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Research Article

Resource Allocation for D2D Communication in Multiservice Cellular Network

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Allowing different services with different requirements to coexist is a hot topic for future communication. In order to meet the different communication requirements of users, this paper proposes a cellular communication system based on filtered orthogonal frequency division multiplexing (filtered-OFDM) supporting device-to-device (D2D) communication. Further, in order to improve the system performance, we study the user resource allocation problem in the system and propose a dynamic iterative resource allocation algorithm based on Hungarian algorithm (DRABH). The algorithm allocates resource blocks for D2D user pairs and all cellular users in the cell under the constraint of the lowest threshold of signal to interference plus noise ratio (SINR), and cellular users have high priority. Under the condition of ensuring that all cellular users can communicate, resource blocks are allocated to as many D2D user pairs as possible to maximize the number of user links in the network. Simulation results show that considering the interference introduced by filtered-OFDM and D2D communication, the proposed resource allocation scheme can significantly improve the number of user links.

1. Introduction

One of the important goals of fifth generation (5G) mobile communication and future communication is to support multiple services, such as machine communication, vehicle-to-vehicle communication, online games, industrial control, the Internet of things, etc., and different services have different system performance requirements [1–3]. Therefore, 5G proposes many candidate waveforms, including filtered orthogonal frequency division multiplexing (filtered-OFDM), universal filtered multicarrier (UFMC), filter bank multicarrier (FBMC), and generalized frequency division multiplexing (GFDM) [4]. Similarly, different users in cellular and device-to-device (D2D) communication systems will have different requirements, such as high rate, low delay, and massive connectivity. Therefore, 5G's new waveform technology can be applied to the traditional cellular D2D communication system to support different user communication scenarios.

In view of the challenges brought by the explosive growth of data faced by 5G and future communication, the communication system combining traditional cellular communication and device-to-device(D2D) communication is a good solution [5, 6]. As one of the key candidate technologies of 5G [7], D2D communication allows two user equipment within a certain distance to communicate directly without passing through the base station [8], which makes it have unique advantages in local data services and provides technical support for building a future network architecture with a higher data transmission rate, wider coverage, and better quality of service [9–11].

According to the way of using resource blocks and the form of communication between users, D2D users mainly have three communication modes [12, 13]: reuse mode, dedicated mode, and cellular mode. In the reuse mode, D2D users and cellular users use the same resource block for communication, which can improve the spectral efficiency (SE) of the system. However, when multiple users share the same resource block for communication, it will cause inter-user interference (IUI) [14, 15]. In dedicated mode, D2D users communicate using separate resource blocks. In the cellular mode, the traditional base station relay mode is used for communication between D2D users. When the communication conditions between users are poor, such as long distance or a poor channel environment, users can only communicate in cellular mode. In addition, resource allocation is an important research direction in D2D communication [16]. Many scholars have studied the resource allocation of D2D users, and their optimization objectives are to maximize SE [14, 17–20], the number of user links [21, 22], and energy efficiency [23–25].

Among many new candidate waveform technologies, filtered-OFDM technology is a better choice in terms of performance, implementation complexity, compatibility, and combination with other communication technologies [26–30]. The authors in [26] give the model diagrams of a filtered-OFDM transmitter and receiver. Filtered-OFDM divides the entire communication band into multiple subbands, and each subband reduces out-of-band attenuation and interference to adjacent subbands through filters at the transmitter and receiver and guard intervals between subbands. Flexible parameter waveform configuration is carried out in each subband to meet the demands of diversified application scenarios [31]. Each subband of filtered-OFDM still adopts a OFDM waveform, which retains the advantages of OFDM, allows the existing OFDM-based design to be quickly applied to the filtered-OFDM-based system, and realizes the backward compatibility of the new radio (NR) physical layer slice to the LTE 4G system [32, 33]. Multiservice system based on filtered-OFDM can realize enhanced mobile broadband, ultra-reliable and low-delay communication scenarios through subband filtering based on users or services [34]. However, there will be complex interference in the system [27, 35–37]. Under the condition that the parameters of each subband are consistent, work in [27] analyzes the interference in a filtered-OFDM system, and a low-complexity intra-subband interference cancellation algorithm is proposed. Work in [35] analyzes and deduces the interference existing in a filtered-OFDM system, including inter-symbol interference (ISI), inter-subcarrier interference (ICI), and inter-subband interference (ITBI) and proposes an algorithm for dynamically designing filter parameters and inter-subband guard intervals so as to improve the bit error rate performance and SE of the system. Work in [36] studies the downlink interference of an asynchronous filtered-OFDM system under different subband configurations and deduces the specific expression of interference.

In this paper, a cellular communication system based on filtered-OFDM and supporting D2D is proposed. The whole frequency band is divided into multiple service subbands to realize the multiservice system and D2D users can multiplex the uplink resources of cellular users in the system for communication to improve the SE of the system. A resource block allows multiple users to multiplex under the condition of satisfying the threshold value of signal to interference plus noise ratio (SINR). The interference introduced by D2D communication and filtered OFDM will affect the system performance. We carefully analyze the interference that users will suffer in the filtered-OFDM-based cellular and D2D communication systems and study the resource allocation problem to maximize the number of user links in the system. User link refers to the communication link established between the transmitter and the receiver that allows them to communicate. The interference that users will suffer includes ISI, ICI, IUI, and ITBI, which are shown in Figure1. Since the resource allocation and the interference of users affect each other, and since the interference of users is very complex and related to the number of users in the system, the optimization problem in this paper is NP-hard. Based on the Hungarian algorithm, we iteratively allocate resources for cellular users and D2D users.

The main contributions of this paper are mainly reflected in the following:

(i) In order to meet the different communication requirements of users in a communication system, filtered-OFDM is applied to cellular and D2D communication systems in this paper. The whole communication band is divided into multiple subbands according to different communication scenarios, and the subband parameters are set according to user requirements.

(ii) In the filtered-OFDM-based cellular and D2D communication systems, users will be subject to ICI, ISI, IUI, and ITBI. We propose a resource allocation problem to maximize the number of user links in the system which is limited by the user SINR threshold and the number of resource blocks used by users.

(iii) Considering that the interference for users is very complex, the optimization goal is NP-hard. This paper proposes a dynamic iterative resource allocation algorithm based on the Hungarian algorithm (DRABH) to resolve the resource allocation problem, which allocates resource blocks for cellular users and D2D users in the cell and improves the user links of the system.

The structure of the paper is as follows: Section 2 describes the system model, including cellular cell model and the filtered-OFDM band division model, and gives the specific expression of interference. In Section 3, the optimization objective is given, and the resource allocation algorithm is proposed. Section 4 gives the simulation results and analyzes the simulation results. Section 5 is the summary of this paper.

2. System Model and Problem Formulation

2.1. System Model. As shown in Figure 2, there is a base station located in the cell center and a plurality of uniformly and independently distributed users in the single-cell cellular network. The filtered-OFDM-based cellular network can support a variety of communication scenarios. For ease of description, take two 5G communication scenarios as

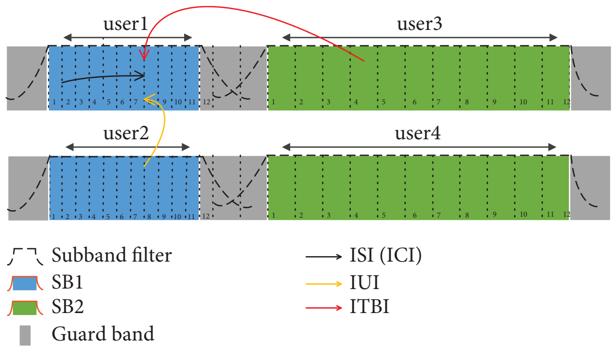

FIGURE 1: Schematic diagram of interference.

