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Research on User Pairing Techniques Based on NOMA in Cognitive Radio Networks

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Abstract

This paper outlined a Non-Orthogonal Multiple Access (NOMA) grouping transmission scheme for cognitive radio networks. To address the problems of small channel gain difference of the middle part users caused by the traditional far-near pairing algorithm, and the low transmission rate of the traditional Orthogonal Multiple Access (OMA) transmission, a joint pairing algorithm was proposed, which provided multiple pairing schemes according to the actual scene. Firstly, the secondary users were sorted according to their channel gain, and then different secondary user groups were divided, and the far-near pairing combined with (Uniform Channel Gain Difference (UCGD) algorithm was used to group the secondary users. After completing the user pairing, the power allocation problem was solved. Finally, the simulation data results showed that the proposed algorithm can effectively improve the system transmission rate.

Keywords

Cognitive Radio, Non-Orthogonal Multiple Access, User Grouping, Power Allocation

1. Introduction

In recent years, due to the rapid growth of future wireless networks and the limited spectrum resources, NOMA technology has the advantages of high spectrum utilization and large system capacity. NOMA technology has been widely studied in academia and industry [1] [2] [3] [4] [5], and there have been numerous researches on NOMA technology and Cognitive Radio (CR) technology. NOMA technology mainly encodes multiple user signals by linear superposition. [5] [6] [7] mention that at the receiver side, Successive Interference Cancellation (SIC) is used to decode and recover the signal in the power domain. However, if a large number of users adopt NOMA to send signals, it will increase the decoding complexity at the receiver side. Therefore, it is often necessary to pair two users. The users who complete the pairing adopt NOMA service. Secondly, in order to ensure the fairness of NOMA users, more power is usually allocated to users with poorer signal gain, and less power is allocated to users with better channel gain. Therefore, it is worth studying how to allocate the power between users to improve the system transmission rate while ensuring the fairness of NOMA users.

2017, in [8] Chinnadurai *et al.* sorted the users according to the channel gain, took the median of the sorting result as the channel gain threshold, divided the users into strong user group and weak user group, and took one user from each group to complete the pairing, and the system performance after pairing was better than that of random pairing. This method can mine the characteristics of channel gain, but in actual application, how to select the appropriate channel gain threshold is a more difficult thing. 2018, in [9] Islam studied the effect of user pairing on the system performance in the fixed power allocation NOMA system (F-NOMA). It is concluded through theoretical analysis and simulation that F-NOMA can provide larger sum rate than the traditional orthogonal multiple access, and the larger the channel gain difference between the paired users, the more the gain increases, and the less the SIC decoding error affects the system performance. 2019, in [10] Zhang Jun proposed an optimal user pairing scheme for the downlink of NOMA, and proved the optimality of the algorithm in the scenario of even number of users. The experimental results show that the system performance obtained by the proposed scheme is better than that of the OMA scenario. 2017, in [11] Ding and Fan *et al.* maximized the system rate by jointly optimizing user pairing and power control, and proved that the larger the channel gain difference between the two users sharing the same subcarrier, the higher the system rate. However, the resource management scheme proposed in this research work is to maximize the rate of the whole NOMA system by sacrificing the rate of users with poor channel quality. Moreover, with the increase of the number of system users, two users with similar channel gain will also be paired under this pairing scheme, which is not conducive to the successful execution of SIC at the receiver side.

In summary, we have found that the current research on SU grouping pairing in CR-NOMA has the following shortcomings: although the greater the difference in channel gains between two users on the same subcarrier, the higher the system rate, grouping in this way will cause strong interference to the middle users, resulting in poor communication quality between them. Secondly, the Uniform Channel Gain Difference (UCGD) pairing mainly balances the difference in channel gains between users, which can alleviate the problem of strong interference from middle users, but UCGD pairing is a static user grouping strategy that cannot support dynamic user access scenarios very well. The grouping pairing algorithm proposed in this paper first pairs SUs based on the near-far pairing strategy to achieve higher transmission rates. Secondly, the near-far pairing strategy faces the problem of strong interference in the middle. Therefore, based on the near-far pairing strategy, this paper combines the UCGD pairing scheme to solve the problem of strong interference from middle users. The specific grouping strategy will be explained in detail in the text.

In this study, it is different from previous work or studies. The goal of this research is to maximize the transmission rate of Cognitive Radio-Non-Orthogonal Multiple Access (CR-NOMA) communication through user pairing and power allocation. More specifically, the main contributions of this work are summarized as follows:

- First, in the CR-NOMA network, we allow the paired secondary users to multiplex Primary User (PU) spectrum resources.
- Subsequently, the user pairing problem is described using a matrix model, and the proposed grouping strategy can adaptively switch to better pairing schemes for different user quantities. For the non-linear power allocation problem, convex optimization is used to achieve successful rate allocation and obtain the optimal solution to improve the overall performance of the network.
- Finally, we provide numerical results to evaluate the effectiveness of our proposed algorithm, which can effectively delay the network lifetime and provide some insights for the CR-NOMA user pairing study.

