility.

INDEX TERMS Heterogeneous spectrum, D2D communication, band selection, channel allocation, channel sharing.

I. INTRODUCTION

The unprecedented growth in mobile devices and applications has triggered an explosion in the data traffic. For instance, global mobile data traffic will grow at a compound annual growth rate of 46 percent between 2017 and 2022, reaching 77.5 exabytes per month by 2022 [1]. In addition, a wide range of emerging services such as augmented reality, e-learning and e-health will continue to proliferate [2]. These developments will lead to an inevitable challenge to satisfy these different service requirements while at the same time supporting large-scale mobile traffic in the future network.

To enhance the network capacity and improve the qualities of service, one proposed method is to shorten the distance between base stations and user equipments [3]. Small cells, which provide ubiquitous wireless connectivity, efficient sharing of macrocells load, and improved quality of service (QoS), is considered as a promising technique to provide an effective solution to address the challenges and requirements that the 5G system will face [4]. Device-to-device (D2D) communications with increased spectral efficiency and reduced communication delay is also a study domain with broad prospects [5]. D2D communication allows nearby users to form D2D pairs and communicate directly without transmitting through base stations or core network, thus significantly improving transmission quality due to short transmission distance [6]. However, performance improvements cannot be achieved unless the serious challenge like co-channel interference between small cell users (SUEs) and D2D pairs is properly tackled, especially when there are many overlapped small cells.

While improving network performance through network densification and advanced techniques, 5G networks can also significantly increase network capacity by adding more

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spectrum resources. Currently, user data, such as video, voice and files, can be transmitted over the authorized communication network or unlicensed frequency bands [7]. The emergence of spectrum sharing technology enables the reuse of licensed frequency bands and potentially open new opportunities to exploit unlicensed spectrum bands [8]. However, heterogeneous spectrum resources, i.e., licensed and unlicensed spectrum bands, further aggravates the complexity of interference problem when it provides more alternative channels for spectrum sharing.

The combination of D2D-assisted small cell networks and the heterogeneous spectrum resource can significantly enhance network performance and user experience. Unfortunately, designing such integrated mechanism is challenging due to following aspects. First, the access management and interference control of heterogeneous spectrum resources in multi-cell networks are very complex. Second, spectrum resource sharing among SUEs and D2D pairs also exacerbates this problem. Third, the centralized resource management of a large number of SUEs and D2D users will produce large-scale signaling interactions, which exacerbates the burden of network management. It is also necessary to consider distributed algorithms to reduce the computational complexity and switching overhead.

To address all aforementioned issues, in this paper, we consider a downlink D2D-assisted small cell networks with heterogeneous spectrum bands. In the considered system model, a heterogenous spectrum pool consisting of different bands is provided for the access channel selection. To improve the spectrum utilization, spectrum sharing between SUEs and D2D users is also considered. We formulate a band selection and channel allocation problem to maximize the satisfaction of all users. Then, we manage to reformulate the problem into a potential game followed by a coalition game and propose a two-stage distributed channel allocation algorithm. In the first potential game, we get the stable matching between different SUEs and channels in different frequency bands using the interference graph. In the second game, according to the channel allocation of SUEs, the final partition between D2D users and SUEs is realized through D2D user transferring. Finally, the theoretically proofs in stability, optimality and convergence of these algorithms are provided. Numerical results verify the advantages of our proposal in system throughput and network utility over other existing schemes.

A. RELATED WORKS

In the future, network densifcation has become one of the irresistible trends. In small cell networks, many researches have been devoted to resource allocation and interference management [9], [10]. In [11], a multidimensional resource allocation algorithm based on noncooperation game theory is proposed to manage the resource allocation in ultra dense networks. Amr Abdelnasser *et al.* [12] present a tier-aware joint sub-channel and power allocation algorithm in orthogonal frequency division multiple access (OFDMA) macrocell-small cell networks.

Capable of enhancing spatial multiplexing and greatly improving service quality, D2D communication has undoubtedly become another general trend in future wireless networks. Motivated by the advantages mentioned above, resource allocation in D2D-assisted small cell networks has been extensively studied [13], [14]. In [15], Ban *et al.* consider a cellular-aided inband overlay D2D network to avoid the co-channel interference between cellular users and D2D users. Some papers investigate the game-theoretic resource allocation in D2D-assisted small cell networks with spectrum underlay access, where interference constraints are imposed to protect the QoS requirements of small cell users [16], [17]. Maghsudi *et al.* propose a channel and power allocation method based on graph theory and game theory in the case of incomplete channel information [16]. In [17], a hierarchical game-based power allocation scheme with heterogeneous statistical QoS constraints is proposed in D2D-assisted cellular networks. In addition, many resource allocation methods based on convex optimization also have been proposed. In [18], with global channel state information, the resource allocation problem is formulated as a nonconvex optimization problem, which is solved using convex approximation techniques. However, with the dense deployment of small cells, these centralized solutions inevitably generate a large amount of signaling interaction and extremely high computational complexity in order to achieve interference management.

Spectrum sharing can utilize the idle spectrum without affecting the rights of primary users, thus improving the utilization of spectrum resources [7]. Extensive researches have been devoted to the issues related to spectrum sharing. In traditional spectrum sharing, secondary users achieve spectrum sharing by sensing the frequency band usage of authorized users. However, incorrect perception results and resource allocation by secondary users often result in a significant degradation in the performance of authorized users. Recent efforts have been focused on applications of dynamic spectrum sharing for wireless communication networks. In [19], a sharing-based resource-allocation algorithm is proposed to design optimal sensing time, bandwidth allocation and power allocation. Chen *et al.* propose a weighted-proportional-fairness-based joint spectrum sensing and resource allocation scheme in cognitive radio networks in [20]. When different spectrum bands are available, spectrum refarming is also an innovative spectrum sharing technique which supports different generations of cellular networks to operate in the same radio spectrum. In [21], Zhang *et al.* consider the spectrum sharing among multiple cellular operators in the unlicensed spectrum. Han *et al.* propose an underlay OFDMA and code division multiple access (CDMA) spectrum sharing system which allows OFDMA network to operate in the spectrum allocated to the CDMA network in [22].

When a large number of small cells are randomly overlapped with heterogeneous spectrum resources, the computational complexity of the resource allocation scheme is large. Unlike the previously mentioned works, we aim to jointly optimize band selection and channel allocation in a decentralized manner. Furthermore, when the data rate exceeds a certain threshold, the service satisfaction of users will not increase significantly. Therefore, in our work, the spectrum sharing between SUEs and D2D pairs, which improves the spectrum utilization, is also considered. Our paper is concerned with the joint band selection and spectrum sharing for D2D-assisted small cells networks.

B. MAIN CONTRIBUTIONS

In this paper, a two-stage distributed channel allocation algorithm in D2D-assisted small cell networks is proposed. The major contributions of this paper are listed as follows:

1) A framework of downlink band selection and channel allocation for D2D communication underlaying small cell networks with heterogeneous spectrum bands is proposed. The heterogeneous spectrum is provided for multi-cell channel access in small cells. The spectrum utilization is improved by spectrum sharing between D2D users and small cell users.

2) By considering transmission rate constraint of SUEs and D2D users, interference level constraint of SUEs, the user satisfaction maximization problem is formulated, which is a NP-hard problem. We transform the optimization problem into two games: a potential game using interference graph and a coalition game with D2D user transfer. In the first potential game, we get the stable matching between different SUEs and channels in different frequency bands. Then, in the second game, the final coalitions between D2D users and SUEs is realized through D2D user transferring.

3) Simulation results show the advantages of our proposed channel allocation algorithm over other algorithms in terms of system throughput and network utility. Besides, the impact of D2D communication and the efficiency of potential game and coalition game are also analyzed. The relationships among required transmission rate, spectrum bands and satisfaction parameter are also investigated.

The reminder of this paper is organized as follows: The list of some important notations is given in Table 1. In Section II, we describe the system model and problem formulation. The channel allocation problem is transformed into potential game and coalition game and the corresponding algorithms for solutions of these two games are proposed in Section III. Simulation results and discussion are presented in Section IV. Finally, we make conclusions in Section V.

TABLE 1. Summary of important notations.

Symbol	Description
$\mathcal{S}$	SBS set
$\mathcal{N}$, $\mathcal{N}_s$, N_s	SUE set, SUE set in small cell s, number of SUEs in small cell s
$\mathcal{D}$, $\mathcal{D}_s$, D_s	D2D pair set, D2D pair set in small cell s, number of D2D pairs in small cell s
$\mathcal{K}$	The set of bands
$P_{s,n}^{k,i}$, $P_{d,d}^{k,i}$	Power of SUE n, D2D pair d in small cell s on subchannel $c_{k,i}$
$h_{s,n}^{k,i}$, $h_{d,d}^{k,i}$	Channel gain of SUE n, D2D pair d on subchannel $c_{k,i}$
$\eta_{s,n}^{k,i}$, $x_{n,d}^{k,i}$	Channel allocation factor of SUE n, D2D pair d on subchannel $c_{k,i}$
$\gamma_{s,n}^{k,i}$, $\gamma_{d,d}^{k,i}$	Signal to interference plus noise ratio of SUE n, D2D pair d on subchannel $c_{k,i}$
$R_{s,n}^{k,i}$, $R_{d,d}^{k,i}$	Transmission rate of SUE n, D2D pair d on subchannel $c_{k,i}$
$\Gamma_{s,n}^{k,i}$, $\Gamma_{d,d}^{k,i}$	Satisfaction degree of SUE n, D2D pair d on subchannel $c_{k,i}$
U_s	the utility of SBS s
U_s	the utility function of player s in potential game
Φ	the potential function of the potential game G_1
Π_n	the coalition n in small sell s
$U_{s,d}\left(\Pi_n\right)$	the quantitative value of each member d in the coalition n at small cell s

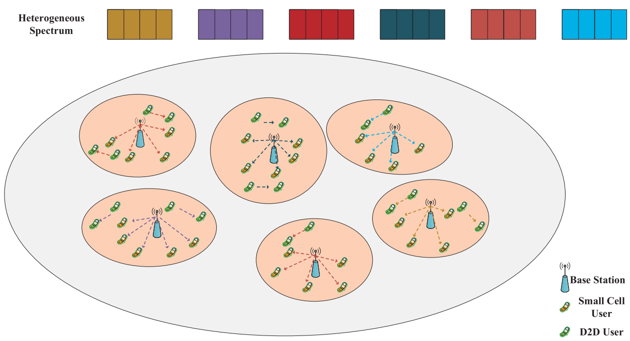

FIGURE 1. Network model.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. SYSTEM MODEL

As showed in Fig. 1, we consider a downlink D2D-assisted multi-small cell scenario with a heterogenous spectrum pool consisting of different bands, in which there exist S small cells labeled as $\mathcal{S} = \{1, 2, \ldots, S\}$. Within the coverage of the sth small cell, the set of SUEs is denoted as $\mathcal{N}_s$ and the number of SUEs is N_s. Let $\mathcal{N}$ denote the SUE set, and we can get $\cup_{s\in\mathcal{S}}\mathcal{N}_s = \mathcal{N}$. Besides these small cell users, there are also users who tend to use D2D communication mode to transmit data to nearby users, which is labeled as $\mathcal{D}_s$, randomly distributed in small cell s. And the number of D2D pairs in small cell s is D_s. Let $\mathcal{D}$ denote the D2D set, and we can get $\cup_{s\in\mathcal{S}}\mathcal{D}_s = \mathcal{D}$. The SUE set in the small cell s contains only the corresponding small cell users, and does not include D2D users in the same small cell. In our model, small cell users and D2D users do not convert to each other.