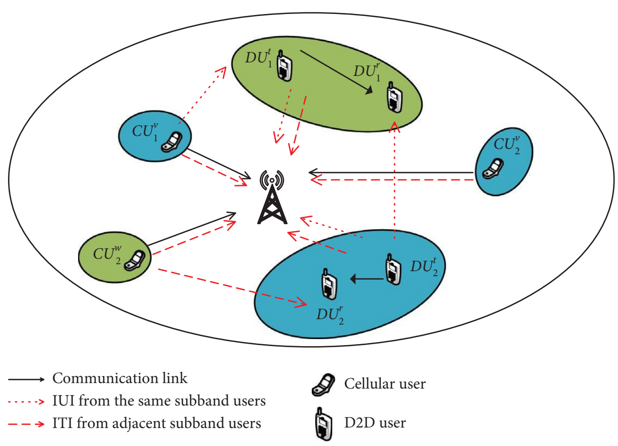

FIGURE 2: D2D communication underlaying filtered-OFDM-based cellular network.

examples, which are massive machine-type communication and ultra-reliable and low-latency communication. The whole communication frequency band is divided into two subbands, subband 1 (SB1) and subband 2 (SB2), as shown in Figure 3. The massive machine-type communication scenario supports a large amount of delay-insensitive user equipment for communication, so the frequency-domain subcarrier interval setting is relatively narrow. The ultra-reliable and low latency communication is for the communication of delay sensitive users, which requires relatively short symbol durations, while the frequency-domain subcarrier interval setting is relatively wide [34]. The frequency band resources of SB1 and SB2 are divided into subcarriers with different intervals. One resource block [38] contains 12 subcarriers in the frequency domain. The base station allocates resource blocks of two subbands to users according to their needs and controls the communication of all users in the cell. There are K resource blocks in the system, represented by set $\mathscr{K}$, in which the number of resource blocks of SB1 and SB2 are K_1 and K_2, respectively.

There are N cellular users and M D2D user pairs in the cell. Corresponding to the two communication scenarios, there are two types of cellular users in the system, delay insensitive cellular users and delay sensitive users. The number of delay-insensitive cellular users and delay-sensitive cellular users is C_1 and C_2, respectively. $u_i^\delta \in \mathscr{C}_\delta, i = \{1, 2, \ldots, C_\delta\}$, where u_i^δ represents the user

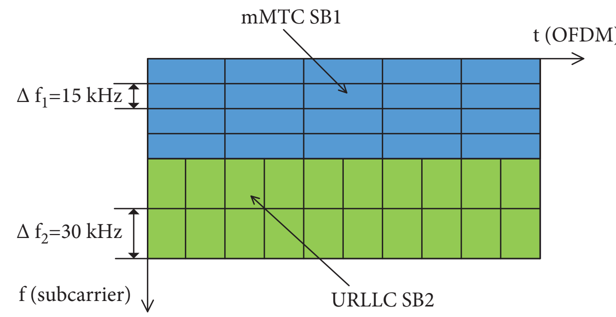

FIGURE 3: Schematic diagram of frequency band division.

numbered i in subband δ and $\mathscr{C}_\delta$ represents the set of all cellular users of subband δ. When δ equals to 1, it represents SB1, and when δ equals to 2, it represents SB2. The set of all cellular users is $\mathscr{C}$, $\mathscr{C} = \mathscr{C}_1 \cup \mathscr{C}_2$, and $N = C_1 + C_2$. Set $\mathscr{D}$ represents the set of M D2D user pairs, $\mathscr{D} = \{(DU_1^t, DU_1^r), \ldots, (DU_j^t, DU_j^r), \ldots, (DU_M^t, DU_M^t)\}$, and each D2D user pair comprises a transmitter and a receiver. Both cellular users and D2D user pairs have the requirements of minimum SINR. For each cellular user, there is at least one resource block to meet the communication demand when there is no D2D user. D2D user pairs can share the uplink resource blocks of cellular users, and idle uplink resource blocks can only be used by D2D user pairs.

For the i th user u_i on the resource block k, the channel from the transmitter t (cellular user or the transmitter of the D2D user pair) to the receiver r (base station or the receiver of the D2D user pair) is modeled as follows:

$$h_i^k = \beta d_{t,r}^{-\alpha}, \tag{1}$$

where β is the shadow fading gain in the channel, and α is the path loss index, and $d_{t,r}$ is the distance from the transmitter to the receiver [38].

2.2. Interference. For the interference of users in filtered-OFDM-based system, many literature have given a complete and detailed analysis and derivation [35, 36]. The frequency-domain symbol of u_i on subband δ can be expressed as follows:

$$\mathbf{S}_{i,N_\delta} = \left[0, \ldots, 0, S_{i,N_\delta}(m_{\text{low}}), \ldots, S_{i,N_\delta}(m_{\text{up}}), 0, \ldots, 0\right], \tag{2}$$

where N_δ represents the Fourier transform length of the subband δ. $S_{i,N_\delta}(m)$ represents the signal of u_i on subcarrier m, and m_{low}, and m_{up} represent the lower and higher subcarrier index of u_i. The corresponding time-domain signal can be denoted as follows:

$$s_{i,N_\delta}(n) = \frac{1}{N_\delta} \sum_{n=0}^{N_\delta - 1} S_{i,N_\delta}(m) e^{j2\pi mn/N_\delta}. \tag{3}$$

The subband receiver filter $f_r^\delta(n)$ is a matched filter of the transmitter filter $f_t^\delta(n)$. The subband transmitter filter and subband receiver filter are regarded as equivalent filters $f_e^\delta(n)$.

$$
\begin{aligned}
f_t^{\delta}(n) &= \left(f_r^{\delta}(-n)\right)^*,\\
f_e^{\delta}(n) &= f_t^{\delta}(n) \otimes f_r^{\delta}(n),\\
F_{e,N_\delta}^{\delta}(m) &= \sum_{n=0}^{N_\delta-1} f_e^{\delta}(n) e^{-j2\pi mn/N_\delta},\\
f_e^{\delta,\overline{\delta}}(n) &= f_t^{\delta}(n) \otimes f_r^{\overline{\delta}}(n),\\
F_{e,N_\delta}^{\delta,\overline{\delta}}(m) &= \sum_{n=0}^{N_\delta-1} f_e^{\delta,\overline{\delta}}(n) e^{-j2\pi mn/N_\delta},
\end{aligned}
\tag{4}
$$

where $(\cdot)^*$ represents complex conjugate and $\otimes$ represents convolution. $f_e^{\delta,\overline{\delta}}(n)$ represents the equivalent filter composed of the transmitter filter of subband δ and the receiver filter of its adjacent subband $\overline{\delta}$.

$$
\begin{aligned}
H_{i,N_\delta}(m) &= \sum_{n=0}^{N_\delta-1} h_i(n) e^{-j2\pi mn/N_\delta},\\
H_{ei,N_\delta}(m) &= F_{e,N_\delta}^{\delta}(m) H_{i,N_\delta}(m),\\
L_{ehi} &= L_{hi} + L_{ft} + L_{fr} - 2,
\end{aligned}
\tag{5}
$$

where h_i represents the channel that u_i communicates with the receiver on the resource block allocated to it. L_{hi}, L_{ft}, and L_{fr} represent the length of channel, transmitter filter, and receiver filter, respectively. The filter and channel are regarded as equivalent channels, and the equivalent channel length from transmitter to receiver of u_i is L_{ehi}.