The remainder of this paper is organized as follows. Section 2 establishes the system and network model, including the system model and relevant grouping matrix description. Section 3 analyzes user pairing and system capacity. In section 4, the system model is presented, and the proposed problem is addressed. Section 5 simulates the proposed scheme. Finally, section 6 summarizes this paper and outlines future research directions.

2. System and Network Model

2.1. System Model

The main consideration of this system is to adopt the downlink model of non-orthogonal multiple access (NOMA) in the CR network. The system adopts the Underlay spectrum sharing method, that is, the secondary user (SU) can simultaneously access spectrum resources within the interference threshold range of the PU. As shown in **Figure 1(a)** and **Figure 1(b)**, several primary and secondary users are randomly generated in the cell, and then M primary users and N secondary users are randomly reserved.

As shown in **Figure 2**, a system model is established for randomly retained M Primary Users and N secondary users (SUs). The whole system communicates under W sub-carriers, where ($M \le W, N \le 2M$). In the communication process, the primary users are given priority in sub-carrier allocation, and each PU uses different sub-carriers to complete the communication. According to the underlay spectrum sharing mode rules, SUs can access the spectrum resources

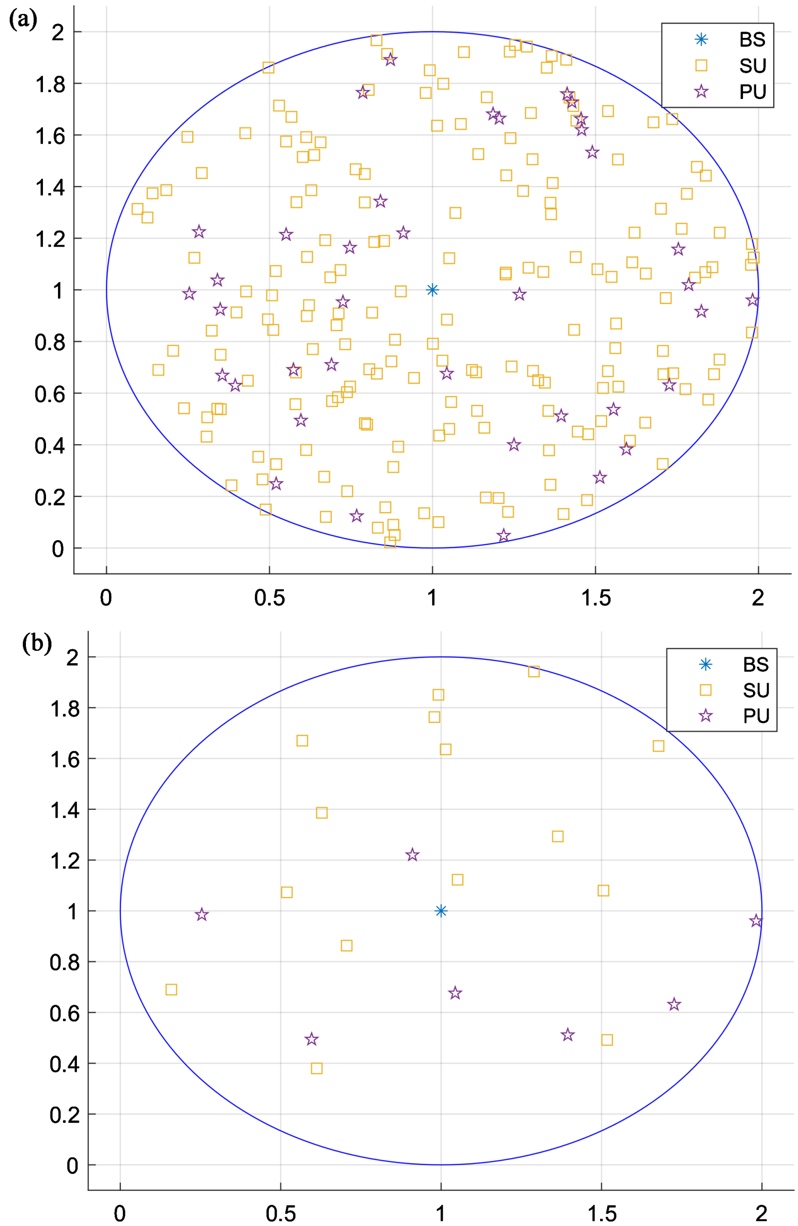

Figure 1. Randomly Generated Primary and Secondary Users. (a) Randomly generate several users; (b) Randomly keep a specified number of users.

shared by the PU on the sub-carrier where the PU is located within the interference threshold of the PU. Assuming that the SU is sorted by channel gain as $h_1 \geq h_2 \geq \cdots \geq h_n$. $h_i = \left|\hat{h}_i\right|^2 \left(1 + d_i^{\alpha}\right)^{-1}$ represents the channel gain coefficient between the secondary user *i* and the Primary base station (PBS), $\left|\hat{h}_i\right|$ represents the Rayleigh fading gain, and d_i represents the distance between the secondary user *i* and the PBS.