The heterogeneous spectrum pool in the system contains many different authorized and unauthorized bands, and each band is composed of a certain number of channels, which have different channel availability probabilities. Denote $\mathcal{K}$ and K as the set of spectrum bands and the corresponding number of bands. Let $\mathcal{C}_k$ and C_k be the set of channels and the corresponding number of channels in band k. Define $c_{k,i}$ as the ith channel in band k. We assume that the channel bandwidth is different for each band, and the bandwidth of channel $c_{k,i}$ is $W_{k,i}$. $p_{k,i}$ is defined as the channel availability probability of $c_{k,i}$. For licensed channels, $p_{k,i} = 1$.

Each small cell selects a spectrum band and small cell users within the coverage of the same SBS are scheduled to orthogonal subchannels in the selected band. Let $\eta_{s,n}^{k,i}$ indicate whether user n in small cell s is served by channel $c_{k,i}$ or not, i.e., $\eta_{s,n}^{k,i} = 1$ when SUE n is served by channel $c_{k,i}$. Meanwhile, SUEs prefer to share their assigned channels with D2D users to improve resource utilization. In the channel sharing model between D2D pairs and SUEs, $x_{n,d}^{k,i}$ is used to indicate whether the channel $c_{k,i}$ allocated to SUE n is shared to D2D pair d. When channel $c_{k,i}$ is shared to D2D pair d, $x_{n,d}^{k,i} = 1$. We assume that each D2D pair can only share the channel allocated one SUE. In addition, while ensuring the communication performance of SUEs, multiple D2D users are allowed to occupy the same channel simultaneously.

B. CHANNEL MODEL

Let $P_{s,n}^{k,i}$ and $P_{d,d}^{k,i}$ denote the transmission power from the SBS s to SUE n and the transmission power in D2D pair d between the transmitter and its receiver on channel i in band k. $h_{s,n}^{k,i}$ is defined as the channel gain from the SBS s to SUE n on channel $c_{k,i}$. And the channel gain in D2D pair d between the transmitter and its receiver on channel $c_{k,i}$ is $h_{d,d}^{k,i}$. Therefore, the signal to interference plus noise ratio (SINR) $\gamma_{s,n}^{k,i}$ from SBS s to SUE n on the subchannel i in band k is as follows:

$$\gamma_{s,n}^{k,i} = \frac{\eta_{s,n}^{k,i} P_{s,n}^{k,i} h_{s,n}^{k,i}}{I_{s,n}^{k,i,inter} + I_{s,n}^{k,i,intra} + N_0}, \tag{1}$$

where N_0 is the white Gaussian noise. And the inter-cell interference $I_{s,n}^{k,i,inter}$ of SUE n on subchannel $c_{k,i}$ is

$$I_{s,n}^{k,i,inter} = \sum_{j\in\mathcal{S},j\neq s}\sum_{l\in\mathcal{N}_j} \eta_{j,l}^{k,i} P_{j,l}^{k,i} h_{j,n}^{k,i} + \sum_{j\in\mathcal{S},j\neq s}\sum_{l\in\mathcal{N}_j}\sum_{d'\in\mathcal{D}_j} \eta_{j,l}^{k,i} x_{l,d'}^{k,i} P_{d',d'}^{k,i} h_{d',n}^{k,i}, \tag{2}$$

where the first term of $I_{s,n}^{k,i,inter}$ is the inter-cell interference from SUEs in other SBSs and the second term of $I_{s,n}^{k,i,inter}$ is the inter-cell interference caused by D2D users in other SBSs. And the intra-cell interference $I_{s,n}^{k,i,intra}$ of SUE n from D2D users occupied the same subchannel i in band k is

$$I_{s,n}^{k,i,intra} = \sum_{d\in\mathcal{D}_s} x_{n,d}^{k,i} P_{d,d}^{k,i} h_{d,n}^{k,i}. \tag{3}$$

In order to guarantee the service performance of SUEs, $I_{s,n}^{k,i} = I_{s,n}^{k,i,inter} + I_{s,n}^{k,i,intra} + N_0$ is defined as the channel interference of the SUE n, and the following constraints should be satisfied:

$$I_{s,n}^{k,i} < I_{s,n}^{thre}. \tag{4}$$

Similarly, the SINR $\gamma_{d,d}^{k,i}$ in D2D pair d between the transmitter and its receiver on subchannel i in band k is as follows:

$$\gamma_{d,d}^{k,i} = \frac{x_{d,d}^{k,i} P_{d,d}^{k,i} h_{d,d}^{k,i}}{I_{d,d}^{k,i,inter} + I_{d,d}^{k,i,intra} + N_0}. \tag{5}$$

And the inter-cell interference $I_{d,d}^{k,i,inter}$ of D2D pair d on the subchannel i in band k is

$$I_{d,d}^{k,i,inter} = \sum_{j\in\mathcal{S},j\neq s}\sum_{l\in\mathcal{N}_j} \eta_{j,l}^{k,i} P_{j,l}^{k,i} h_{j,d}^{k,i} + \sum_{j\in\mathcal{S},j\neq s}\sum_{l\in\mathcal{N}_j}\sum_{d'\in\mathcal{D}_j} \eta_{j,l}^{k,i} x_{l,d'}^{k,i} P_{d',d'}^{k,i} h_{d',d}^{k,i}, \tag{6}$$

where the first term of $I_{d,d}^{k,i,inter}$ is the inter-cell interference from SUEs in other SBSs, and the second term of it is the inter-cell interference caused by D2D users. And the intra-cell interference $I_{d,d}^{k,i,intra}$ of D2D pair d is

$$I_{d,d}^{k,i,intra} = \eta_{s,n}^{k,i} P_{s,n}^{k,i} h_{s,d}^{k,i} + \sum_{d''\in\mathcal{D}_s,d''\neq d} x_{n,d''}^{k,i} P_{d'',d''}^{k,i} h_{d'',d}^{k,i}, \tag{7}$$

where the first term of $I_{d,d}^{k,i,intra}$ is the intra-cell interference from SUE n and the second item of (7) is the intra-cell interference caused by other D2D users occupied the same subchannel i in band k.

The transmission rate from the SBS s to SUE n on the subchannel i in band k is

$$R_{s,n}^{k,i} = p_{k,i} W_{k,i} \log_2\left(1 + \gamma_{s,n}^{k,i}\right). \tag{8}$$

The transmission rate from the D2D transmitter d to its receiver on the subchannel i in band k is

$$R_{d,d}^{k,i} = p_{k,i} W_{k,i} \log_2\left(1 + \gamma_{d,d}^{k,i}\right). \tag{9}$$

Considering that SUEs and D2D users have certain transmission rate requirements, we use service satisfaction to indicate the user experience [23], which is similar to the concept of quality of experience (QoE). Specifically, when data rate of SUE s is higher than $R_{s,n}^{Tar}$, which is the target transmission rate of SUE n from the SBS s, the satisfaction of SUE n from SBS s will increase slowly. When it is lower than $R_{s,n}^{Tar}$, the satisfaction will decrease significantly. The service satisfaction of SUE n on subchannel $c_{k,i}$ is defined as follows:

$$\Gamma_{s,n}^{k,i} = 1 - \exp\left(-\alpha \frac{R_{s,n}^{k,i}}{R_{s,n}^{Tar}}\right), \tag{10}$$

where α is the steepness factor of the satisfaction curve. And we can conclude that satisfaction values range from 0 to 1.

Similarly, the satisfaction of D2D pair d on subchannel $c_{k,i}$ is

$$\Gamma_{d,d}^{k,i} = 1 - \exp\left(-\alpha \frac{R_{d,d}^{k,i}}{R_{d,d}^{Tar}}\right), \tag{11}$$

where $R_{d,d}^{Tar}$ is the target transmission rate from the D2D transmitter d to its receiver.

C. PROBLEM FORMULATION

In the considered scenario with a heterogeneous spectrum pool, the key issue for channel allocation is to provide channel selection and sharing schemes for SUEs and D2D pairs to meet their satisfaction degree requirements, while ensuring that the interference of SUEs is within a certain range.

Denote $\mathbf{B} = \{B_1, B_2, \ldots, B_S\}$ as the band selection vector, where B_s is the band selection of small cell s, i.e., $B_s = \left\{k : \eta_{s,n}^{k,i} = 1, n \in \mathcal{N}_s\right\}$. Define the channel allocation of SUEs in different small cells as $\mathbf{X} = \{X_1, X_2, \ldots, X_S\}$, where X_s is the SUE channel allocation in small cell s and $X_s = \left\{n : \eta_{s,n}^{k,i} = 1, \forall i \in \mathcal{C}_k, n \in \mathcal{N}_s\right\}$. Define the channel sharing vector of D2D pairs in different SBSs as $\mathbf{Y} = \{Y_1, Y_2, \ldots, Y_S\}$, where Y_s represents the channel sharing set of D2D users in SBS s and $Y_s = \left\{x_{n,d}^{k,i}, \forall i \in \mathcal{C}_k, n \in \mathcal{N}_s, d \in \mathcal{D}_s\right\}$.