Since the length of the subband filter is usually half of the time-domain OFDM symbol, which is longer than the cyclic prefix of the symbol, users will be affected by multipath interference. Moreover, the subcarriers between adjacent subbands are not orthogonal. Although the filter can reduce the out-of-band attenuation of subband signals due to the tailing phenomenon of the filter, the subbands cannot be completely isolated. In terms of SE, a large protection interval cannot be set between adjacent subbands, and thus users of different subbands still have interference.

As shown in Figure 1, in the filtered-OFDM-based cellular network D2D communication system, the interference suffered by users is relatively complex. Taking the subcarrier numbered 8 of user 1 in SB1 as an example, its receiver will be subject to the following four types of interference when receiving signals.

(i) ICI: interference from the symbol itself owing to the use of filters.

(ii) ISI: interference from symbols before and after the current symbol.

(iii) IUI: interference from other users who use the same resource block as the user.

(iv) ITBI: interference from users on adjacent subbands.

According to the interference analysis method provided by [36], the interference analysis of the system proposed in this paper is carried out. In order to facilitate interference analysis and calculation, take $N_{\delta'} \geq N_\delta + L_{ehi} - 1$ and fill the end of user time-domain signal $s_{i,N_\delta}(n)$, time-domain filter $f_t(n)$, $f_r(n)$, and time-domain channel $h_i(n)$ with zero to $N_{\delta'}$ and perform fast Fourier transform (FFT) with length $N_{\delta'}$ to obtain $S_{i,N_{\delta'}}(m')$, $F_{t,N_{\delta'}}(m')$, $F_{r,N_{\delta'}}(m')$, and $H_{i,N_{\delta'}}(m')$. In this way, the time-domain linear convolution operation of signal, filter, and channel is the same as that of cyclic convolution operation, resulting in point multiplication of frequency-domain signal, filter and channel with length $N_{\delta'}$. $S'_{q,N_\delta}(m')$ represents the frequency-domain signal obtained by zeroing and FFT of the user's q th symbol with cyclic prefix.

Taking the user u_i of subband δ as the analysis target, the interference is analyzed in frequency domain. ICI, ISI, and IUI are collectively referred to as inner-subband interference (INBI). In the communication systems in which cellular communication and D2D communication based on filtered-OFDM coexist, the interference $I_i(m)$ received by the receiver of u_i includes two types of interference, and it can be expressed as follows:

$$
\begin{aligned}
I_i(m) &= I_{i,\mathrm{INBI}}(m) + I_{i,\mathrm{ITBI}}(m)\\
&= I_{i,\mathrm{SI}}(m) + I_{i,\mathrm{IUI}}(m) + I_{i,\mathrm{ITBI}}(m).
\end{aligned}
\tag{6}
$$

The first type is INBI. There are two reasons for intra-subband interference. On the one hand, the group delay $L_{fd,\delta}$ of subband δ filter is usually half of the OFDM symbol duration [26], which is longer than the duration of the cyclic prefix. The transmitter sends continuous OFDM symbols to the receiver. Then, due to the group delay characteristics of the filter, when the receiver receives the q th OFDM symbol sent by the transmitter, it will be subject to the interference $I_{i,\mathrm{SI}}(m)$ from itself, including the interference $\mathrm{ICI}_i^{q,pre}(m)$ and $\mathrm{ICI}_i^{q,\mathrm{post}}(m)$ where the superscript q represents the number of the disturbed symbol, pre and post represent the first half and second half of the q th symbol causing interference, and the subscript i represents the user number, and the interference $\mathrm{ISI}_i^{q,q-1}(m)$ from the $(q-1)$ th OFDM symbol and the interference $\mathrm{ISI}_i^{q,q+1}(m)$ from the $(q+1)$ th OFDM symbol; that is, the inter symbol interference are marked by the black arrow in Figure 1.

$$
\begin{aligned}
I_{i,\mathrm{SI}}(m) = {} & \mathrm{ISI}_i^{q,q-1}(m) + \mathrm{ISI}_i^{q,q+1}(m) - \mathrm{ICI}_i^{q,\mathrm{pre}}(m)\\
& - \mathrm{ICI}_i^{q,\mathrm{post}}(m).
\end{aligned}
\tag{7}
$$

The derivation idea of all interferences is the same. Taking $\mathrm{ISI}_i^{q,q-1}(m)$ as an example,

$$\mathrm{ISI}_i^{q,q-1}(m) = \sum_{n=0}^{L_i^{q,q-1}} r_i^{q,q-1}(n) e^{-j2\pi mn/N_\delta} e^{-j2\pi m\left(n+L_{fd,\delta}\right)/N_\delta}, \tag{8}$$

$$r_i^{q,q-1}(n) = \frac{1}{N_{\delta'}} \sum_{m'=0}^{N_{\delta'}-1} \left(\left(S_{q-1,N_{\delta'}}(m') F_{t,N_{\delta'}}(m')\right) H_{i,N_{\delta'}}(m') F_{r,N_{\delta'}}(m') \right) e^{j2\pi m'\left(n+L_{q,q-1}\right)/N_{\delta'}}. \tag{9}$$

$r_i^{q,q-1}$ represents the time-domain interference of the $(q-1)$ th symbol received by the user i when receiving the q th symbol, and the frequency-domain interference is obtained through the Fourier transform. The components of other interference expressions are shown in Table 1. The expression in parentheses is the $(q-1)$ th time-domain symbol received by the receiver of u_i after passing through the transceiver filter and channel, with the length of N'_δ. By translating the $(q-1)$ th symbol, the time-domain interference signal caused by it to the q th symbol is obtained, and $L_{q,q-1}$ represents the length of translation to the left, that is, time-domain shift. Then, the time-domain interference signal is transformed by FFT with length N_δ to obtain the frequency-domain interference of the $(q-1)$ th symbol to the q th symbol, where n represents the index of time-domain interference symbol, with the value range from 0 to $L_i^{q,q-1}$.

On the other hand, multiple users are allowed to communicate on one resource block, so the signals sent by other users using the same resource block as u_i will cause interference to the receiver of u_i; that is, the IUI marked by the orange arrow in Figure 1. Considering that u_j and u_i use the same resource block, in addition to the filter and OFDM symbol duration, IUI is also related to the time difference between the signals sent by u_i and u_j received by the receiver of u_i. For convenience of description, it is considered that the receiver of u_i receives the q th useful symbol at the same time as the q^* th symbol sent by u_j. The receiver of u_i will be subject to the interference $\mathrm{IUI}_{i,j}^{q,q^*-1}(m)$, $\mathrm{IUI}_{i,j}^{q,q^*}(m)$, and $\mathrm{IUI}_{i,j}^{q,q^*+1}(m)$ of the corresponding symbol of u_j, where the superscript represents the symbol number, and the subscript represents the user number, that is, the q th symbol of the i th user and the (q^*-1) th, q^* th and (q^*+1) th symbols of the j th user, respectively, as well as the interference from the CP of the corresponding symbol. Take $N_{\delta'} \geq N_\delta + L_{ehij} - 1$,

$$I_{\mathrm{IUI}_{i,j}}(m) = \mathrm{IUI}_{i,j}^{q,q^*-1}(m) + \mathrm{IUI}_{i,j}^{q,CPq^*}(m) + \mathrm{IUI}_{i,j}^{q,q^*}(m) + \mathrm{IUI}_{i,j}^{q,CPq^*+1}(m) + \mathrm{IUI}_{i,j}^{q,q^*+1}(m). \tag{10}$$

