

# Resource Allocation Algorithms for Multiuser Cooperative OFDMA Systems with Subchannel Permutation

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*Abstract*—In this paper, we investigate resource allocation for a multi-user OFDMA cooperative system. Aiming at minimizing the total transmission power under target rate constraints for each user, we propose centralized and decentralized subchannel, bit, and power allocation schemes. First, assuming knowledge of the instantaneous channel gains for all links in the entire network, centralized resource allocation algorithms with subchannel permutation, in which the subchannels are reallocated at the relay nodes, are considered. Then, a decentralized resource allocation scheme is proposed for ad hoc network. Simulation results show that significant performance gains can be achieved, especially when subchannel permutation is employed.

## I. INTRODUCTION

Cooperative transmissions have attracted much attention in the last few years. It has been demonstrated that the benefits of multi-antenna transmission can be achieved by cooperative transmission without requiring multiple antennas at individual nodes (for example, see [1]-[2]).

Orthogonal Frequency Division Multiplexing Access (OFDMA), a multiple access technique in which the subchannels of an OFDM symbol are shared by multiple users, has significant advantages that have made it the natural choice for commercial broadband wireless networks, such as IEEE802.16 (WiMAX) [3], as well as for the long-term evolution of third-generation cellular systems [4]. Currently, relay and cooperative networks with OFDM(A) transceivers have been proposed for applications in several emerging systems. IEEE 802.16's Relay Task Group [5] is a developing standard for 802.16-based multihop networks. Also, relaying is considered in IEEE 802.11s [6], a developing mesh networking standard.

In multiuser OFDMA systems, multiuser diversity can be easily achieved by the allocation of subchannels to users. In particular, the channels are independent for each user; this means that a subchannel in a deep fade for one user might be good for another user. For each user, bit and power allocation among subchannels is an efficient method to exploit the frequency diversity inherent in frequency-selective channels. Over the past decade, the resource allocation problem for multiuser OFDMA systems has been extensively investigated (for example, see [7]). In particular, different subchannel, power, and bit allocation schemes with diverse optimization objectives have been studied.

The resource allocation problem in cooperative OFDMA networks, however, has received much less attention. In [8], a centralized utility maximization framework for cooperative OFDMA cellular networks is proposed. The proposed solution not only allocates power and bandwidth, but also selects relaying strategies for each user. In [9], aiming at maximizing the achievable sum rate from all the sources to the destination, a centralized source, relay, and subchannel allocation problem for an OFDMA relay network is studied. In these works, however, the assumption that the relay node uses the same subchannel to relay the information transmitted by the source node limits the performance gain.

In [10], we considered the resource allocation problem with a single source-destination pair and multiple assisting relay nodes. Specifically, we employ subchannel permutation, in which the subchannels are reallocated at the relay nodes, and devise bit-loading algorithms for cooperative OFDM systems that use a decode-and-forward relaying strategy. Simulation results indicate that significant performance gains can be achieved by the proposed algorithms, especially with subchannel permutation at the relay nodes.

In this paper, we extend the work in [10] to the scenario with multiple source-destination pairs and multiple assisting relay nodes. Our objective is to minimize the total transmission power by allocating subchannels, bits, and power to each user based on the instantaneous channel gains. In particular, subchannel permutation, which works well in single source-destination scenarios, is also adopted in these multiuser scenarios. We first formulate the optimization problem and show that, without subchannel permutation, the problem is similar to that in traditional systems. Then, subchannel permutation is considered, and two resource allocation algorithms are proposed. Simulation results demonstrate that significant performance gains can be achieved using the proposed algorithms, even with large numbers of relay nodes. The above resource allocation schemes are based on the assumption that a central controller knows all the channel gains in the entire system and performs the allocation algorithm. To perform the resource allocation in ad hoc networks, we also consider these algorithms for decentralized systems.

The paper is organized as follows. The system model is described in Section II. In Section III, we propose centralized resource allocation algorithms with subchannel permutation. Decentralized algorithms are considered in Section IV and simulation results are given in Section V. Finally, Section VI summarizes and concludes the paper.

## II. SYSTEM MODEL

We consider a cooperative system with  $M$  source-destination pairs and  $K$  relay nodes, as shown in Fig. 1. An OFDMA transceiver with  $N$  subchannels is available at each node. We assume perfect time and frequency synchronization among nodes and the inclusion of a cyclic prefix that is long enough to accommodate the delay spread of the channel. We also assume that the fading on each subchannel is slowly varying.

A two-stage transmission protocol is adopted. In the first stage, the source nodes transmit and the other nodes listen - the links in this stage are called the source-relay (SR) links and the source-destination (SD) links. In the second stage, the relays retransmit the message to the destination - the links in this stage are called the relay-destination (RD) links. Here, we adopt a *selective* decode-and-forward relaying strategy. In particular, each source subchannel can only be relayed by one relay node. The selected relay node will fully decode the received information, re-encode it, and then forward it to the destination. Orthogonal transmission is assumed in each stage, that is, a specific subchannel can only be used by one node. Hence, OFDMA is adopted in each stage as a multiple access technique. Different source subchannels may select different relay nodes, similar to the selective OFDMA relaying in [11]. The destination nodes employ maximal ratio combining to combine the received signals from the first and second stages. With these assumptions, there is no interference in the entire network.