Denote U_s as the utility of SBS s, and it is defined as follows:

$$U_s = \sum_{n\in\mathcal{N}_s}\sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{C}_k}\eta_{s,n}^{k,i}\Gamma_{s,n}^{k,i} + \sum_{d\in\mathcal{D}_s}\sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{C}_k}x_{n,d}^{k,i}\Gamma_{d,d}^{k,i}. \quad (12)$$

The goal of the channel allocation optimization problem is to maximize the overall network utility, which is the total service satisfaction of all SUEs and D2D users in our considered system. Then, the channel assignment problem can be formulated as

$$\begin{aligned}
P1 : & U(\mathbf{B}, \mathbf{X}, \mathbf{Y}) \\
&= \sum_{s\in\mathcal{S}}\sum_{n\in\mathcal{N}_s}\sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{C}_k}\eta_{s,n}^{k,i}\Gamma_{s,n}^{k,i} \\
&\quad + \sum_{s\in\mathcal{S}}\sum_{d\in\mathcal{D}_s}\sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{C}_k}x_{n,d}^{k,i}\Gamma_{d,d}^{k,i}, \\
s.t.\ & C1 : \eta_{s,n}^{k,i} \in \{0,1\}, \quad \forall i \in \mathcal{C}_k,\ s \in \mathcal{S},\ n \in \mathcal{N}_s, \\
& C2 : x_{n,d}^{k,i} \in \{0,1\}, \quad \forall i \in \mathcal{C}_k,\ s \in \mathcal{S},\ d \in \mathcal{D}_s, \\
& C3 : R_{s,n}^{k,i} \geq R_{s,n}^{Tar}, \\
& C4 : R_{d,d}^{k,i} \geq R_{d,d}^{Tar}, \\
& C5 : \sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{C}_k}\eta_{s,n}^{k,i} \leq 1, \quad \forall s \in \mathcal{S},\ n \in \mathcal{N}_s, \\
& C6 : \sum_{n=1}^{\mathcal{N}_s}\eta_{s,n}^{k,i} \leq 1, \quad \forall s \in \mathcal{S},\ k \in \mathcal{K},\ i \in C_k, \\
& C7 : \sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{C}_k}x_{n,d}^{k,i} \leq 1, \quad \forall s \in \mathcal{S},\ d \in \mathcal{D}_s, \\
& C8 : I_{s,n}^{k,i} < I_{s,n}^{thre}, \quad \forall i \in \mathcal{C}_k,\ s \in \mathcal{S},\ n \in \mathcal{N}_s,
\end{aligned} \quad (13)$$

where C1 and C2 denote that $\eta_{s,n}^{k,i}$ and $x_{n,d}^{k,i}$ are binary variables. C3 and C4 are the transmission rate requirements of SUEs and D2D pairs. C5 and C6 are the constraints of the channel allocation factor. C5 means that only one channel can be allocated per SUE, and C6 ensures that the SUEs in the same SBS should be assigned with different channels. C7 means that D2D can only share the channel of one SUE. C8 is the interference constraint of SUE s.

Due to the complex interference and channel sharing relationship between SUEs and D2D users, the previously proposed problem P1 is a non-convex and mixed integer non-linear problem (MINLP) which is NP-hard. Inspired by [24] and [25], in the next section, a two-stage distributed channel allocation algorithm based on potential game and coalition game is proposed to solve the proposed problem.

III. CHANNEL ALLOCATION USING POTENTIAL GAME AND COALITION GAME

In this section, the game model and game analysis of potential game and coalition game are presented. Finally, based on the corresponding game algorithm, a two-stage distributed channel allocation algorithm is proposed.

A. GAME MODEL OF POTENTIAL GAME

Since the heterogeneous frequency bands are shared by all small cells, inter-cell interference is inevitably generated between adjacent small cells due to the use of the same frequency band. The performance of each cell is affected by part of its neighboring cells. The interference graph $Q = (\mathcal{V}, \xi)$ is an unidirectional graph, which is used to represent the interference relationship between small cells, with $\mathcal{V}$ denoting the set of small cell base stations and ξ representing the potential interference between each small cell. And an example of the interference graph is shown in Fig. 2. Interference graphs represent only potential distance-based interference relationships. The interference of two small cells is also affected by the allocated frequency band. For example, when two small cells use the same frequency band and the distance between them is less than a predefined interference distance threshold, there is mutual interference between them. Denote $\mathcal{Z}_s = \{j \in \mathcal{V}, (j, s) \in \xi\}$ as the neighboring interfered SBSs set of SBS s.

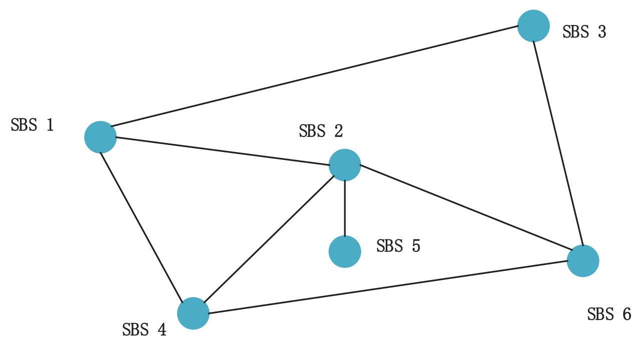

FIGURE 2. Interference graph.

We define a local game $G_1 = \left\{\mathcal{S}, \{B_s \otimes X_s\}_{s\in\mathcal{S}}, \left\{\bar{U}_s\right\}_{s\in\mathcal{S}}\right\}$, where $\mathcal{S}$ is the player set, i.e., the set of SBSs, $\{B_s \otimes X_s\}$ is the band selection and channel allocation set of SUEs in player s. $\bar{U}_s$ is the utility function of potential game for player s, which is defined as follows:

$$\begin{aligned}
\bar{U}_s\left(Q_s, Q_{\mathcal{Z}_s}\right) &= \bar{\Gamma}_s^{sue} + \sum_{z\in\mathcal{Z}_s}\bar{\Gamma}_z^{sue} \\
&= \sum_{n\in\mathcal{N}_s}\sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{C}_k}\eta_{s,n}^{k,i}\bar{\Gamma}_{s,n}^{k,i} \\
&\quad + \sum_{z\in\mathcal{Z}_s}\sum_{n\in\mathcal{N}_z}\sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{C}_k}\eta_{z,n}^{k,i}\bar{\Gamma}_{z,n}^{k,i},
\end{aligned} \quad (14)$$

where Q_s and $Q_{\mathcal{Z}_s}$ represents the band selection and channel allocation set of small cell s and its neighboring small cells, while $\bar{\Gamma}_s^{sue}$ is the total service satisfaction of SUES in small cell s with the strategies Q_s and $Q_{\mathcal{Z}_s}$. And $Q_s = \{B_s, X_s\}$. Since the first stage only completes the channel allocation of SUEs, the definition of $\bar{\Gamma}_s^{sue}$ and $\bar{\Gamma}_{s,n}^{k,i}$ here is different from that mentioned before. $\bar{\Gamma}_{s,n}^{k,i}$ can be obtained by (8), (10) and $\bar{\gamma}_{s,n}^{k,i}$, where $\bar{\gamma}_{s,n}^{k,i} = \frac{\eta_{s,n}^{k,i} P_{s,n}^{k,i} h_{s,n}^{k,i}}{\sum_{j\in\mathcal{S}, j\neq s}\sum_{l\in\mathcal{N}_j} \eta_{j,l}^{k,i} P_{j,l}^{k,i} h_{j,n}^{k,i} + N_0}$ only considers the interference between SUE users. The utility of the player s is the total service satisfaction of SUEs in small cell s and its neighboring small cells. Here, there is potential interference between adjacent small cells, but no interference is considered between non-adjacent small cells beyond the distance threshold. Considered these adjacent small cells as a group, the overall utility maximization can be obtained by continuously maximize the satisfaction of each group of small cells.

B. GAME ANALYSIS OF POTENTIAL GAME

Definition 1: A strategy profile $\mathbf{Q}_{s\in\mathcal{S}}^* = \left(B_1^*, B_2^*, \ldots, B_S^*, X_1^*, X_2^*, \ldots, X_S^*\right)$ is a Nash equilibrium (NE) if and only if

$$\bar{U}_s\left(Q_s^*, \mathbf{Q}_{-s}^*\right) \geq \bar{U}_s\left(Q_s, \mathbf{Q}_{-s}^*\right), \quad \forall s \in S, \tag{15}$$

where $\mathbf{Q}_{-s}^*$ is the strategy profile of all other players except the SBS s. NE means that no participant intends to change its strategy because there is no utility improvement when it unilaterally changes the strategy.

Theorem 1: The proposed game G_1 has at least one pure NE strategy.

In this paper, the theory of potential game is used to prove Theorem 1.

Definition 2: When the potential function of one game satisfies (16), this game is a potential game.

$$\bar{U}_s\left(a'_s, a_{-s}\right) - \bar{U}_s\left(a_s, a_{-s}\right) = \Phi\left(a'_s, a_{-s}\right) - \Phi\left(a_s, a_{-s}\right). \tag{16}$$

where $\tilde{U}_s$ and Φ are the utility function and the potential function. And the strategies of player s and other players in this game are a_s and a_{-s}. And a'_s is the new strategy for player s.

In the exact potential game, when the strategy of participant s is changed from a_s to a'_s, the change in the utility function is equal to the change in the potential function. Based on this, the proof that game G_1 is a potential game is given below.