The second type is the ITBI marked by the red arrow in Figure 1. Due to the different subband parameters and the existence of a protection interval between subbands, the subcarriers of different subbands are no longer orthogonal. Filtered-OFDM reduces ITBI by transmitter and receiver filters and inter-subband guard interval. Considering the frequency band utilization, the protection interval should not be too large. Although the filter can suppress the out-of-band attenuation of subband signals to a great extent, the tailing phenomenon of the filter still causes interference between subbands, and the receiver of u_i of subband δ will be interfered by u_j of adjacent subband $\overline{\delta}$. In addition to the filter properties, OFDM symbol duration and asynchronous relative time difference between interference signal and useful signal, the different OFDM symbol duration of different subband users will also affect the ITBI. Similarly, for ease of description, it is assumed that the duration of the two subband symbols is the same, and the receiver of u_i receives the q th symbol transmitted by u_i at the same time as the $q\prime$ th symbol transmitted by u_j. If the symbol duration of the subband becomes shorter and other conditions remain unchanged, u_i will be disturbed by more symbols of u_j. Take $N_{\delta,\overline{\delta}} \geq N_{\overline{\delta}} + L_{ehij} - 1$,

$$I_{i,\mathrm{ITBI}}(m) = \mathrm{ITBI}_{i,j}^{q,q'-1}(m) + \mathrm{ITBI}_{i,j}^{q,CPq'}(m) + \mathrm{ITBI}_{i,j}^{q,q'}(m) + \mathrm{ITBI}_{i,j}^{q,CPq'+1}(m) + \mathrm{ITBI}_{i,j}^{q,q'+1}(m). \tag{11}$$

From the perspective of frequency domain, the SINR of cellular user u_i communicating on the k th resource block can be denoted as [36].

$$\gamma_i^k = x_i^k \cdot \frac{E\left[S_{i,N_\delta}(m) H_{ei,N_\delta}(m) \left(S_{i,N_\delta}(m) H_{ei,N_\delta}(m)\right)^*\right]}{E\left[\left(I_i^k(m) + Z_i^k(m)\right)\left(I_i^k(m) + Z_i^k(m)\right)^*\right]}, \tag{12}$$

where x_i^k is the resource block use indicator of the cellular user. When $x_i^k = 1$, it means that the cellular user i uses the resource block k to communicate with the base station, otherwise, the value of x_i^k is 0. $I_i^k(m)$ represents the frequency-domain interference suffered by u_i on the resource block numbered k. The interference of u_i mainly comes from itself, users using the same resource block as u_i and users using the resource blocks of its adjacent subbands.

Table 1: Values of each part in interference expression [36].

Interference type	Frequency-domain interference symbol	Time-domain shift	Index range of time-domain interference symbols
$\mathrm{ISI}_i^{q,q-1}(m)$	$S_{q-1,N_{\delta'}}(m')F^{\delta}_{e,N'_{\delta}}(m')H_{i,N_{\delta'}}(m')$	$L_{q,q-1} = N_{\delta} + L_{CPi} + L_{fd,\delta}$	$[0, L_i^{q,q-1}],\ L_i^{q,q-1} = L_{ehi} - L_{CPi} - L_{fd,\delta} - 2$
$\mathrm{ISI}_i^{q,q+1}(m)$	$S_{q+1,N'_{\delta}}{}'(m')F^{\delta}_{e,N'_{\delta}}(m')H_{i,N_{\delta'}}(m')$	$L_{q,q+1} = L_{fd,\delta} - N_{\delta}$	$[L_i^{q,q+1}, N_{\delta} - 1],\ L_i^{q,q+1} = N_{\delta} - L_{fd,\delta}$
$\mathrm{ICI}_i^{q,\mathrm{pre}}(m)$	$S_{q,N_{\delta'}}{}'(m')F^{\delta}_{e,N'_{\delta}}(m')H_{i,N_{\delta'}}(m')$	$L_{q,pre} = N_{\delta} + L_{CPi} + L_{fd,\delta}$	$[0, L_i^{q,\mathrm{pre}}],\ L_i^{q,\mathrm{pre}} = L_{ehi} - L_{CPi} - L_{fd,\delta} - 2$
$\mathrm{ICI}_i^{q,\mathrm{post}}(m)$	$S_{q,N_{\delta'}}(m')F^{\delta}_{e,N'_{\delta}}(m')H_{i,N_{\delta'}}(m')$	$L_{q,post} = L_{fd,\delta} - N_{\delta}$	$[L_i^{q,\mathrm{post}}, N_{\delta} - 1]L_i^{q,\mathrm{post}} = N_{\delta} - L_{fd,\delta}$
$\mathrm{IUI}_{i,j}^{q,q^*-1}(m)$	$S_{q^*-1,N_{\delta'}}(m')F^{\delta}_{e,N'_{\delta}}(m')H_{ji,N_{\delta'}}(m')$	$L_{q,q^*-1} = N_{\delta} + L_{CPi} + L_{fd,\delta}$	$[0, L_i^{q,q^*-1}],\ L_i^{q,q^*-1} = L_{ehij} - L_{CPi} - L_{fd,\delta} - 2$
$\mathrm{IUI}_{i,j}^{q,CPq^*}(m)$	$S_{CPq^*,N_{\delta'}}(m')F^{\delta}_{e,N'_{\delta}}(m')H_{ji,N_{\delta'}}(m')$	$L_{q,CPq^*} = L_{CPi} + L_{fd,\delta}$	$[0, L_{i,j}^{q,CPq^*}],\ L_{i,j}^{q,CPq^*} = L_{ehij} + L_{CPj} - L_{CPi} - L_{fd,\delta} - 2$
$\mathrm{IUI}_{i,j}^{q,q^*}(m)$	$S_{q^*,N'_d}(m')F^{d}_{e,N'_d}(m')H_{ji,N'_d}(m')$	$L_{q,q^*} = L_{fd,\delta}$	$[0, L_{i,j}^{q,q^*}]L_{i,j}^{q,q^*} = N_{\delta}$
$\mathrm{IUI}_{i,j}^{q,CPq^*+1}(m)$	$S_{CPq^*+1,N_{\delta'}}(m')F^{\delta}_{e,N'_{\delta}}(m')H_{ji,N_{\delta'}}(m')$	$L_{q,CPq^*+1} = L_{fd,\delta} - N_{\delta}$	$[0, L_{i,j}^{q,CPq^*+1}]L_{i,j}^{q,CPq^*+1} = N_{\delta} - L_{fd,\delta}$
$\mathrm{IUI}_{i,j}^{q,q^*+1}(m)$	$S_{q^*+1,N_{\delta'}}(m')F^{\delta}_{e,N'_{\delta}}(m')H_{ji,N_{\delta'}}(m')$	$L_{q,q^*+1} = L_{fd,\delta} - N_{\delta} - L_{CPj}$	$[L_{i,j}^{q,q^*+1}, N_{\delta}]L_{i,j}^{q,q^*+1} = N_{\delta} - L_{fd,\delta} + L_{CPj}$
$\mathrm{ITI}_{i,j}^{q,q'-1}(m)$	$S_{q\prime-1,N_{\delta\bar{\delta}}}(m')F^{\delta,\bar{\delta}}_{e,N_{\delta\bar{\delta}}}(m')H_{ji,N_{\delta\bar{\delta}}}(m')$	$L_{q,q\prime-1} = N_{\delta} + L_{CPi} + L_{fd,\delta}$	$[0, L_i^{q,q'-1}],\ L_i^{q,q'-1} = L_{ehij} - L_{CPi} - L_{fd,\delta} - 2$
$\mathrm{ITBI}_{i,j}^{q,CP\acute{q}}(m)$	$S_{CPq\prime,N_{\delta\bar{\delta}}}(m')F^{\delta,\bar{\delta}}_{e,N_{\delta\bar{\delta}}}(m')H_{ji,N_{\delta\bar{\delta}}}(m')$	$L_{q,CPq\prime} = L_{CPi} + L_{fd,\delta}$	$[0, L_{i,j}^{q,CP\acute{q}}],\ L_{i,j}^{q,CP\acute{q}} = L_{ehij} + L_{CPj} - L_{CPi} - L_{fd,\delta} - 2$
$\mathrm{ITBI}_{i,j}^{q,\acute{q}}(m)$	$S_{q\prime,N_{\delta\bar{\delta}}}(m')F^{\delta,\bar{\delta}}_{e,N_{\delta\bar{\delta}}}(m')H_{ji,N_{\delta\bar{\delta}}}(m')$	$L_{q,q\prime} = L_{fd,\delta}$	$[0, L_{i,j}^{q,\acute{q}}]L_{i,j}^{q,\acute{q}} = N_{\delta}$
$\mathrm{ITBI}_{i,j}^{q,CPq'+1}(m)$	$S_{CPq\prime+1,N_{\delta\bar{\delta}}}(m')F^{\delta,\bar{\delta}}_{e,N_{\delta\bar{\delta}}}(m')H_{ji,N_{\delta\bar{\delta}}}(m')$	$L_{q,CPq\prime+1} = L_{fd,\delta} - N_{\delta}$	$[0, L_{i,j}^{q,CPq'+1}]L_{i,j}^{q,CPq'+1} = N_{\delta} - L_{fd,\delta}$
$\mathrm{ITBI}_{i,j}^{q,q'+1}(m)$	$S_{q\prime+1,N_{\delta\bar{\delta}}}(m')F^{\delta,\bar{\delta}}_{e,N_{\delta\bar{\delta}}}(m')H_{ji,N_{\delta\bar{\delta}}}(m')$	$L_{q,q\prime+1} = L_{fd,\delta} - N_{\delta} - L_{CPj}$	$[L_{i,j}^{q,q'+1}, N_{\delta}L_{i,j}^{q,q'+1} = N_{\delta} - L_{fd,\delta} + L_{CPj}]$