2.2. Carrier Allocation Model

As mentioned previously, PU prioritizes the subcarriers for allocation. In this paper, a $M \times W$ matrix $A = \left|A(i,j)\right|, \{i \in [1,\cdots,M], j \in [1,\cdots,N]\}$ is used to

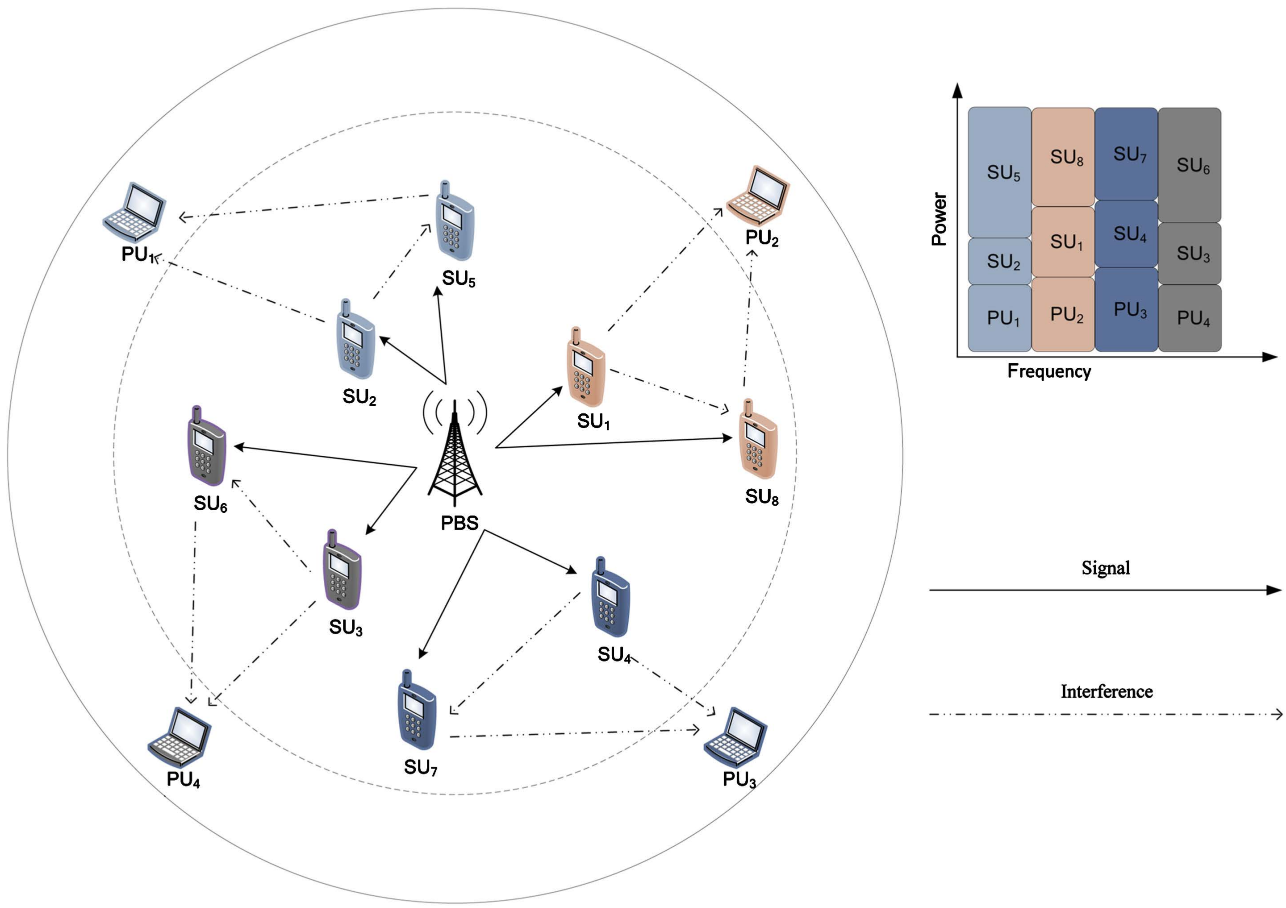

Figure 2. System Model for PU and SU Communication.

represent the subcarrier allocation. Where $A(i,j)=1$ indicates that PU_i completes the communication on subcarrier *j*. According to the communication of each primary user on different subcarriers, the related constraints of matrix A can be obtained as follows:

$$A(i,j)\in(0,1),\forall i\in[1,\cdots,M],j\in[1,\cdots,W] \tag{1a}$$

$$\sum_{j=1}^{W}A(i,j)\in(0,1),\forall i\in[1,\cdots,M] \tag{1b}$$

$$\sum_{i=1}^{M}A(i,j)\in(0,1),\forall j\in[1,\cdots,W] \tag{1c}$$

As shown in Equation (1a), the values in matrix A are all either 0 or 1. According to each primary user using different subcarriers for communication, Equations ((1b), (1c)) in the equation indicates that there can be at most one 1 in each row and column of matrix A.