Proof: The potential function of G_1 is given by

$$\Phi\left(Q_s, \mathbf{Q}_{-s}\right) = \sum_{s\in\mathcal{S}} \bar{\Gamma}_s^{sue}\left(Q_s, \mathbf{Q}_{-s}\right). \tag{17}$$

Then, we have

$$\Phi\left(Q_s, \mathbf{Q}_{-s}\right) = \bar{\Gamma}_s^{sue}\left(Q_s, \mathbf{Q}_{Z_s}\right) + \sum_{j\in\mathcal{Z}_s} \bar{\Gamma}_j^{sue}\left(Q_s, \mathbf{Q}_{\mathcal{Z}_j}\right) + \sum_{n\neq s, n\notin\mathcal{Z}_s} \bar{\Gamma}_n^{sue}\left(Q_n, \mathbf{Q}_{\mathcal{Z}_n}\right). \tag{18}$$

Considering that the decision set of each player contains two decision variables, any change in bandwidth selection and channel allocation of SUEs will lead to the change of its policy set. Suppose an arbitrary participant, such as small cell s, the band selection of small cell s is changed from B_s to B'_s. Then, the following formula gives the change of the potential function.

$$\begin{aligned}
&\Phi\left(Q'_s, \mathbf{Q}_{-s}\right) - \Phi\left(Q_s, \mathbf{Q}_{-s}\right) \\
&= \Phi\left(B'_s, X_s, \mathbf{Q}_{-s}\right) - \Phi\left(B_s, X_s, \mathbf{Q}_{-s}\right) \\
&= \bar{\Gamma}_s^{sue}\left(B'_s, X_s, \mathbf{Q}_{\mathcal{Z}_s}\right) - \bar{\Gamma}_s^{sue}\left(B_s, X_s, \mathbf{Q}_{\mathcal{Z}_s}\right) \\
&\quad + \sum_{j\in\mathcal{Z}_s} \bar{\Gamma}_j^{sue}\left(B'_s, X_s, \mathbf{B}'_{\mathcal{Z}_j}, \mathbf{X}_{\mathcal{Z}_j}\right) \\
&\quad - \sum_{j\in\mathcal{Z}_s} \bar{\Gamma}_j^{sue}\left(B_s, X_s, \mathbf{B}_{\mathcal{Z}_j}, \mathbf{X}_{\mathcal{Z}_j}\right) \\
&\quad + \sum_{n\neq s, n\notin\mathcal{Z}_s} \bar{\Gamma}_n^{sue}\left(Q_n, \mathbf{Q}_{\mathcal{Z}_n}\right) - \sum_{n\neq s, n\notin\mathcal{Z}_s} \bar{\Gamma}_n^{sue}\left(Q_n, \mathbf{Q}_{\mathcal{Z}_n}\right).
\end{aligned} \tag{19}$$

The change of utility function is given by

$$\begin{aligned}
&\bar{U}_s\left(Q'_s, \mathbf{Q}_{-s}\right) - \bar{U}_s\left(Q_s, \mathbf{Q}_{-s}\right) \\
&= \bar{\Gamma}_s^{sue}\left(B'_s, X_s, \mathbf{Q}_{Z_s}\right) - \bar{\Gamma}_s^{sue}\left(B_s, X_s, \mathbf{Q}_{Z_s}\right) \\
&\quad + \sum_{j\in\mathcal{Z}_s} \bar{\Gamma}_j^{sue}\left(B'_s, X_s, \mathbf{B}'_{\mathcal{Z}_j}, \mathbf{P}_{\mathcal{Z}_j}\right) \\
&\quad - \sum_{j\in\mathcal{Z}_s} \bar{\Gamma}_j^{sue}\left(B_s, X_s, \mathbf{B}_{\mathcal{Z}_j}, \mathbf{P}_{\mathcal{Z}_j}\right).
\end{aligned} \tag{20}$$

When the bandwidth selection of the small cell s changes, the data rate and service satisfaction of SUEs in small cell n, where $n \neq s, n \notin \mathcal{Z}_s$, do not change because small cell n and small cell s are not adjacent small cells. Therefore, similar to [26], the following equation can be obtained from (19) and (20).

$$\Phi\left(Q'_s, \mathbf{Q}_{-s}\right) - \Phi\left(Q_s, \mathbf{Q}_{-s}\right) = \bar{U}_s\left(Q'_s, \mathbf{Q}_{-s}\right) - \bar{U}_s\left(Q_s, \mathbf{Q}_{-s}\right). \tag{21}$$

When the channel allocation of SUEs in small cell s changes from X_f to X'_f, and the frequency band selection of all small cells remains unchanged, the channel allocation of the change of channel allocation in the small cell s does not affect the other neighboring cells in the downlink communication network. This is determined by the unique characteristics of the downlink in small cell networks [27]. If small cell s only changes the channel selection of some SUEs, the interference received by each SUE in small cell $j \in \mathcal{Z}_s$ is still determined by the distance between the corresponding SUE and the SBS s, so the interference of each SUE received in small cell j does not change. Therefore, when small cell s changes its channel allocation of SUEs from X_f to X'_f, we have

$$\begin{aligned}
&\Phi\left(B_f, X'_s, \mathbf{Q}_{-s}\right) - \Phi\left(B_s, X_s, \mathbf{Q}_{-s}\right) \\
&= \bar{U}_s\left(B_s, X'_s, \mathbf{Q}_{Z_s}\right) - \bar{U}_s\left(B_s, X_s, \mathbf{Q}_{Z_s}\right).
\end{aligned} \tag{22}$$

The above analysis shows that when SBS s unilaterally changes its strategy, the change of potential function is the same as that of SBS s utility function. We conclude that the game G_1 is a potential game. And each potential game has at least one NE strategy. Therefore, Theorem 1 is proved. □

Theorem 2: The Nash equilibrium of the game G_1 proposed in this paper can achieve the maximization of the utility function of all small cells locally or globally.

Similar to [28], the local or global maximization of the potential function can be achieved by obtaining the Nash equilibrium of the potential game G_1. In this paper, the potential function of the potential game G_1 is defined as the service satisfaction of users in all small cells, that is, the defined utility function. As we all know, traditional iterative algorithms in the potential game are easily trapped in an undesirable equilibrium leading to a local optimal utility value. The best NE serves as the global optimum of the network utility. Theorem 2 has been proved.

In order to obtain the best NE, the mixed strategy learning algorithm is used to achieves the globally optimal utility value of the potential game, which has the favorable property of equilibrium selection and exploring global optimum.

C. ITERATIVE ALGORITHM OF POTENTIAL GAME

Since the set of frequency band selection and channel allocation in game G_1 is limited, the Nash equilibrium of the potential game can be realized through the iterative algorithm of resource allocation by using the characteristics of the potential game. However, it is important to note that the solution obtained may be a local optimal solution rather than the global solution.. Therefore, using the interference graph and the characteristics of band and channel allocation in small cell networks, the following channel allocation algorithm is proposed.

1) Initialization: Each small cell randomly chooses a frequency band, assign the corresponding channels to SUEs, that is, initialization $B_s(t_1 = 0), X_s(t_1 = 0), \forall s \in \mathcal{S}$, where t_1 is the number of iterations.

2) Small cell selection: Randomly select of a group of non-adjacent small cells $\tilde{S}$. Each small cell s in $\tilde{S}$ uses (12) to calculate its utility function by communicating with adjacent nodes.

3) Best response: In order to obtain the global solution, similar to [24], the mixed strategy is adopted. The frequency band selection and channel allocation of other small cells remain unchanged, and each small cell s calculates its utility function according to the definition of (14), i,e, $\bar{U}_{s,m}\left(\tilde{B}_{s,m}, X_s, \mathbf{B}_{-s}\right), \forall \tilde{B}_{s,m} \in \tilde{\mathbf{B}}_s, \forall s \in \tilde{S}$. In order to obtain the global maximization of Nash equilibrium, the mixed strategy is adopted here, which is given by

$$p_{s,m}(t_1+1) = \frac{\exp\left\{\beta \bar{U}_{s,m}\right\}}{\sum\limits_{\tilde{B}_{s,m}\in\tilde{\mathbf{B}}_s} \exp\left\{\beta \bar{U}_{s,m}\right\}}, \tag{23}$$

where β is the positive parameter. $p_{s,m}(t_1)$ represents the probability that SBS s chooses the mth strategy at iteration t_1. Then, the optimal strategy of maximizing utility function is selected for SBS s in $\tilde{S}$.

4) Best channel allocation: Since the channel allocation of SUEs is independent between small cells, the optimal channel allocation can be performed independently with the band selection of each cell.

Without losing generality, we assume that the selected SBS serves N_s SUEs with selected frequency band which consists of C_k channels. The optimization goal of channel allocation in the selected small cell is to maximize the total user satisfaction of SUEs in this small cell. And the channel assignment problem can be formulated as follows:

$$\begin{aligned}
&\max \sum_{n\in\mathcal{N}_s}\sum_{i\in\mathcal{C}_k} \eta_{s,n}^{k,i}\bar{\Gamma}_{s,n}^{k,i}\\
&s.t.\ C1: \eta_{s,n}^{k,i} \in \{0,1\}, \quad \forall i \in \mathcal{C}_k,\ n \in \mathcal{N}_s,\\
&\quad C3: R_{s,n}^{k,i} \geq R_{s,n}^{Tar},\\
&\quad C5: \sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{C}_k} \eta_{s,n}^{k,i} \leq 1,\ n \in \mathcal{N}_s,\\
&\quad C6: \sum_{n=1}^{\mathcal{N}_s} \eta_{s,n}^{k,i} \leq 1,\ k \in \mathcal{K},\ i \in C_k,\\
&\quad C8: I_{s,n}^{k,i} < I_{s,n}^{thre}, \quad \forall i \in \mathcal{C}_k,\ n \in \mathcal{N}_s.
\end{aligned} \tag{24}$$

By transforming the above problem into a maximum weight binary matching problem, we can solve it in polynomial time [29]. As we all know, the Hungarian algorithm is one of the effective algorithms to solve the above problem, so we use it to solve the channel allocation problem of SUE [30].

5) Stop: When no improvement of the overall utility function can be made, that is, the improvement of the utility function is less than a predetermined value ε_{pote}, the iterative algorithm is stopped. Otherwise, repeat steps 2, 3 and 4. By adjusting the parameters of the mixed strategy and the potential game precision, the Nash equilibrium of the potential game can infinitely approach the globally optimal utility values of G_1.

And the procedure of the proposed potential game based channel selection algorithm (PGBC) is illustrated in Algorithm 1.