Therefore, the result of user and resource block allocation will affect the interference of u_i, and the different values of x_i^k and y_j^k will affect the value of $I_i^k(m)$. $Z_i^k(m)$ is the frequency-domain noise on the resource block k.Similarly, the SINR of D2D users can also be derived.

2.3. Problem Formulation. Compared with D2D user pairs, cellular users in the cell have a high priority. Communication between D2D user pairs can only be carried out when D2D user pairs meet the requirements of minimum SINR and the interference to cellular users will not make the communication rate of cellular users less than the given threshold. Given the transmission power of cellular user and D2D user, the minimum communication rate thresholds of cellular user and D2D user pair are expressed in $r_{\min^c}$ and $r_{\min^d}$, respectively, which are obtained according to the minimum SINR. The objective function of maximizing the number of user links in the cell can be expressed as follows:

$$\begin{aligned}
&\max_{y_j^k} \sum_{k=1}^{K} \sum_{j=1}^{M} y_j^k, \\
\text{s.t.} &\sum_{k=1}^{K_\delta} x_i^k \log_2\left(1+\gamma_i^k\right) \geq r_{\min^c}, \quad i \in [1, C_\delta], \\
&\sum_{k=1}^{K_\delta} x_i^k = 1, \quad i \in [1, C_\delta], \\
&x_i^k \in \{0,1\}, \quad i \in [1, N], k \in [1, K], \\
&\sum_{i=1}^{N} x_i^k \leq 1, \quad k \in [1, K], \\
&\log_2\left(1+\gamma_j^k\right) \geq r_{\min^d}, \quad j \in [1, M], k \in [1, K], \\
&\sum_{k=1}^{K} y_j^k \leq 1, \quad j \in [1, M], \\
&y_j^k \in \{0,1\}, j \in [1, M], k \in [1, K],
\end{aligned} \tag{13}$$

the relationship between the D2D user pair and the resource block is represented by y_j^k. If $y_j^k = 1$, D2D user pair j uses the resource block k for communication, otherwise, $y_j^k = 0$. Due to the interference between D2D users and cellular users, the value of the resource block use indicator y_j^k of D2D users will be affected by the resource block use indicator x_i^k of cellular users. At the same time, the value of y_j^k will also affect the SINR γ_i^k of cellular users, which may affect the allocation between cellular users and resource blocks. Therefore, the allocation of D2D user pairs and resource blocks must meet the constraints (13b)–(13e). Constraint (13b) is the minimum communication rate constraint for cellular users. Constraint (13c) means that each cellular user occupies one resource block. Constraint (13d) gives the value range of the cell user resource use indicator x_i^k, which is 1 or 0. Constraint (13e) points out that different cellular users cannot use the same resource block. u_j represents the D2D user pair numbered j in the set $\mathcal{D}$, and the constraint (13f) guarantees that if the resource block k is used by the D2D user pair u_j, the communication rate of u_j on the resource block k shall meet the minimum communication rate demand. Constraint (13g) states that each D2D user pair uses at most one resource block. Constraint (13h) represents the value range of the resource use indicator y_j^k of the D2D user pairs.

Due to the interference between adjacent subband users and the interference between users using the same resource block, the optimization problem is a nonlinear constrained optimization problem, which is difficult to solve directly [39].

3. Resource Allocation

In this section, by transforming the resource allocation process into a bipartite graph matching problem, the DRABH algorithm is proposed. The Hungarian algorithm [40] is a classical algorithm to solve the minimum weight matching of a bipartite graph. The DRABH algorithm solves the matching problem between users and resource blocks through the Hungarian algorithm to allocate communication resources for cellular users and D2D users in the cell. By minimizing interference to the users as much as possible, the number of user links in the cell is significantly increased.

The process of allocating resource blocks to users is regarded as a weighted bipartite graph matching problem. The two groups of vertices in the bipartite graph are resource blocks and users without resource blocks. When the user numbered i can communicate with the resource block numbered k, there is an edge with weight between the user i and the resource block k. To describe the weights between users and resource blocks, the following definitions are made.

Definition 1. The difference between the user's actual data rate and the minimum rate required by the user is the user's data rate margin on the resource block.

Definition 2. The maximum interference that the user can withstand is the interference value received by the user when the user's communication rate is equal to the minimum communication rate. The interference margin is the difference between the maximum interference that the user can bear and the actual interference received by the user when communicating on the resource block. The interference margin of u_i on resource block k is ΔI_i^k.

Definition 3. There are two groups of users, each consisting of a sender and a receiver. When the two transmitters share a resource block to communicate with their receivers, the two groups of users will interfere with each other. If the interference between users causes either of the communication links to fail to meet the communication conditions, the two groups of users are neighbor users to each other. $\mathcal{N}_i^C$ represents the set of neighbor users of the cellular user numbered i, and $\mathcal{N}_j^D$ represents the set of neighbor users of the D2D user numbered j.