2.3. Grouping Model

Before assigning the subcarriers to the secondary users, this paper groups every two secondary users into one group for NOMA communication. For the sake of convenience, we use an *N*-row *K*-column matrix

$B = \left|B(i,j)\right|, \{i \in [1,\cdots,N], j \in [1,\cdots,K]\}$ to represent the grouping of the secondary users. Similarly, when $B(i,j)=1$, it indicates that the *i*-th SU is in the *j*-th group. The related constraints of matrix B are as follows:

$$B(i,j) \in (0,1), \forall i \in [1,\cdots,N], j \in [1,\cdots,K] \tag{2a}$$

$$N/2 \le K \le (N+1)/2 \tag{2b}$$

$$\sum_{i=1}^{N} B(i,j) \le 2, \forall j \in [1,\cdots,K] \tag{2c}$$

$$\sum_{j=1}^{K} B(i,j) = 1, \forall i \in [1,\cdots,N] \tag{2d}$$

As shown in Equation (2a), the values in matrix B are all either 0 or 1. In this paper, two SUs are grouped as one, so when N is even, $K = N/2$, and when N is odd, $K = N/2+1$. Therefore, as shown in Equation (2b), $N/2 \le K \le N/2+1$. Equations (2c) and (2d) respectively indicate that each group can have up to two users and each user can only be in one group.

After the SUs grouping is considered, the next thing to consider is the SUs carrier selection problem. Similarly, a K-row W-column matrix $C = \left|C(i,j)\right|, \{i \in [1,\cdots,K], j \in [1,\cdots,W]\}$ is used to represent the SUs group access problem. When $C(i,j)=1$, it indicates that the SUs in the *i*-th group communicates in the *j*-th sub-carrier. Therefore, it is not difficult to obtain the relevant constraints of matrix C as follows:

$$C(i,j) \in (0,1), \forall i \in [1,\cdots,K], j \in [1,\cdots,W] \tag{3a}$$

$$\sum_{i=1}^{K} C(i,j) \in (0,1), \forall j \in [1,\cdots,W] \tag{3b}$$

$$\sum_{j=1}^{W} C(i,j) = 1, \forall i \in [1,\cdots,K] \tag{3c}$$

As shown in Equation (3a), the values in matrix C are all either 0 or 1. As each SU group uses a different subcarrier to complete the communication process, each row of matrix C also contains only one 1, as shown in Equation (3c). Since SU groups may not occupy all subcarriers, each column has at most one 1, as shown in Equation (3b).

3. System Capacity Analysis and User Pairing

3.1. User Pairing

Users can be divided into strong and weak users according to their channel gain coefficients. Moreover, if users are interfered by strong users, the problem of how to reasonably pair strong and weak users needs to be solved. We call the first $n/2$ users strong users and the last $n/2$ users weak users.

Far-Near Pairing

As in [12] By maximizing the difference in channel gain between users, pairing is done between the user with the strongest channel gain among the strong users and the user with the weakest channel gain among the weak users. Therefore, strong interference exists for the users in the middle part. The specific allocation scheme is shown in Equation (4).

$$\begin{vmatrix} SU_1 & SU_n \\ SU_2 & SU_{n-1} \\ & \cdots \\ SU_{n/2} & SU_{n/2+1} \end{vmatrix}. \tag{4}$$

UCGD Pairing

As in [13] UCGD pairing is a method of pairing by balancing the channel gain difference between users. It first combines strong users and weak users, and then forms a more balanced pairing scheme. The specific allocation scheme can be expressed by Equation (5).

$$\begin{vmatrix} SU_1 & SU_{n/2+1} \\ SU_2 & SU_{n/2+2} \\ & \cdots \\ SU_{n/2} & SU_n \end{vmatrix} \tag{5}$$

JPS Pairing

In this paper, we propose a Joint Pairing Scheme (JPS) by combining the existing UCGD and near and far pairing schemes, firstly, we also sort the users according to the channel gain coefficients between them, and secondly, we divide the N SUs (N is an even number) into an even number block P blocks, where P is an even number and $2 \le P \le N/2$. Firstly, the user blocks are paired near and far, and the pairing scheme of the user groups is carried out between the users in the paired user blocks using the UCGD scheme. The specific pairing scheme can be specified by an example shown in **Figure 3**.