Theorem 3: In the potential game G_1, $\mathcal{B} = \mathcal{B}_1 \otimes \cdots \otimes \mathcal{B}_S$ is the strategy set of all band selection, and the potential game can converge to the unique stable distribution, which is given by

$$\pi(\mathbf{B}, \mathbf{X}) = \frac{\exp\{\beta\Phi(\mathbf{B}, \mathbf{X})\}}{\sum\limits_{\mathbf{B}\in\mathcal{B}} \exp\{\beta\Phi(\mathbf{B}, \mathbf{X})\}}. \tag{25}$$

Proof: When the spectrum selection strategy is $\tilde{\mathbf{B}}$, the corresponding channel allocation $\mathbf{X}$ is also determined. The band selection is $\tilde{\mathbf{B}}$, then we can get $\mathbf{X} = f\left(\tilde{\mathbf{B}}\right)$. Next, we only need to pay attention to the impact of the strategy of band selection. The set of strategies in the PGBC algorithm is discrete, and the current strategy is not affected by the

Algorithm 1 PGBC Algorithm

1: **Initialization:**
2: Initialization $B_s(t_1 = 0), X_s(t_1 = 0), \forall s \in \mathcal{S}$;
3: Set potential game precision ε_{pote};
4: $k = 1, \lambda(0) = 1, t_1 = 1$.
5: **Iteration:**
6: Random selection of a group of non-adjacent SBS $\tilde{S}$;
7: Calculate utility according to (12);
8: **for** each $s \in \tilde{S}$ **do**;
9: Calculate $\tilde{U}_s$ according to (14);
10: Update mixed strategy according to (23).
11: Each SBS determines user scheduling
12: strategy independently based on
13: Hungarian algorithm.
14: **end for**
15: Stop when the improvement of the overall utility
16: function is smaller than ε_{pote}.
17: **Finalization:**
18: The final band selection and channel allocation of
19: SUEs are obtained.

previous strategy, so $\tilde{\mathbf{B}}$ is a discrete time Markov process, also an irreducible and aperiodic process. Therefore, it has a unique stable distribution.

We prove that the only stable distribution is (25) by proving that the distribution satisfies the balanced equation of the Markov process. Suppose a and b are two states in the spectrum selection process, where $a, b \in \tilde{\mathbf{B}}$, we just need to proof that $\pi(a)p(b|a) = \pi(b)p(a|b)$. Assume that state a is determined by $\left\{\tilde{B}_1, \tilde{B}_2, \cdots, \tilde{B}_S\right\}$, $\tilde{S} = \left\{1, 2, \cdots, \left|\tilde{S}\right|\right\}$ is a randomly selected set of non-adjacent small cells. The probability that each small cell is selected in the iteration is $\frac{1}{S}$. The state b can be expressed as $\left\{\tilde{B}_1, \tilde{B}_2, \cdots, \tilde{B}_{\left|\tilde{S}\right|}, \tilde{B}_{\left|\tilde{S}\right|+1}, \cdots \tilde{B}_S\right\}$. There are $\left|\tilde{S}\right|$ small cells who simultaneously update their strategies. Therefore, after omitting the iteration index, the conditional probability $p(b|a)$ is expressed as (26).

$$p(b|a) = \frac{\left|\tilde{S}\right|}{S} \prod_{s\in\tilde{S}} \frac{\exp\left\{\beta \bar{U}_s\left(\tilde{B}'_s, \tilde{\mathbf{B}}_{\mathcal{Z}_s}, f\left(\tilde{B}'_s, \tilde{\mathbf{B}}_{\mathcal{Z}_s}\right)\right)\right\}}{\sum_{\tilde{\mathbf{B}}_s} \exp\left\{\beta \bar{U}_s\left(\tilde{B}_s, \tilde{\mathbf{B}}_{\mathcal{Z}_s}, f\left(\tilde{B}_s, \tilde{\mathbf{B}}_{\mathcal{Z}_s}\right)\right)\right\}}. \tag{26}$$

According to (25), it can be obtained that

$$\begin{aligned} &\pi(a)p(b|a) \\ &= \lambda \exp\{\beta\Phi(a, f(a))\} \\ &\quad \cdot \prod_{s\in\tilde{S}} \exp\left\{\beta\bar{U}_s\left(\tilde{B}'_s, \tilde{\mathbf{B}}_{\mathcal{Z}_s}, f\left(\tilde{B}'_s, \tilde{\mathbf{B}}_{\mathcal{Z}_s}\right)\right)\right\} \\ &= \lambda \exp\left\{\beta\Phi(a, f(a)) + \beta \sum_{s\in\tilde{S}} \bar{U}_s\left(\tilde{B}'_s, \tilde{\mathbf{B}}_{\mathcal{Z}_s}, f\left(\tilde{B}'_s, \tilde{\mathbf{B}}_{\mathcal{Z}_s}\right)\right)\right\}, \end{aligned} \tag{27}$$

where $\lambda = \frac{\left|\tilde{S}\right|}{S \sum_{a\in\tilde{\mathbf{B}}} \exp\{\beta\Phi(a, f(a))\}} \cdot \prod_{s\in\tilde{S}} \frac{1}{\sum_{\tilde{\mathbf{B}}_s} \exp\left\{\beta\bar{U}_s\left(\tilde{B}_s, \tilde{\mathbf{B}}_{Z_s}, f\left(\tilde{B}_s, \tilde{\mathbf{B}}_{Z_s}\right)\right)\right\}}$.

Similarly, we can get

$$\begin{aligned} &\pi(b)p(a|b) \\ &= \lambda \exp\left\{\beta\Phi(b, f(b)) + \beta \sum_{s\in\tilde{S}} \bar{U}_s\left(\tilde{B}_s, \tilde{\mathbf{B}}_{\mathcal{Z}_s}, f\left(\tilde{B}_s, \tilde{\mathbf{B}}_{\mathcal{Z}_s}\right)\right)\right\}. \end{aligned} \tag{28}$$

Compared the state a with the state b, there are $\left|\tilde{S}\right|$ small cells changed their policies. When the state a is represented as $a = a(0)$, the state b is $a\left(\left|\tilde{S}\right|\right)$. We can get

$$\begin{aligned} &\Phi(b, f(b)) - \Phi(a, f(a)) \\ &= \Phi\left(a\left(\left|\tilde{S}\right|\right), f\left(a\left(\left|\tilde{S}\right|\right)\right)\right) - \Phi(a(0), f(a(0))) \\ &= \sum_{i=1}^{\left|\tilde{S}\right|} \{\Phi(a(i), f(a(i))) - \Phi(a(i-1), f(a(i-1)))\}. \end{aligned} \tag{29}$$

Since the small cells in $\tilde{S}$ are all non-adjacent small cells, the conclusion can be drawn according to the nature of the potential function in the potential game, which is given by

$$\begin{aligned} &\sum_{i=1}^{\left|\tilde{S}\right|} \{\Phi(a(i), f(a(i))) - \Phi(a(i-1), f(a(i-1)))\} \\ &= \sum_{s=1}^{\left|\tilde{S}\right|} \left\{\bar{U}_s(a(i), f(a(i))) - \bar{U}_s(a(i-1), f(a(i-1)))\right\} \\ &= \bar{U}_s\left(\tilde{B}'_s, \tilde{\mathbf{B}}_{\mathcal{Z}_s}, f\left(\tilde{B}'_s, \tilde{\mathbf{B}}_{\mathcal{Z}_s}\right)\right) - \bar{U}_s\left(\tilde{B}_s, \tilde{\mathbf{B}}_{\mathcal{Z}_s}, f\left(\tilde{B}_s, \tilde{\mathbf{B}}_{\mathcal{Z}_s}\right)\right). \end{aligned} \tag{30}$$

Therefore, we can prove that $\pi(a)p(b|a) = \pi(b)p(a|b)$. Theorem 3 is proved. □

Theorem 4: When β is sufficiently large, the PGBC algorithm can converge to the global optimal solution with an arbitrarily high probability.

Proof: Suppose the global optimal solution of the PGBC algorithm is $(\mathbf{B}^*, \mathbf{X}^*)$, which corresponds to the largest utility function and potential function. Therefore, for any non-optimal strategy choice, it can be obtained that $\Phi(\mathbf{B}^*, \mathbf{X}^*) > \Phi(\mathbf{B}, \mathbf{X})$. And when β is large enough, we can get $\exp\{\beta\Phi(\mathbf{B}^*, \mathbf{X}^*)\} \gg \exp\{\beta\Phi(\mathbf{B}, \mathbf{X})\}$. From Theorem 3 we can get $\lim_{\beta\to\infty} \pi(\mathbf{B}^*, \mathbf{X}^*) = 1$. The probability 1 is given to the globally optimal solution $(\mathbf{B}^*, \mathbf{X}^*)$ which maximizes the potential function, while other non-optimal solutions are in probability 0. Theorem 4 is proved. □

The computational complexity of PGBC algorithm is dominated by step 3 and step 4. In step 3, the utility functions on all bands are calculated and compared, so the computational complexity is $\mathcal{O}(K)$. In the step of best channel allocation, the computational complexity is $\mathcal{O}(C_k N_s)$ that small cell s needs to allocate channels in the selected frequency band to all SUEs. Therefore, the computational complexity of our proposed algorithm 1 is $\mathcal{O}(KC_k N_s)$.

D. GAME MODEL OF COALITION GAME

After the channel allocation of SUEs is completed, the interference of some SUEs does not exceed their threshold. In order to improve spectrum utilization, channels allocated to SUEs with small interference could be shared to D2D pairs.

In the channel sharing phase, there are N_s SUEs and D_s D2D pairs in small cell s, in which SUEs choose to share the channel resource allocated to D2D pairs. We assume that $N_s < D_s$, and D_s D2D pairs form N_s alliances to maximize the sum satisfaction degree of small cell s. We denote the coalitions as $\Pi = \left\{\Pi_1, \Pi_2, \ldots, \Pi_{N_s}\right\}$, where $\Pi_x \cap \Pi_y = \emptyset$ for any $x \neq y$ and $\cup_{x=1}^{N_s} \Pi_x = \mathcal{D}_s$.