In order to accommodate more D2D user pairs in a resource block in addition to cellular users, the data rate margin of cellular users should be as large as possible when resource blocks are initially allocated to cellular users. Therefore, the weight between the cellular user and the resource block is set to the reciprocal of the data rate margin of the cellular user communicating on the resource block. The weight between the cellular user numbered i and the resource block numbered k can be denoted as follows:

$$\mathscr{W}(i,k) = \begin{cases} \dfrac{1}{\left(r_i^k - r_{\min^c}\right)}, & \text{if } r_i^k > r_{\min^c}, \\ \infty, & \text{else}, \end{cases} \tag{14}$$

when allocating a resource block to a target D2D user pair, it is necessary to consider the interference of the information sent by the target D2D sender with the users allocated to the resource blocks. On the other hand, it is also necessary to consider the interference of the user with the resource blocks allocated to the receiver of the target user. The smaller the channel gain between users, the smaller the interference between users. The larger the interference margin of the target user, the more space there is on the resource block to accommodate more users. Therefore, in order to minimize the interference between the target user and the user allocated to the resource block, the weight between the D2D user pair and the resource block is set as the ratio of the maximum channel gain between the transmitter of the D2D user pair and the receiver of the users allocated to the resource blocks to the interference margin of the target user pair on the resource block. The weight between the D2D user pair i and the resource block k can be denoted as follows:

$$\mathscr{W}(i,k) = \frac{\max h_{ij}}{\Delta I_i^k} u_j \in \frac{\mathscr{D}}{\widehat{\mathscr{U}}}, \tag{15}$$

where $\widehat{\mathscr{U}}$ represents the set of all users not allocated to the resource block, and $\mathscr{D}/\widehat{\mathscr{U}}$ means that the user in set $\widehat{\mathscr{U}}$ is removed from set $\mathscr{D}$.

The number of users in the system is more than the number of resource blocks, so users are grouped and matched with resource blocks for multiple rounds. Cellular users and D2D users are two types of principal users in the system. The result of the resource block allocation of one type will affect the performance distribution of the other type on each resource block. Therefore, the DRABH algorithm iterates the resource allocation of cellular users and D2D users until the change trend in the number of user links in the system does not rise.

In order to reduce the complexity of the algorithm, the following two aspects are optimized. On the one hand, the neighbor user set $\mathscr{N}_i^D$ of each D2D user is calculated, and the set $\mathscr{T}$ represents the user set participating in each round of allocation. When grouping D2D users, select the D2D user with the largest number of neighbor users and its neighbor users not allocated to the resource block from $\widehat{\mathscr{U}}$ to form $\mathscr{T}$. On the other hand, after the resource block has been allocated to the cellular user, the neighbor users of the cellular user can be calculated in advance, and then in the process of allocating the resource block to the target D2D user, if the target D2D user encounters the neighbor cellular user on a resource block, the weight between the D2D user and the resource block is directly set to infinity, $\mathscr{W}(i,k) = \infty$, which indicates that there is no edge between the D2D user pair and the resource block.

Since cellular users have higher priority, cellular users are a group and matched with resource blocks first. After the resource allocation process for cellular users is completed, the neighbor users of each cellular user on its own resource block are calculated. Then, D2D users are grouped, and each group is matched with the resource blocks. When each group of users matches the resource blocks, the resource blocks may have been allocated to other users. At this time, the problem caused by multiple users reusing one resource block should be considered. Before each new round of allocation, record the current allocation results with $\mathscr{P}_1$ and $\mathscr{P}_2$. Record the user set on the two subbands at the end of the current allocation process with $\mathscr{U}_1$ and $\mathscr{U}_2$,

$$\begin{aligned} \mathscr{U}_1 &= \mathscr{P}_1 \cup \mathscr{A}_1, \\ \mathscr{U}_2 &= \mathscr{P}_2 \cup \mathscr{A}_2, \end{aligned} \tag{16}$$

where $\mathscr{A}_1$ and $\mathscr{A}_2$ represent the allocation result of this round. The users assigned to the resource blocks are excluded from $\widehat{\mathscr{U}}$, $\widehat{\mathscr{U}} = \widehat{\mathscr{U}}/\mathscr{A}_1/\mathscr{A}_2$.

The premise of allocating resource blocks for D2D users is to ensure that it cannot cause serious interference that causes the inability of cellular users to communicate. Therefore, after each group of target users matches the resource blocks, it is determined whether all users in $\mathscr{U}_1$ and $\mathscr{U}_2$ meet the minimum data rate demands. If there are D2D users who do not meet the demand, it is necessary to move them back from $\mathscr{U}_1$ or $\mathscr{U}_2$ to $\widehat{\mathscr{U}}$. If the data rate of a cellular user is less than the minimum rate demand due to this allocation, the D2D user pair with the minimum SINR using the same resource block as the cellular user is eliminated. If there is no D2D user pair using the same resource block as the cellular user, the users newly allocated to the adjacent subband will be eliminated because the users allocated to the adjacent subband have caused great interference to the cellular user. Repeat the culling process until all users of the allocated resource blocks meet the performance demands. If all users are allocated to the resource blocks or the number of users that can communicate no longer increases with the allocation, the packet D2D allocation is stopped.

In order to enable as many D2D user pairs to communicate with each other as possible, each resource block should be fully utilized. Once $\widehat{\mathscr{U}}$ is not empty after multiple rounds of resource block allocation for D2D users through the Hungarian algorithm; that is, there are D2D users who are not allocated to resource blocks, try to allocate resource blocks for D2D users in $\widehat{\mathscr{U}}$ through single user resource block matching. For each D2D user pair in $\widehat{\mathscr{U}}$, match it with each resource block in the two subbands, respectively. If adding this D2D user will not cause the allocated users in SB1 and SB2 to fail to communicate, the matching is successful, otherwise the matching fails.

The processes of matching cellular users and D2D users with resource blocks are repeated iteratively. When all users are

for $u_i \in \mathscr{D}$ **do**
  for $u_j \in \mathscr{D}$ **do**
    $k \leftarrow \operatorname{argmin}_{k \in \mathscr{K}} h_{ji}$;
    if $u_i \neq u_j$ *and* $r_i^k < r_{\min^d}$ **then**
      $\mathscr{N}_i^D \leftarrow \mathscr{N}_i^D \cup \{u_j\}, \mathscr{N}_j^D \leftarrow \mathscr{N}_j^D \cup \{u_i\}$;
Initialization: $\mathscr{T} \leftarrow \mathscr{C}$, $\mathscr{W}(i,k)$, $\widehat{\mathscr{U}} \leftarrow \mathscr{C} \cup \mathscr{D}$
repeat
  Assign resource blocks to cell users through Hungarian algorithm;
  for $u_i \in \mathscr{C}$ **do**
    for $u_j \in \mathscr{D}$ **do**
      $y_j^k \leftarrow 1$;
      if $r_i^k < r_{\min^c}$ **then**
        $\mathscr{N}_i^C \leftarrow \mathscr{N}_i^C \cup \{u_j\}$;
  repeat
    $u_i \leftarrow \operatorname{argmax}_{u_i \in \widehat{\mathscr{U}}} |\mathscr{N}_i^D|, \mathscr{T} \leftarrow u_i \cup (\mathscr{N}_i^D \cap \widehat{\mathscr{U}})$;
    for $u_i \in \mathscr{T}$ **do**
      for $k \leftarrow 1$ **to** K **do**
        Calculate $\mathscr{W}(i,k)$
    Assign resource blocks to target users through Hungarian algorithm;
    repeat
      Update the interference received by each user according to equation (6);
      for $u_i \in \mathscr{U}_1$ **do**
        if $u_i \in \mathscr{D}$ *and* $r_i^k < r_{\min^d}$ **then**
          $\mathscr{U}_1 \leftarrow \mathscr{U}_1/\{u_i\}, \widehat{\mathscr{U}} \leftarrow \widehat{\mathscr{U}} \cup \{u_i\}$;
        else if $u_i \in \mathscr{C}$ *and* $r_i^k < r_{\min^c}$ **then**
          if $\mathscr{U}_1^k/\{u_i\} \in \varnothing$ **then**
            $\mathscr{U}_2 \leftarrow \mathscr{U}_2/\mathscr{A}_2, \widehat{\mathscr{U}} \leftarrow \widehat{\mathscr{U}} \cup \mathscr{A}_2$
        else
          $\mathscr{U}_1 \leftarrow \mathscr{U}_1/\{u_j\}, u_j = \arg\min_{u_j \in \mathscr{U}_1^k, j \neq i} r_j^k, \widehat{\mathscr{U}} \leftarrow \widehat{\mathscr{U}} \cup \{u_j\}$
      Do the same for $u_i \in \mathscr{U}_2$;
    until $r_i^k \geq r_{\min}, u_i \in \mathscr{U}_1 \cup \mathscr{U}_2$;
  until $|\mathscr{U}_1| + |\mathscr{U}_2| = |\mathscr{C}| + |\mathscr{D}|$ *or* $(|\mathscr{U}_1| + |\mathscr{U}_2| < |\mathscr{P}_1| + |\mathscr{P}_2|)$;
  for $i \leftarrow 1$ **to** M **do**
    if $u_i \in \widehat{\mathscr{U}}$ **then**
      for $k \leftarrow 1$ **to** K_1 **do**
        $\mathscr{U}_1 \leftarrow \mathscr{U}_1 \cup \{u_i\}, \widehat{\mathscr{U}} \leftarrow \widehat{\mathscr{U}}/\{u_i\}$;
        if *all the assigned users meet the demands of SINR* **then**
          Break;
        else
          $\mathscr{U}_1 \leftarrow \mathscr{U}_1/\{u_i\}, \widehat{\mathscr{U}} \leftarrow \widehat{\mathscr{U}} \cup \{u_i\}$;
  The matching process in SB2 is the same as that in SB1
until $(|\mathscr{U}_1| + |\mathscr{U}_2| = |\mathscr{C}| + |\mathscr{D}|)$ or no more users can communicate;