In **Figure 3**, we know that there are currently 20 SUs, of which the even numbered block $P = 4$, *i.e.*, each block contains 5 users. Then block pairing is performed for P-blocks by way of far and near pairing. Second, after completing block pairing, the users within the block pairing are paired in user groups by UCGD, for example, block 1 and block 4 in the figure are paired in block pairing, then for the users within block 1 and block 4 in combination, the user groups formed by block 1 and block 4 are paired in user pairs, and the users

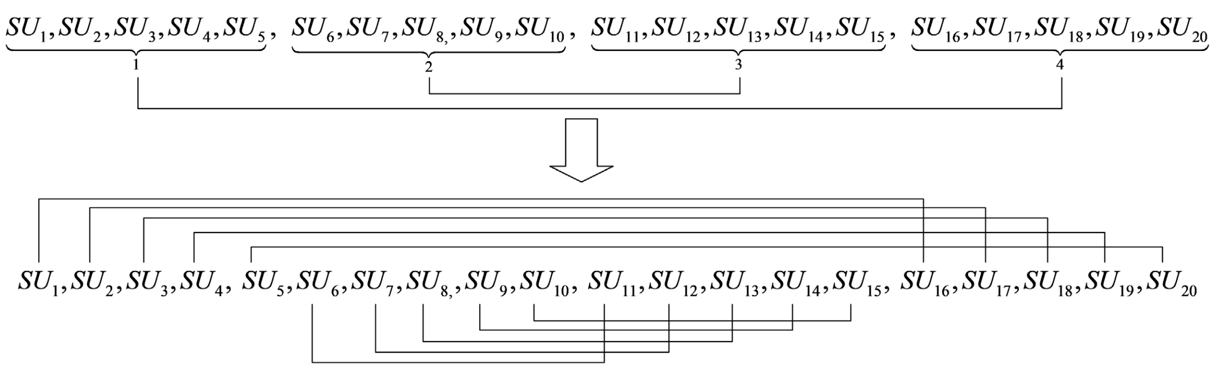

Figure 3. JPS pairing example chart.

within the two blocks are paired in combination in turn, *i.e.*, SU_1 and SU_{16} are paired. SU_2 and SU_{17} are paired. And so on. In this case, the value of P in our example is 5. Of course, this is only one case, and in the case of $N = 20$, there are other values of P such as $P = 10$ and $P = 2$. You can divide the P values according to the actual situation.

3.2. System Capacity Analysis

As in [8], at the transmitting end, PBS transmits signals using linear superposition coding. When SU_j and SU_k are paired in the rth group, the signal transmitted by the user can be represented as:

$$s_r = \sum_{i=1}^{N} B(i,r) P_i x_i = P_j x_j + P_k x_k \tag{6a}$$

$$\sum_{i=1}^{N} B(i,r) P_i = P_j + P_k = P_{PBS} \tag{6b}$$

In Equations (6a) and (6b), $j,k \in (1,2,\cdots,N)$, $j < k$ and $\forall r \in \{1,\cdots,K\}$. P_i and x_i respectively represent the transmission powers of SU_i and the signals sent. P_{PBS} represents the transmission power of the base station. Since users are sorted in an ordered sequence based on channel gains, when $j < k$, $h_j \ge h_k$. According to the NOMA principle, more power should be allocated to SU_i with poorer channel conditions, *i.e.*, $P_j < P_k$.

As shown in **Figure 4**, as in [14] according to the SIC principle, at the receiving end, the signal of the user with higher power, SU_k, is detected first. After

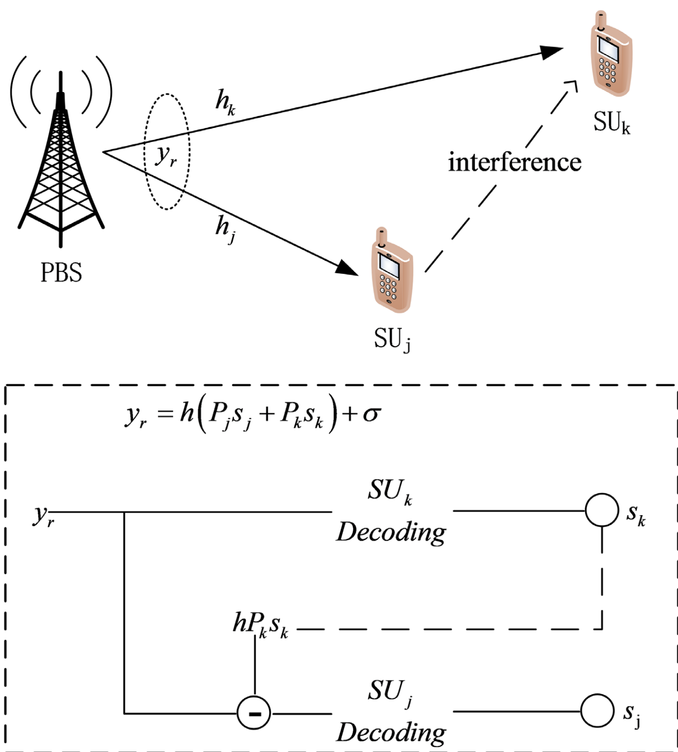

Figure 4. SIC detection process.

detecting the signal of SU_k, the signal of SU_k is eliminated from the signal and then the signal of SU_j is detected. For SU_k, when the signal of SU_k is detected, the signal of SU_j is treated as interference. Similarly, for SU_j, after eliminating the signal of SU_k, the signal of SU_j is detected, so the signal of SU_k is not treated as interference with the signal of SU_j.