If many users occupy the same channel, co-channel interference increases sharply, and the transmission rate and service satisfaction drop drastically. D2D users tend to select channels that are occupied by fewer users and switch from channels with higher interference to those with less interference. D2D users constantly change their choices of shared channel until their experienced utilities are maximized. This process is similar to the coalition formation process, so we use the coalitional game [31] to complete channel sharing between D2D users and SUEs. We use the coalition gam with transferable utility [32] to model the channel sharing.

Definition 3: Denote $(\mathcal{D}_s, U_s)$ as a coalition game with a transferable utility. In this coalition game, $\mathcal{D}_s$ is the players set, i.e., the set of D2D users. U_s is the transferable utility of all coalitions.

$U_s(\Pi_n)$ is the transferable utility of coalition Π_n, which is a real number that can be used to indicate the increase and decrease utility of coalition Π_n caused by the transfer of D2D pairs. We assign the value of $U_s(\Pi_n)$ to all members according to the contribution of each member in the coalition. $U_{s,d}(\Pi_n)$ is defined as the individual contribution of D2D pair d in coalition Π_n by allocating the transferable utility to all coalition members, including a SUE, and it is given by

$$U_{s,d}(\Pi_n) = \frac{\Gamma_{d,d}^{k,i} U_s(\Pi_n)}{\Gamma_{s,n}^{k,i} + \sum\limits_{d \in \mathcal{D}_s} \Gamma_{d,d}^{k,i}}. \tag{31}$$

E. ITERATIVE ALGORITHM OF COALITION GAME

Before putting forward the coalitional game algorithm, we first introduce preference order and acceptance probability for channel sharing selection of D2D pairs to better understand the process of coalition formation game.

For D2D pairs d in small cell s, the preference order $\succ_d$ is defined as a complete, reflexive, and transitive binary relation between two coalitions. $\Pi_n \succ_d \Pi_{n'}$ means d prefers being a member of coalition Π_n than $\Pi_{n'}$, where $\Pi_n \subseteq \mathcal{D}_s$ and $\Pi_{n'} \subseteq \mathcal{D}_s$. According to the individual contribution of D2D users and the interference situation of the SUE user in each coalition, the preference order of D2D pair $d \in \mathcal{D}_s$ is defined as follows:

$$\begin{aligned} \Pi_n \succ_d \Pi_{n'} \Leftrightarrow\ & U_{s,d}(\Pi_n) > U_{s,d}(\Pi_{n'}) \\ & \& U_{s,j}(\Pi_k) \geq U_{s,j}(\Pi_k \backslash d) \\ & \& I_{s,n}^{k,i} < I_{s,n}^{thre}, \quad \forall j \in \{\Pi_k \backslash d\},\ k = n, n', \quad \forall o \in \Pi_{n'},\ s \in \mathcal{S}. \end{aligned} \tag{32}$$

D2D pair d prefers being a member of Π_n over $\Pi_{n'}$ when all of the following conditions are satisfied: the individual contribution of D2D pair d increases, while the individual profits of other members in these two coalitions do not decrease, and the interference of SUEs does not exceed the interference threshold. In this mechanism, each D2D user can leave its current coalition and join another coalition according to the defined preference order. Since the preference order of the D2D user is obtained by local information, it may deviate from the global optimal solution. Therefore, when the new coalition is not the best choice of D2D pair d, it should also consider joining the coalition with a certain probability to obtain the global optimization. Similar to [31], we design an acceptance probability.

The acceptance probability is $\phi_{n,n'}(T_{t_2}) = \exp\{[U_s(\Pi_{n'}) - U_s(\Pi_n)]/T_{t_2}\}$, where $T_{t_2} = T_0/\log(t_2 - 1)$. T_0 is a predefined fixed value and t_2 represents the corresponding number of switch. Generally speaking, when the number of formation iterations increases large enough, the final stable coalition is close to the global optimal result.

According to the preference order and acceptance probability, a coalition game algorithm with D2D user transfer for channel sharing (CGAD) is proposed in algorithm 2.

The computational complexity of CGAD algorithm is dominated by step 2. In the worst case when all D2D pairs in small cell s need to verify all coalitions, the computational complexity of step 2 is $\mathcal{O}(N_s D_s)$. Therefore, in total, the computational complexity of Algorithm 2 is $\mathcal{O}(SN_s D_s)$.

F. GAME ANALYSIS OF COALITION GAME

Theorem 5: A coalitional structure $\Pi = \{\Pi_1, \Pi_2, \ldots, \Pi_c, \ldots\}$ is Nash-stable if $\forall d \in \mathcal{D}_s$ and $d \in \Pi_n \in \Pi$, $\Pi_n \succ_d \Pi_{n'} \cup \{d\}$ for all $\Pi_{n'} \in \Pi \backslash \Pi_n \cup \{\Phi\}$ [33].

According to the above definition and conceptual form in hedonic game [34], the final stability of Π_{fin} is determined by the existence of Nash stability which lets if $\forall d \in \mathcal{D}_s$ and $d \in \Pi_n \in \Pi$, $\Pi_n \succ_d \Pi_{n'} \cup \{d\}$ for all $\Pi_{n'} \in \Pi \backslash \Pi_n \cup \{\emptyset\}$. The stability of this proposed coalition game are guaranteed as follows.

Theorem 6: With a random initial coalition set of D2D pairs, the CHAD algorithm can always converge to the coalition set which is Nash stable.

Proof: During channel sharing, D2D users randomly join or leave one coalition based on preference order and acceptance probability. In small cell s, the number of SUEs is limited, that is, the number of coalitions is limited. So the switching operation of D2D users will terminate with probability 1, and the final coalition set Π_{fin} will also be obtained

Algorithm 2 CGAD Algorithm

Step 1 **Initialization:**
Randomly choose one SBS $s \in S$ as the considered SBS.
Set the current channel allocation of SBS s as the initial partition F_{ini}.
Set the current partition as $\Pi_{ini} \rightarrow \Pi_{cur}$, and set the iteration index $0 \rightarrow t_2$.
Step 2 **Iteration:**
  Uniformly randomly choose one D2D pair $d \in \mathcal{D}_s$,
  and denote its coalition as $\Pi_n \in \Pi_{cur}$;
  Uniformly randomly choose another coalition
  $\Pi_{n'} \in \Pi_{cur}$, $\Pi_{n'} \neq \Pi_n$, and set $t_2 + 1 \rightarrow t_2$;
  if The switch operation from Π_n to $\Pi_{n'} \cup \{\phi\}$
  satisfying $\Pi_{n'} \succ_d \Pi_n$ **then**
    D2D pair d leaves its current coalition Π_c,
  and joins the new coalition $\Pi_{n'}$;
    Update the current partition set as follows
  $(\Pi_{cur} \backslash \{\Pi_{n'}, \Pi_n\}) \cup \{\Pi_n \backslash \{d\}, \Pi_{n'} \cup \{d\}\} \rightarrow \Pi_{cur}$;
  else
    Draw a random number ρ uniformly distributed
  in (0, 1], and set $T_{t_2} = T_0 / \log(t_2 - 1)$;
    if $\rho < \phi_{n,n'}\left(T_{t_2}\right)$ then
    Let d join $\Pi_{n'}$, and update the partition set as
  $(\Pi_{cur} \backslash \{\Pi_{n'}, \Pi_n\}) \cup \{\Pi_n \backslash \{d\}, \Pi_{n'} \cup \{d\}\} \rightarrow \Pi_{cur}$.
    end if
  end if
until The partition converges to the final Nash-stable partition Π_{fin}.

with probability 1. Suppose that the final partition Π_{fin} obtained by the CGAD algorithm is not Nash-stable. This means there is a D2D pair of $d \in \Pi_n$ and a coalition $\Pi_{n'} \in \Pi$ and $\Pi_{n'} \cup \{d\} \succ_d \Pi_n$. According to the preference order and acceptance probability, D2D pair of d tends to transfer to coalition $\Pi_{n'}$, which contradicts the fact that Π_{fin} is the final coalition set. Therefore, the proof that the final partition Π_{fin} obtained by CGAD algorithm must be Nash-stable is given. □

Theorem 7: The CHAD algorithm can always converge to the corresponding global optimal solution.

It can be seen that the process of the coalition game in CHAD algorithm is a Markov chain. $\left\{\Pi\left(T_{t_2}\right)\right\}$ is used to indicate the state of coalitions in the t_2th iteration. Denote $\mathbb{S}$ as all states in the Markov chain. According to the concept of stable limiting distribution in [35], we first prove that the Markov chain formed by the coalition game is ergodic. In the CHAD algorithm, when there is a preference coalition $\Pi_{n'}$, the switch is performed with probability 1, or when there is no preference coalition, the switch is performed with probability $\phi_{n,n'}$. Therefore, it can obtained that

$$\phi_{n,n'} = \begin{cases} 1, & \textit{if } \Pi_{n'} \succ_d \Pi_n, \\ \exp\left(\dfrac{U_s\left(\Pi_{n'}\right) - U_s\left(\Pi_n\right)}{T_{t_2}}\right), & \textit{otherwise}. \end{cases} \tag{33}$$

When D2D pair d changes its coalition choice, the utility functions of other coalitions have not changed and we can get

$$\phi_{n,n'} = \begin{cases} 1, & \textit{if } U_s\left(\Pi'\right) \geq U_s\left(\Pi\right), \\ \exp\left(\dfrac{U_s\left(\Pi'\right) - U_s\left(\Pi\right)}{T_{t_2}}\right), & \textit{if } U_s\left(\Pi'\right) < U_s\left(\Pi\right). \end{cases} \tag{34}$$

where Π and Π' are the coalition sets of D2D pair d before and after its switch operation. It can be obtained that

$$\lim_{T_{t_2} \to 0} \phi_{n,n'}\left(T_{t_2}\right) = \begin{cases} 0, & \textit{if } U_s\left(\Pi'\right) < U_s\left(\Pi\right), \\ 1, & \textit{if } U_s\left(\Pi'\right) \geq U_s\left(\Pi\right). \end{cases} \tag{35}$$