Algorithm 1: Dynamic Iterative Resource Allocation Based on Hungarian Algorithm (DRABH).

allocated to the resource block or the number of access users in the system does not increase, the final resource allocation of all users in the system is completed. Use $|\mathscr{R}|$ to represent the number of users in the collection $\mathscr{R}$ and $\mathscr{U}_\delta^k$ represents the set of all users communicating using resource block k in subband δ. Algorithm 1 gives the detailed steps of the DRABH algorithm.

4. Simulation Results

Table 2 shows the basic parameters of a filtered-OFDM system. The 5G protocol indicates that the subcarrier spacing is optional, including 15 kHz, 30 kHz, 60 kHz, 120 kHz, etc. The baseband sampling rate is related to the subcarrier interval and the FFT length, and is the product of the two. The parameter settings of filtered-OFDM refer to [36, 41]. For ease of description, two subbands are considered in this paper. The analysis method for multiple subbands is the same as that of the two subbands. In order to reduce the ITBI caused by the nonorthogonality of different subband carriers, a subband transmitter filter and a subband receiver matched filter are introduced into each subband. In this paper, the window function method is used to design the subband filter, and the window function is the Hanning window. The filter length is half of the subband symbol length. Because ITBI mainly comes from users on adjacent subbands, protection intervals are usually inserted between adjacent subbands to further reduce ITBI. The wider the protection bandwidth, the smaller the interference between adjacent subbands, but the frequency band utilization will be reduced. In the simulation, the protection bandwidth

Table 2: Filtered-OFDM parameters.

Subband	SB1		SB2
Sampling rate (MHz)		30.72	
Subband bandwidth (MHz)	7.2, 1.44, 2.16		1.44, 2.88, 4.32
Subcarrier spacing (kHz)	15		30
CP length	144		72
FFT length	2048		1024
Filter length	1024		512
Number of resource blocks per subband		4, 8, 12	

Table 3: Simulation parameters.

Parameters	Value
Cell radius	250 m
Number of cellular users	4, 8, 12
Uplink's transmit power	15 dBm
D2D's transmit power	25 dBm
Path loss exponent	4
Shadow fading	Log-normal distribution (mean: 0 dB, SD: 8 dB)
Thermal noise	−174 dBm/Hz
SINR demand of cellular users	5 dB
SINR demand of D2D users	20 dB

between two adjacent subbands is set to 45 kHz; that is, each of the two subbands contributes a subcarrier as the protection interval.

Referring to the parameter settings of D2D system in [8, 38], Table 3 shows the main simulation parameters. Cellular users and D2D user pairs are evenly and randomly distributed in a cell with a radius of 250 m, and the distance between the transmitter and the receiver of each D2D user pair is no more than 50 m.

The performance of the DRABH algorithm proposed in this paper is compared with that of the D2D resource allocation algorithm based on vertex coloring method and branch and bound method (DRBCB) algorithm which is proposed in [22] and the random allocation algorithm. By studying the existing D2D communication resource allocation algorithms, if the user self-interference and IUI are ignored, the resource allocation problem of the communication system can be solved by DRBCB. Firstly, the algorithm groups users by vertex coloring method. The interference between users in the same group is small, and the same resource blocks can be reused. Then, if there are users who are not allocated to the resource block, continue to allocate the resource block to the user through the branch and bound method. However, the DRBCB algorithm does not fully consider the interference that users may receive. When the number of users in the system increases, it will have a certain impact on the system's performance. The random allocation algorithm adopts Monte Carlo simulation. The base station randomly allocates resource blocks to all users and then eliminates users who cannot communicate according to the minimum communication rate demands of each user.

Figures 4 and 5, respectively, show the changes in the number of user links and SE with the number of D2D user pairs. (a)–(c) the three subgraphs consider that the number of cellular users and resource blocks is equal; that is, each cellular user uses a single resource block for communication, and D2D users can only reuse the resource block of cellular users for communication. The number of resource blocks in each subband is 4, 8 and 12 respectively. Subgraph (d) considers that there are 5 cellular users and 12 resource blocks in each subband, that is, the number of cellular users is less than the number of resource blocks, and there are spare resource blocks for D2D users to use alone.

It can be seen from the simulation results that as the number of resource blocks increases, the number of user links also increases. That's because the total number of users increases, and the number of resource blocks that D2D users can choose to reuse also increases. The result of resource allocation will affect the interference received by all users and further affect the number of user links and the SE of the system. The main purpose of this paper is to enable as many users as possible to communicate. Sometimes, some resource allocation results in the maximum number of user links, but the SE is not the maximum. Therefore, with the increase in the number of users in the system, the number of user links continues to increase, but the SE may fluctuate.

The performance of the DRABH algorithm is better than the DRBCB algorithm and the random allocation algorithm. In the process of resource allocation, the DRABH algorithm comprehensively considers the interference that users will