Let SU_j and SU_k be the *r*th group of users, and from the matrix *C*, it can be determined that the subcarrier ω on which the *r*th group of users SU_j and SU_k are located can be expressed by Equation (7):

$$\omega = \sum_{i=1}^{W} C(r,i)\,i \tag{7}$$

Since matrix C records the subcarrier access information for each user, to determine the specific subcarrier on which the current group of users is located, it is only necessary to calculate the cumulative product of each column in the *r*th row. This is because each row has only one element equal to 1 and the rest are 0. Therefore, the received signal of the *r*th group of users on subcarrier ω can be expressed by Equation (8).

$$y_r = \sum_{i \le N, z \le W} B(i,r)\,C(r,z)\left|h_i\right|^2 P_i s_i + \eta = \left|h_j\right|^2 P_j^{(\omega)} s_j + \left|h_k\right|^2 P_k^{(\omega)} s_k + \eta \tag{8}$$

As in Equation (8), η represents additive Gaussian white noise with mean 0 and variance σ^2, and $P_j^{(\omega)}$ is the power of SU_j on the subcarrier ω.

According to Shannon's equation, we can know that the system capacity in the *r*th group can be expressed by equation (9):

$$R_r = \sum_{i=1}^{N} B(i,r)\,R_{(r,i)} = R_{(r,j)} + R_{(r,k)} = \log\left(1 + SINR_{(r,j)}^{(\omega)}\right) + \log\left(1 + SINR_{(r,k)}^{(\omega)}\right) \tag{9}$$

As in Equation (9), R_r represents the cumulative channel capacity of the *r*th group of users, $R_{(r,j)}$ and $R_{(r,k)}$ represent the channel capacity of SU_j and SU_k in the *r*th group, respectively. $SINR_{(r,j)}^{(\omega)}$ represents the signal-to-noise ratio of SU_j when transmitting on the subcarrier ω. And it is not difficult to derive the general Equation (10) of $SINR_{(r,i)}^{(\omega)}$:

$$SINR_{(r,i)}^{(\omega)} = \frac{a_i P^{(\omega)} \left|h_i\right|^2}{\sum_{m=1}^{i-1} B(m,r)\,a_m P^{(\omega)} \left|h_i\right|^2 + \eta} \tag{10}$$

In Equation (10), a_i represents the power allocation factor of the SU_i. $a_i P^{(\omega)}$ represents the total transmission power from the base station to the SU_i on subcarrier ω.

4. Problem Solution Method

4.1. Mathematical Modeling

Given the constraint of interference temperature for the primary user, the objective of this paper is to maximize the sum of channel capacities of secondary user groups by jointly considering subcarrier allocation strategies and secondary user grouping. Based on Shannon's formula principle, we can obtain the following mathematical model:

$$\max_{a_i} \sum_{r=1}^{K} R_r \tag{11a}$$

$$\text{s.t.}(1a)\text{-}(3c), (4b) \tag{11b}$$

$$\gamma_{(r,i)}^{(\omega)} \le SINR_{(r,i)}^{(\omega)} \quad \forall r,i,\omega \tag{11c}$$

$$\Gamma_{SU(r)}^{(\omega)} \le {}^{th}\Gamma_{PU}^{(\omega)} \quad \forall r,i,\omega \tag{11d}$$

Equation (11a) is the objective function, which is equivalent to Equation (9) representing the sum of transmission rates of two secondary users within the same group. Equations (11b)-(11d) represent constraint conditions. Equation (11b) is one of these constraints. As in Equation (11b) represents the constraint conditions of the matrix mentioned earlier. As in Equation 11(c) represents the QoS threshold γ that the secondary users in the *r*th group need to meet on the subcarrier ω. Equation 11(d) represents that the cumulative interference of the secondary users on the subcarrier ω cannot exceed the interference temperature threshold of the primary user.

$$\Gamma_{SU(r)}^{(\omega)} = \sum_{i=1}^{N} B(i,r) a_i P^{(\omega)} |h_i|^2 \tag{12}$$

As in Equation (12) $\Gamma_{SU(r)}^{(\omega)}$ represents the cumulative interference generated by the secondary user group r on the subcarrier ω.

4.2. Solving Power Problems

Subsequently, by making simple transformations to the constraints and objective function, we can easily obtain the following equation:

$$\max_{a_i} \quad R = \log\left(1 + \frac{a_i P^{(\omega)} |h_j|^2}{\eta}\right) + \log\left(1 + \frac{(1-a_j) P_j^{(\omega)} |h_j|^2}{a_i P^{(\omega)} |h_j|^2 + \eta}\right) \tag{13a}$$

$$\text{s.t.} \frac{\gamma_i \eta}{P^{\omega} |h_i|^2} \le a_i \le \frac{P^{\omega} |h_i|^2 - \eta\gamma_j}{P^{\omega} |h_j|^2 \gamma_j + P^{\omega} |h_i|^2} \tag{13b}$$