When $U_s\left(\Pi'\right) = U_s\left(\Pi\right)$, there is $\lim_{T_{t_2} \to 0} \phi_{n,n'}\left(T_{t_2}\right) = 1 > 0$ Therefore, the conditions in Theorem 8.1 of Chapter 7 of [35] are satisfied. Based on this, we define $\Pi_{n,n'}\left(T_{t_2}\right)$, which is given by

$$\begin{aligned} \phi_{n,n'}^{\inf}\left(T_{t_2}\right) &= \inf_{\substack{\Pi \in \mathbb{S} \\ \Pi' \in \mathbb{S}'}} \phi_{n,n'}\left(T_{t_2}\right) \\ &= \inf_{\substack{\Pi \in \\ U_s\left(\Pi'\right) > U_s\left(\Pi\right)}} \exp\left(-\left(\frac{U_s\left(\Pi\right) - U_s\left(\Pi'\right)}{T_{t_2}}\right)\right) \\ &\geq e^{\frac{-\Delta}{T_{t_2}}}. \end{aligned} \tag{36}$$

where $\Delta = \sup\left\{U_s\left(\Pi\right) - U_s\left(\Pi'\right), \Pi \in \mathbb{S}'\right\}$, which is a constant. And $T_{t_2} = T_0 / \log(t_2 - 1)$, so we can set $T_0 \leq T\Delta$ and have

$$\begin{aligned} \sum_{t_2=1}^{\infty}\left(\phi_{n,n'}^{\inf}\left(T_{t_2 T}\right)\right)^T &\geq \sum_{n=1}^{\infty}\left(\exp\left(\frac{-T\Delta}{T_0}\log(t_2 T - 1)\right)\right) \\ &\geq \sum_{t_2=1}^{\infty}\left(\exp\left(\frac{-T\Delta}{T_0}\log\frac{1}{t_2 T}\right)\right) \\ &\geq \sum_{t_2=1}^{\infty}\left(\frac{1}{t_2 T}\right) = \infty. \end{aligned} \tag{37}$$

According to the Theorem 8.2 in Chapter 6 of [35], $\left\{\Pi\left(T_{t_2}\right)\right\}$ is ergodic. It is also irreducible. So the finite distribution of $\left\{\Pi\left(T_{t_2}\right)\right\}$ is also its stable distribution. The state in $\left\{\Pi\left(T_{t_2}\right)\right\}$ can be converted to each other with a limited number of iterations, so it is also positive recurrent. Based on the condition of stable distribution, there is a unique stable distribution $\pi\left(\Pi\right)$, which is given by

$$\pi\left(\Pi\right) = \frac{\exp\left(U_s\left(\Pi\right)/T_{t_2}\right)}{\sum_{\Pi' \in \mathbb{S}} \exp\left(U_s\left(\Pi'\right)/T_{t_2}\right)}. \tag{38}$$

We set the maximal utility of the coalition game as $\Omega = \{\mathcal{Q} \in \mathbb{S}, U_s(\mathcal{Q}) \geq U_s(\mathcal{P}), \forall \mathcal{P} \in \mathbb{S}\}$. Define $w = \max_{\Pi' \in \mathbb{S}} U_s\left(\Pi'\right)$, convert (38) with it, we can obtain that

$$\pi\left(\Pi\right) = \frac{\exp\left(\dfrac{-\left(w - U_s\left(\Pi\right)\right)}{T_{t_2}}\right)}{\sum_{\Pi' \in \mathbb{S}} \exp\left(\dfrac{-\left(w - U_s\left(\Pi'\right)\right)}{T_{t_2}}\right)}$$

$$= \frac{\exp\left(\frac{-(w-U_s(\Pi))}{T_{t_2}}\right)}{|\Omega| + \sum\limits_{\Pi'\notin\Omega} \exp\left(\frac{-\left(w-U_s\left(\Pi'\right)\right)}{T_{t_2}}\right)}. \quad (39)$$

As the number of iterations increases, it can be obtained that

$$\lim_{T_{t_2}\to 0} \exp\left(\frac{-\left(w-U_s\left(\Pi'\right)\right)}{T_{t_2}}\right) = \begin{cases} 1, & if\ \Pi' \in \Omega, \\ 0, & if\ \Pi' \notin \Omega. \end{cases} \quad (40)$$

Bring (40) into (39), it can be obtained that

$$\lim_{T_{t_2}\to 0} \pi(\Pi) = \begin{cases} \frac{1}{|\Omega|}, & if\ \Pi \in \Omega, \\ 0, & if\ \Pi \notin \Omega. \end{cases} \quad (41)$$

We can conclude that as the number of iterations increases, the stable distribution eventually converges to the maximum utility of the coalition game with probability 1. And Theorem 7 is proved. □

G. TWO-STAGE DISTRIBUTED CHANNEL ALLOCATION

In D2D-assisted dense networks, the channel sharing allocation problem P1 with the heterogeneous spectrum pool is solved by the proposed two-stage distributed channel allocation algorithm (TDCA), i.e., algorithm 3. Algorithm 3 mainly consists of algorithm 1 and algorithm 2. The algorithm 3 consists of four parts. Firstly, SUEs and D2D users sets, spectrum and channel sets of each small cell are given. In the second step, the initial channel allocation results of SUEs in all small cells are obtained according to algorithm 1. In the third step, the channel sharing results of SUEs and D2D users in each small cell are obtained by using algorithm 2. In the fourth step, the channel sharing results are mapped to obtain the corresponding channel allocation results, which is the solution of the proposed optimization problem P1.

Algorithm 3 TDCA Algorithm

1: **Step 1:** The set of the SUEs $\mathcal{N}$ and D2D users $\mathcal{D}$, the set of heterogeneous spectrum bands $\mathcal{K}$ and sub-channels in each band is given.
2: **Step 2:** The band selection **B** the channel allocation of SUEs is obtained according to the PGBC algorithm.
3: **Step 3:** Get the final Nash-stable partition Π_{fin} in each small cell s according to the CGAD algorithm.
4: **Step 4:** Map the Nash-stable partitions got from step 3 into the channel allocation solution **X** and **Y** to obtain the final solution of problem P1.

Theorem 8: After a certain number of calculations, the proposed TDCA algorithm converges to the final stable results of band selection and channel allocation.

It is obvious that algorithm 3 is composed of the PGBC algorithm and the CGAD algorithm. Based on the finite strategy set of game G_1 and Theorem 6 of coalition game, it can be concluded that the proposed TDCA algorithm converges to the final stable result of band selection and channel allocation. And the final stable solution of channel allocation can infinitely approach the globally optimal utility value by adjusting parameter settings and the number of iteration.

Since the computational complexities of Algorithm 1 and Algorithm 2 are $\mathcal{O}(KN_sC_k)$ and $\mathcal{O}(SN_sD_s)$, the computational complexities of Algorithm 3 is $\mathcal{O}(\max(KN_sC_k, SN_sD_s))$.

IV. PERFORMANCE EVALUATION

A. PARAMETERS

In order to illustrate the performances of the proposed two-stage distributed channel allocation algorithm in solving the spectrum selection and channel sharing problem for D2D-assisted small cell networks with heterogeneous spectrum, numerical simulations are conducted. Firstly, the system throughput and network utility of the proposed algorithm are compared and analyzed. In addition, the impact of D2D communication and the efficiency of potential game and coalition game are also analyzed. We also evaluate the system performance with different spectrum bands and service satisfaction. The simulation scenario is a multi-cell scenario supporting multi-spectrum communication, in which SUEs and D2D users are randomly distributed in each cell. The path loss model and shadow fading in wireless communication are also considered. Other simulation parameters are given in Table 2.

TABLE 2. Simulation parameters.

Parameters	Value
Number of SBSs	25
Number of SUEs	$[50:500]$
Number of D2D users	$[50:500]$
Number of Bands	$K=3$
Number of subchannels	20
Subchannel bandwidth	$B=0.05(MHz)$
Noise power density	$N_0=10^{-12}\,(W/Hz)$
Cell radius	$100m$
Interference distance	$350m$
Transmit power of SUE	$20dBm$
Transmit power of D2D user	$17dBm$
Interference threshold of SUE	$-90dBm$
Required data rate	$[1,1.5,2,2.5]Mb$
Learning parameter	β=20
Channel availability probability $p_{k,i}$	$[0.8,1]$
Satisfaction parameter α	0.8

B. NUMERICAL RESULTS

The proposed TDCA algorithm are compared with the coalition formation algorithm (TCFA) in [31] and the concurrent best response iterative algorithm (CBSI) in [24]. Since the specific system models in [24] and [31] are different from our system model, the algorithms compared in this paper need to be modified. In TCFA algorithm, the final channel allocation result is obtained only through the coalition formation game in each small cell, without considering the spectrum selection

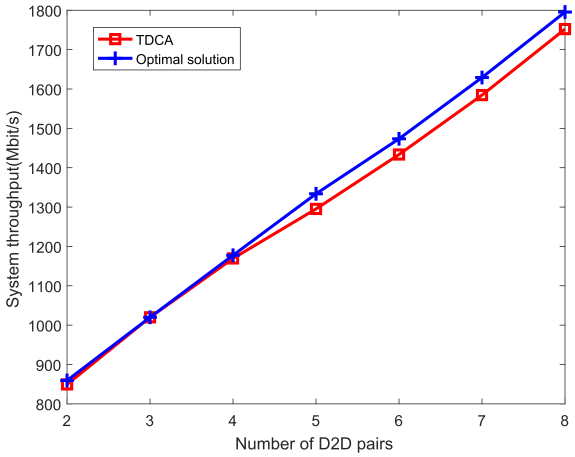

FIGURE 3. System throughput of TDCA algorithm and optimal solution versus the number of D2D pairs.

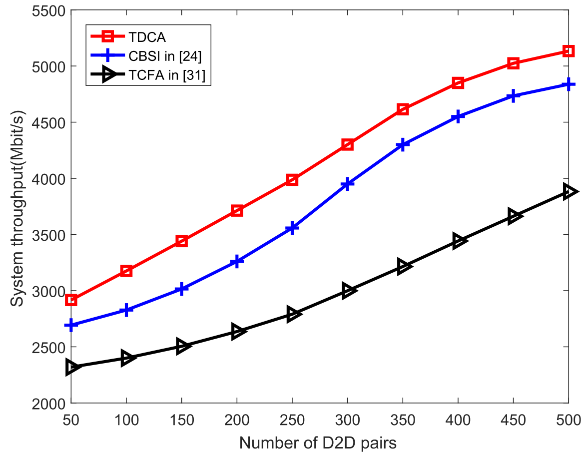

FIGURE 4. System throughput versus the number of D2D users when the number of SUEs and SBSs is 500 and 25.