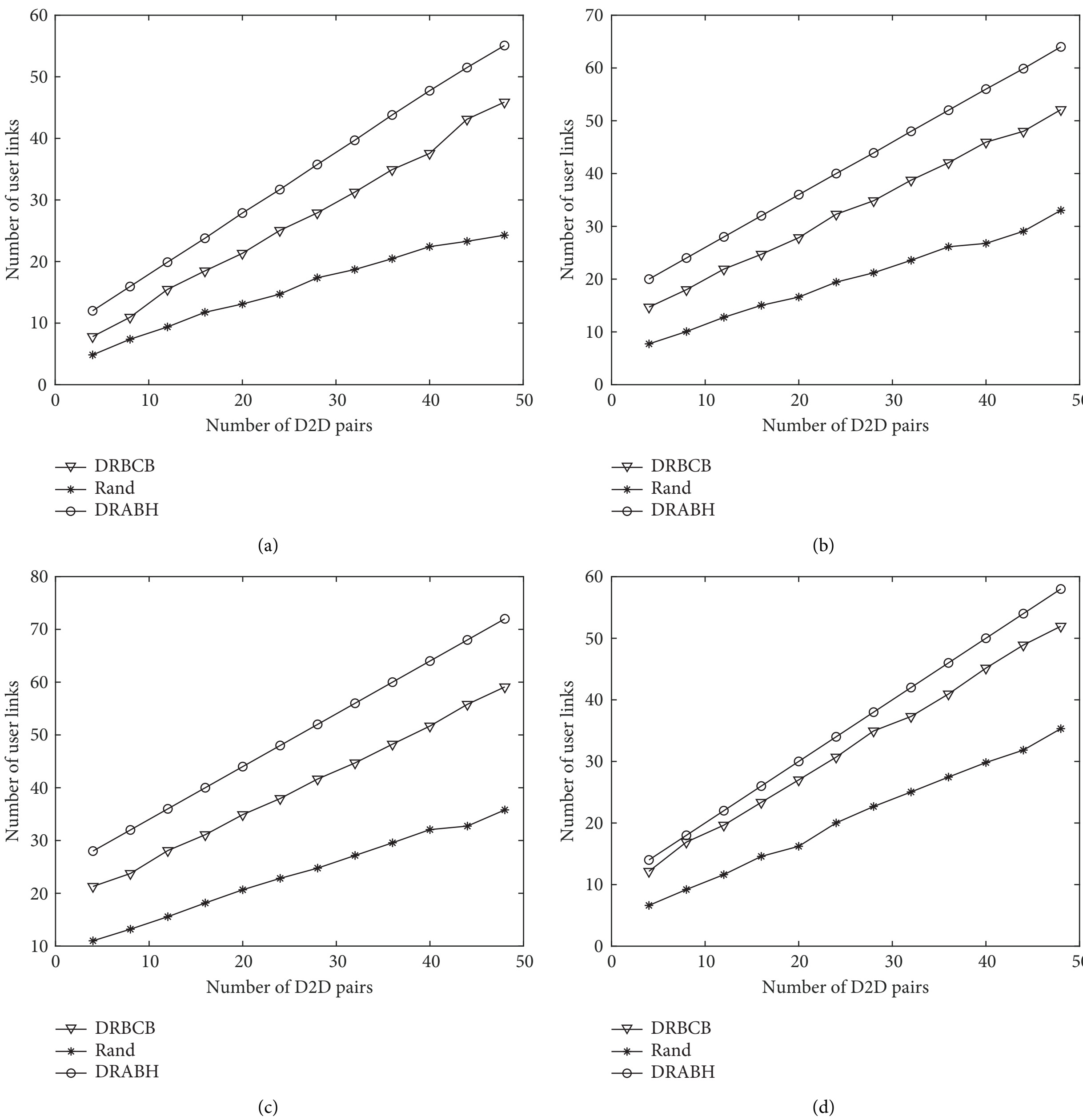

Figure 4: Number of user links under different number of D2D users.

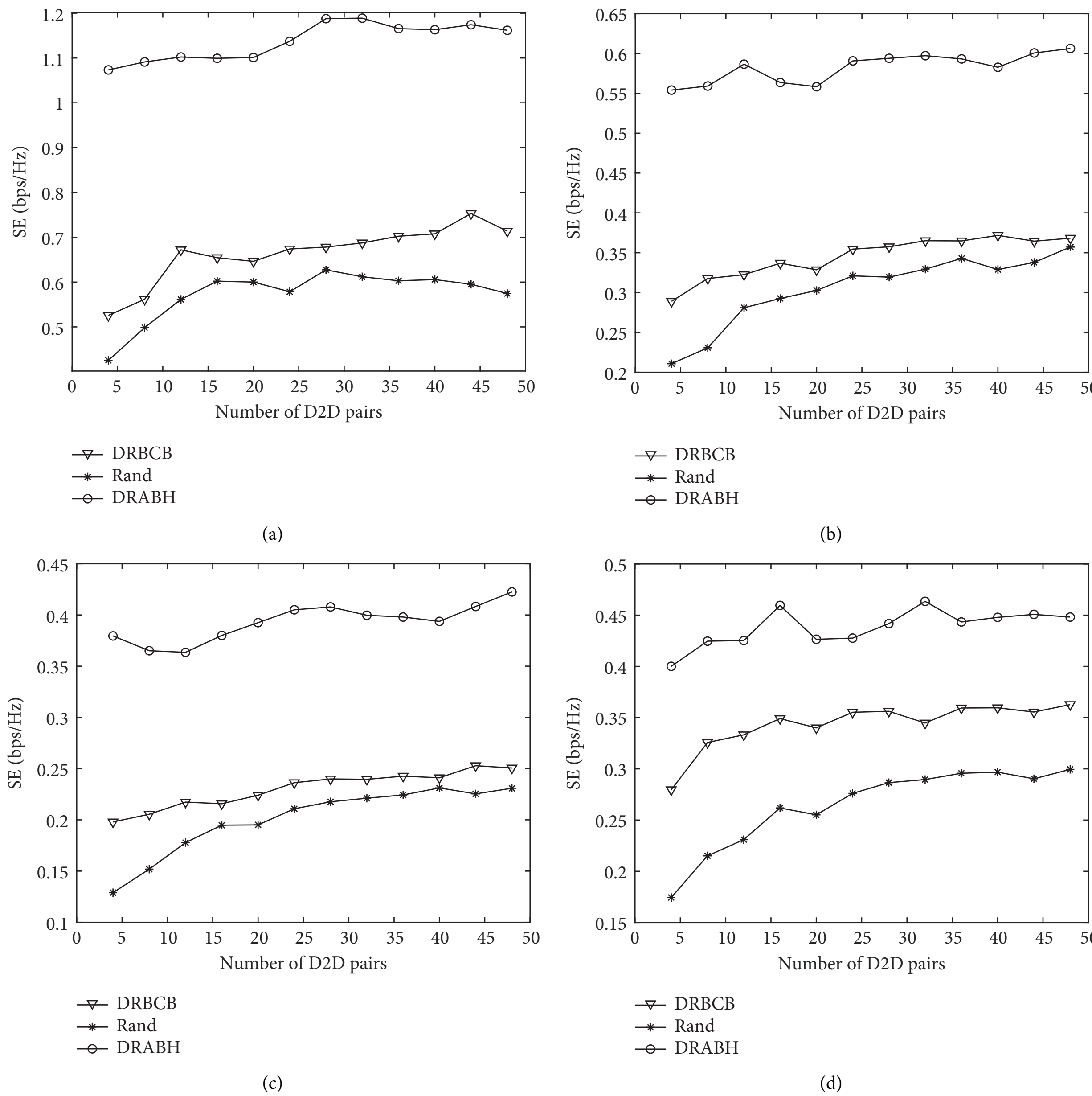

Figure 5: SE of the system under different number of D2D users.

suffer and takes it as one of the factors affecting the result of resource block allocation.

5. Conclusion

D2D communication allows users to reuse resource blocks and communicate directly with users close to each other, which can improve system performance. Many existing D2D resource allocation problems are in OFDM-based cellular cells. In order to support multiservice communication, this paper proposes a cellular communication system based on filtered-OFDM supporting D2D communication and provides different band parameter settings for different services. Based on the new system model, in order to improve the number of user links, this paper proposes the DRABH algorithm. The interference with user communication is fully considered, and communication resources are allocated to as many users as possible under the condition of ensuring the minimum communication rate. The simulation results show that the DRABH algorithm can significantly improve the number of user links in the system.

In addition to the number of user links and the SE, delay is also an important communication performance. In the future, we will further consider such factors as user data, the length of the user data queue, and user capability to optimize the user communication delay in the communication system proposed in this paper.

Data Availability

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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