For the Equations (13a) and (13b) above, it is not difficult to see that this is a convex optimization problem. Therefore, for convex optimization problems, we can use the Lagrangian function to solve them. The Lagrangian function constructed for the above equations is as follows:

$$L(a_i, \lambda) = R + \lambda_1 \left(\frac{\gamma_i \eta}{P^{\omega} |h_i|^2} - a_i\right) + \lambda_2 \left(a_i - \frac{P^{\omega} |h_i|^2 - \eta\gamma_j}{P^{\omega} |h_j|^2 \gamma_j + P^{\omega} |h_i|^2}\right) \tag{14}$$

As shown in Equation (14), a_i represents the power allocation factor of the SU_i. λ_1 and λ_2 are Lagrange multipliers. Finally, by using the KKT conditions and taking the partial derivatives of a_i, λ_1, and λ_2, we have the following relationships:

$$\frac{\partial L}{\partial a_i}=\frac{\partial R}{\partial a_i}-\lambda_1+\lambda_2=0 \tag{15a}$$

$$\frac{\partial L}{\partial \lambda_1}=\frac{\gamma_i\eta}{P^{\omega}\left|h_i\right|^2}-a_i=0 \tag{15b}$$

$$\frac{\partial L}{\partial \lambda_2}=a_i-\frac{P^{\omega}\left|h_i\right|^2-\eta\gamma_j}{P^{\omega}\left|h_j\right|^2\gamma_j+P^{\omega}\left|h_i\right|^2}=0 \tag{15c}$$

$$\frac{\gamma_i\eta}{P^{\omega}\left|h_i\right|^2}-a_i\leq 0 \tag{15d}$$

$$a_i-\frac{P^{\omega}\left|h_i\right|^2-\eta\gamma_j}{P^{\omega}\left|h_j\right|^2\gamma_j+P^{\omega}\left|h_i\right|^2}\leq 0 \tag{15e}$$

$$\lambda_1,\lambda_2\geq 0 \tag{15f}$$

$$0<a_i<1/2 \tag{15g}$$

Equations (15a)-(15c) represent the partial derivatives of a_i, λ_1, and λ_2, respectively. Equations (15d)-(15e) represent the original constraints, while Equation (15f) represents the non-negativity of Lagrange multipliers. As SU_i represents a user with higher channel gain, according to the NOMA principle, it is allocated less power. Therefore, its power allocation factor needs to be less than 1/2, as shown in Equation (15g).

It can be seen from $\frac{\partial R}{\partial a_i}-\lambda_1+\lambda_2=0$ that:

when $\lambda_1>0,\lambda_2=0$, $a_i=\frac{\gamma_i\eta}{P^{\omega}\left|h_i\right|^2}$,

when $\lambda_1=0,\lambda_2>0$, $a_i=\frac{P^{\omega}\left|h_i\right|^2-\eta\gamma_j}{P^{\omega}\left|h_j\right|^2\gamma_j+P^{\omega}\left|h_i\right|^2}$.

5. Simulation Result

In this paper, MATLAB is used to simulate data in the CR-NOMA hybrid network. The noise power spectrum density in the system is $n=-174\text{ dbm}$. The coverage range of the base station is 1000 meters, the path loss is 4, and the bandwidth of each user group is 1 Hz. When the number of secondary users is $N=40$, the secondary users are paired in pairs, containing 20 groups. Figure 5 compares the total transmission rate of each user group under the condition of $N=40$ between the JPS algorithm proposed in this paper and the UCGD and Far-Near pairing algorithms. The base station transmission power P = 14 db. Since all three algorithms are based on the number of 40 secondary users, they are sorted according to the channel gain and then divided into secondary user groups. The situation of secondary user 1 in each group is the same, but secondary user 2 is different. Therefore, an interlaced fluctuation occurs. As the number of groups increases, the path loss increases, resulting in a gradual decrease in the transmission rate of the overall user group.

In **Figure 6**, this paper compares the JPS NOMA scheme with the OMA transmission scheme in terms of transmission power from 10 to 15 dB, SU_1 and SU_2 of the two algorithms, and the total transmission rate. It can be observed that the system throughput of the proposed JPS algorithm is larger than that of the OMA transmission. Therefore, the proposed algorithm has an advantage over OMA in terms of throughput.

In **Figure 7**, it can be observed that the JPS and far-near, USGD algorithms have higher throughput when the transmit SNR is greater than 13 dB in the