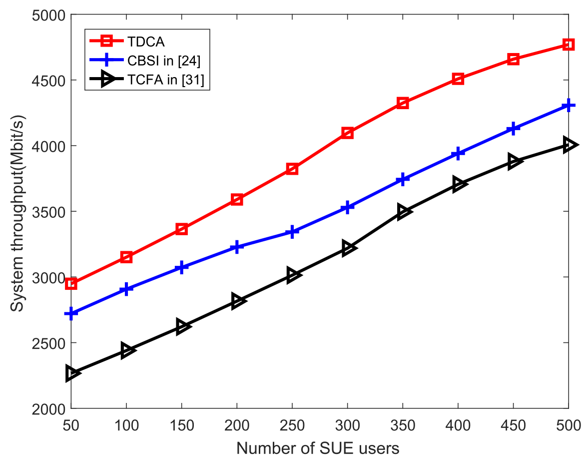

FIGURE 5. System throughput versus the number of SUEs when the number of D2D pairs and SBSs is 500 and 25.

of different small cells. In the CBSI algorithm, the frequency band selection and channel allocation are accomplished by the interference graph.

To demonstrate the proposed TDCA algorithm converges close to the system optimal solution, we compare the proposed algorithm with the exhaustive search. The result of the exhaustive search can only be obtained when the number of small cells and users is small. In the parameter setting, we set the number of SBSs, SUEs, spectrum bands, and channels to 25, 100, 3 and 4, and change the number of D2D pairs from 50 to 200. In Fig. 3, the system throughput of TDCA algorithm is almost the same as that of the optimal solution. In order to further quantitatively analyze the optimal convergence results of the proposed TDCA algorithm, the average deviation between the results of TDCA algorithm and the exhaustive algorithm is calculated, and it is defined as

$$\text{AverageDeviation} = \frac{1}{7}\sum_{z=1}^{7}\frac{R^{opti}(z) - R^{TDCA}(z)}{R^{opti}(z)}, \tag{42}$$

where $R^{opti}(z)$ and $R^{TDCA}(z)$ are defined as the system throughput of the exhaustive algorithm and TDCA algorithm, respectively, with the number of simulation processes z. When the number of D2D pairs is changed, the average deviation is about 1.57%.

Then, the performance of system throughput in the TDCA algorithm, CBSI algorithm and TCFA algorithm are compared in Fig. 4 and Fig. 5. From these two figures, we can observe that the TCFA algorithm performs the worst as expected, because it only reduces co-channel interference in each small cell through coalition formation process. And the interference among small cells is not considered, which results in the worst performance of the TCFA algorithm when multiple small cells occupied the same spectrum are close to each other. Conversely, the CBSI algorithm outperform the above TCFA approach by co-spectrum interference management among multiple small cells. The system throughput of our proposed TDCA algorithm is much better than the other two algorithms. In addition to reducing interference between different small cells through potential games, some D2D users transfer from congested channels to the uncongested channels to reduce intra-cell interference through coalition game.

To demonstrate the advantages of the proposed algorithm in improving D2D transmission performance, the percentage curves of D2D transmission rate in the total system throughput are shown in Fig. 6. The percentage curve has a decreasing trend with the increasing number of SUEs. This is obviously due to the increase of SUE users, the amount of data transmitted of SUE increases, while the amount of data transmitted by D2D users decreases accordingly. Because CBSI algorithm can not properly solve the intra-cell interference problem and TCFA algorithm neglects the inter-cell interference management, so the performance of TDCA algorithm is better than these two algorithms. With the increase of the number of SUEs, higher ratio of D2D data rate can be obtained in TDCA algorithm. This clearly demonstrates the superiority

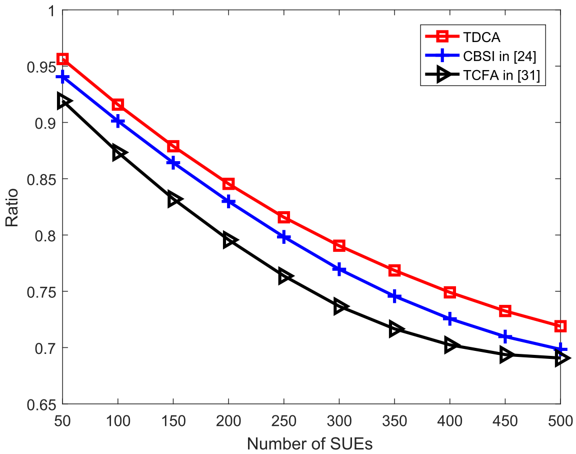

FIGURE 6. Ratio of D2D communication versus the number of SUEs when the number of D2D users and SBSs is 500 and 25.

of the proposed TDCA algorithm in channel sharing via D2D transferring.

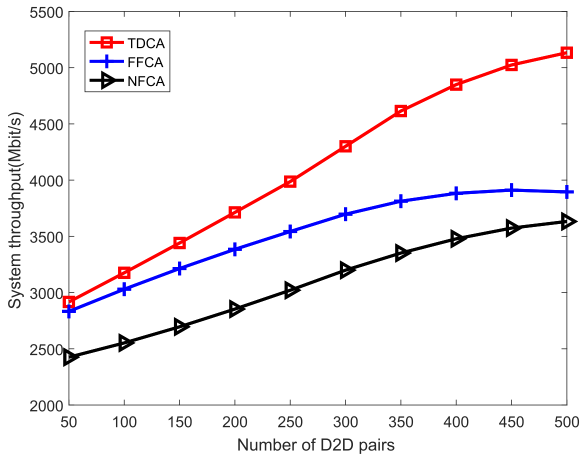

FIGURE 7. System throughput versus the number of D2D users when the number of SUEs and SBSs is 500 and 25.

The efficiency of potential game can be seen from the CBSI algorithm and TDCA algorithm in Fig. 4 and Fig.5. The proposed TDCA algorithm is also compared with the furthest first coalition algorithm (FFCA) and the nearest first coalition algorithm (NFCA) to justify the selection of the coalition formation game. In FFCA algorithm, the subchannel allocated to one SUE is shared with the D2D pairs which are the furthest to this SUE. In NFCA, the channel resource is also allocated to the D2D pairs which are nearest to the SUE occupied it. Fig. 7 illustrates the system throughput of different algorithms with the increasing number of D2D pairs. Compared with other schemes, the proposed TDCA algorithm has the best performance. Because the coalition formed of adjacent D2D users and SUE, which leads to the increased interference in each small cell, the performance of NFCA algorithm is the worst. Unlike the NFCA method, FFCA algorithm reduces unnecessary interference, so its performance is better than that of the NFCA method.

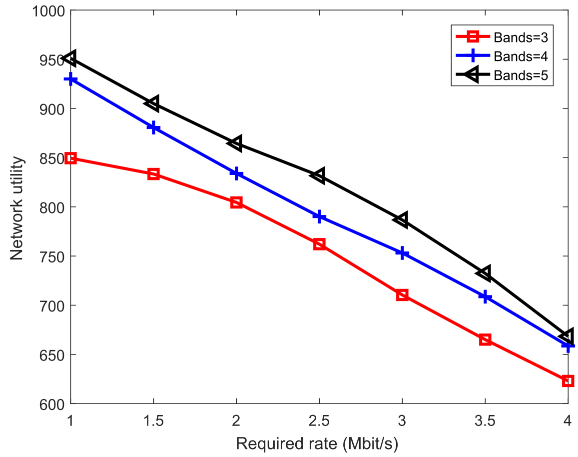

FIGURE 8. Network utility versus user requirement for different bands.

Fig. 8 shows the performance of network utility with different spectrum bands. In the simulation settings, all users have the same required transmission rate. With the increasing transmission rate requirement of SUEs and D2D pairs, the network utility value is decreasing. It can lead to higher network utility when there are more spectrum selected, which reduce the interference between small cells.

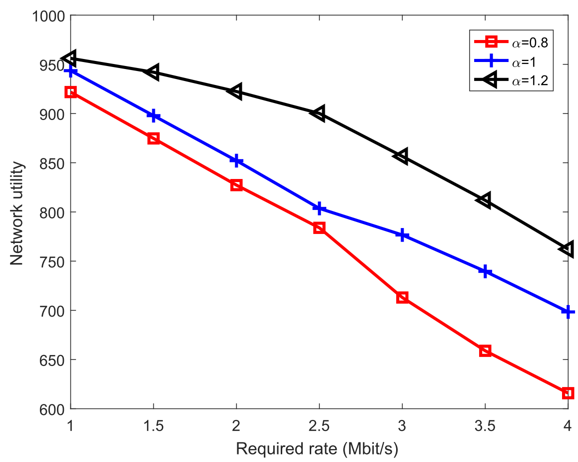

FIGURE 9. Network utility versus user requirement for different satisfaction parameter α.

The relationship between the network utility and satisfaction parameter α is evaluated in Fig. 9. We can see that the network utility decreases as the required rate of users increases. When there is a larger α, the same transmit rate can lead to greater service satisfaction, resulting in greater system utility.

V. CONCLUSION

In this paper, we have studied the channel allocation problem for downlink D2D-assisted small cell networks with heterogeneous spectrum bands. We have formulated a band selection and channel allocation problem to maximize the system utility and proposed a two-stage distributed channel allocation algorithm. And the optimization problem was reformulated into a potential game followed by a coalition game. Then, we have proposed a potential game based channel selection algorithm to obtain the final band selection and channel allocation of SUEs and a coalition-based algorithm to obtain the final coalition between D2D pairs and SUEs through D2D pairs transferring. The theoretical proofs of the Nash-stable equilibrium in these algorithms also have been proved. Finally, simulation results have demonstrated that the proposed TDCA algorithm could achieve a higher system throughput performance and a better network utility.

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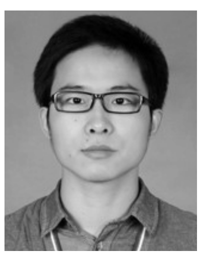

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