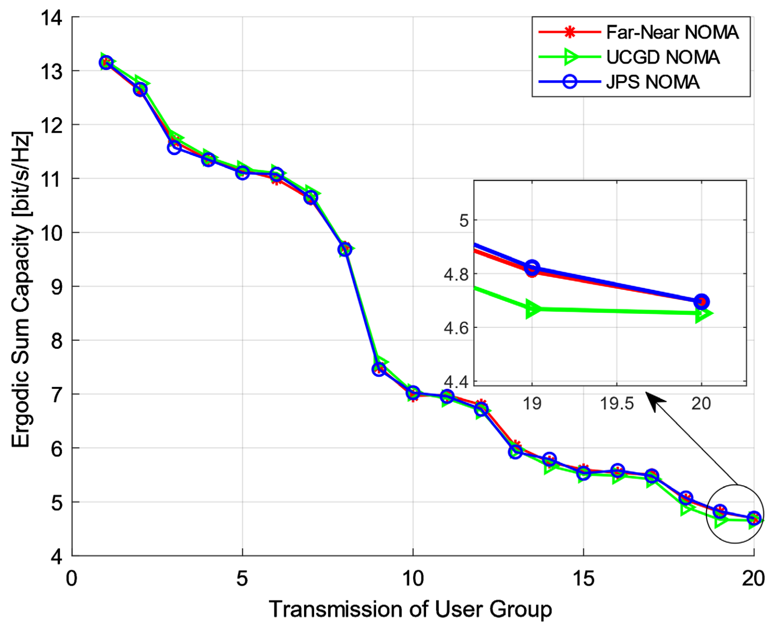

Figure 5. Group-wise user transmission rate comparison.

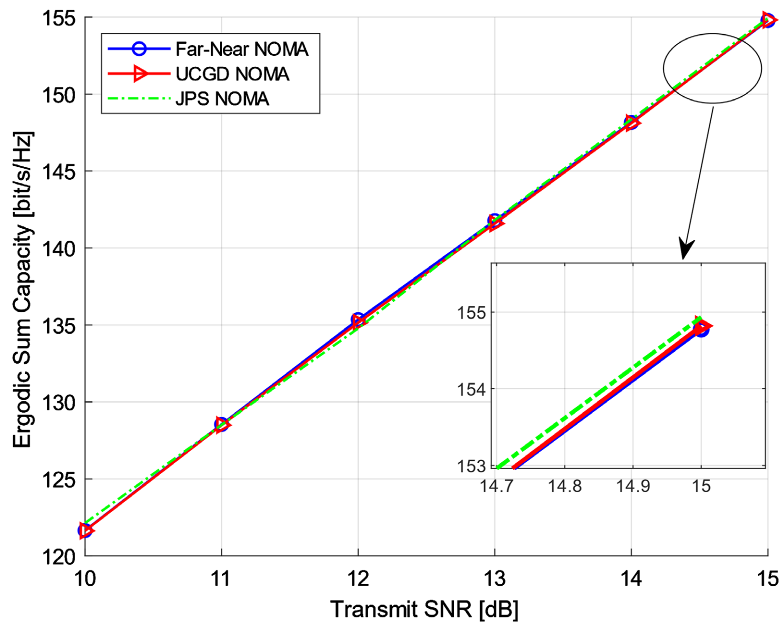

Figure 6. Comparison of transmission rate performance of different pairing schemes.

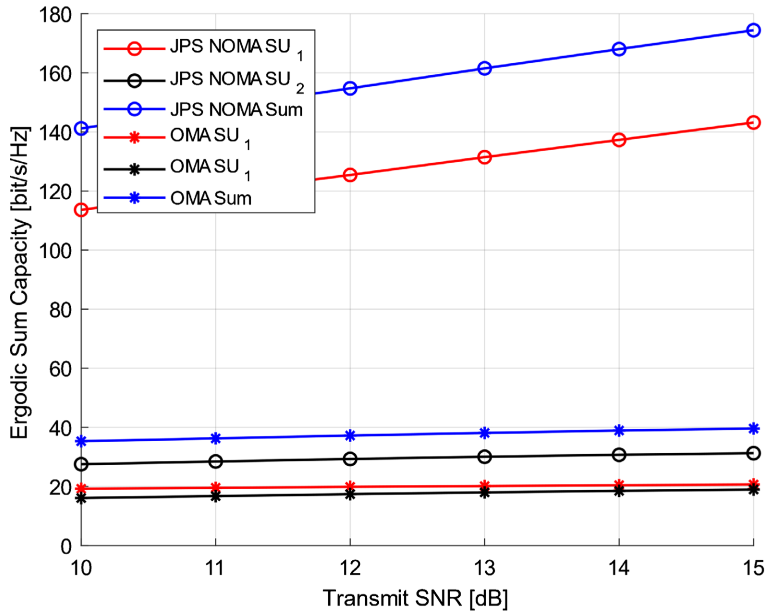

Figure 7. Comparison of total transmission rate between JPS and OMA.

10 - 15 dB range. Moreover, the JPS algorithm can flexibly adjust the number of users in each group to form different pairing schemes.

6. Conclusion

This paper proposes an SU-based pairing algorithm by combining CR and NOMA to improve system throughput while ensuring multiple constraints such as interference temperature, QoS quality, and power limitations. The proposed algorithm can generate different pairing schemes in a CR-NOMA multi-user system and select the best pairing scheme based on the actual scenario. However, there are still shortcomings in this study. For example, although the grouping strategy proposed in this paper can adaptively select the best pairing scheme according to the number of users, the simulation results did not meet our expected results. In future work, we will conduct further research in more complex and comprehensive multi-cell and multi-user network environments and optimize the proposed scheme, considering more complex scenario.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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