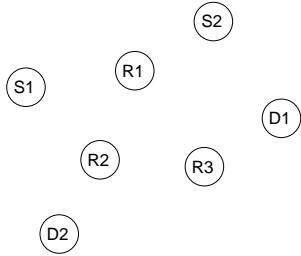


Fig. 1. A system with two source-destination pairs and three possible relay nodes.

Centralized and decentralized resource allocation algorithms are both considered in this paper. In a centralized system, a central controller first collects the instantaneous channel gains of all links in the system. Then, it performs global optimization and broadcasts the decisions to each node. In decentralized systems, however, each node only has its local channel information. How to achieve good performance with minimal internode communications is a challenging problem.

We assume that the target data rate of user  $m$  is  $R_m$  bits per OFDM symbol (block). Let  $b_{m,n}$  denote the number of bits assigned to source subchannel  $n$  of user  $m$ ;  $b_{m,n}$  can take values in the set  $B = \{0, 1, \dots, B_{max}\}$ . Note, with the OFDMA transmission assumption, if  $b_{m',n} \neq 0$ ,  $b_{m,n} = 0$  for all  $m' \neq m$ . Further, denote the channel response of subchannel  $n$  from source node  $m$  to relay node  $k$ , from source node  $m$  to its destination node, and from relay node  $k$  to destination node  $m$  as  $H_{s_m r_k}(n)$ ,  $H_{s_m d}(n)$  and  $H_{r_k d_m}(n)$ ,

respectively. In general, these include path loss, shadowing, and Rayleigh fading. For convenience, let  $G_{s_m r_k}(n)$ ,  $G_{s_m d}(n)$  and  $G_{r_k d_m}(n)$  denote the channel power gains,  $\|H_{s_m r_k}(n)\|^2$ ,  $\|H_{s_m d}(n)\|^2$  and  $\|H_{r_k d_m}(n)\|^2$ , respectively.

Let  $\gamma(b_{m,n})$  be the required received SNR per symbol in subchannel  $n$  for reliable reception of  $b_{m,n}$  bits/symbol. As in [12], the SNR per symbol for subchannel  $n$  is

$$\gamma(b_{m,n}) = \rho * (2^{2b_{m,n}} - 1) \quad (1)$$

The parameter  $\rho$  ranges from 1 to about 6.4, depending on the degree of coding [12]. The required received power  $P_{req}(b_{m,n})$  can be written as

$$P_{req}(b_{m,n}) = \gamma(b_{m,n})N_0 \quad (2)$$

where  $N_0$  is the double-sided noise power spectral density level with the assumption that each subchannel has a normalized bandwidth.

As in [10], each subchannel can operate in two different modes: direct or cooperative transmission. Each subchannel compares the required power of these two modes and selects the one which has the minimum required power to achieve reliable reception at the destination node. The minimum power required for the direct transmission mode is

$$P_{s_m d}^D(n) = \frac{P_{req}(b_{m,n})}{G_{s_m d}(n)} \quad (3)$$

The minimum power required for cooperative transmission using subchannel  $j$  at relay node  $k$  is then

$$P_{s_m r_k d}^C(n, j) = P_{req}(b_{m,n}) \frac{\Delta_{s_m r_k d}(n, j)}{G_{s_m r_k}(n)G_{r_k d_m}(j)} \quad (4)$$

where  $\Delta_{s_m r_k d}(n, j) = G_{s_m r_k}(n) + G_{r_k d_m}(j) - G_{s_m d}(n)$  [10].

Here, for cooperative transmission, we define an equivalent channel power gain  $G_{s_m r_k d}^C(n, j)$ , given by

$$G_{s_m r_k d}^C(n, j) = \frac{G_{s_m r_k}(n)G_{r_k d_m}(j)}{\Delta_{s_m r_k d}(n, j)} \quad (5)$$

Thus, the minimum power required for cooperative transmission for subchannel  $n$  using subchannel  $j$  at relay node  $k$  is

$$P_{s_m r_k d}^C(n, j) = \frac{P_{req}(b_{m,n})}{G_{s_m r_k d}^C(n, j)} \quad (6)$$

When the channel gains of the SR and the RD links are both greater than the channel gains of the SD links, i.e.,  $G_{s_m d}(n) < \min\{G_{s_m r_k}(n), G_{r_k d_m}(j)\}$  for any  $k$ , cooperative transmission requires less power than direct transmission.

We use  $\beta_m(n) \in \{0, 1\}$  to indicate the mode in which subchannel  $n$  of user  $m$  operates. Let  $\beta_m(n) = 1$  indicate direct transmission. Also, we use  $\alpha_{s_m r_k}(n, j) \in \{0, 1\}$  to indicate whether or not subchannel  $n$  is used in cooperation with subchannel  $j$  at relay node  $k$  for user  $m$ . Our objective is to allocate subchannels, bits, and power to each user to minimize the total transmitting power  $P_T$ . Mathematically, we can formulate the optimization problem as

$$P_T = \min_{b_{m,n} \in B} \sum_{m=1}^M \sum_{n=1}^N \frac{P_{req}(b_{m,n})}{G_m(n)} \quad (7)$$

where

$$G_m(n) = \begin{cases} G_{s_m d}(n) & \text{if } \beta_m(n) = 1 \\ G_{s_m r_k d}(n, j) & \text{if } \alpha_{s_m r_k}(n, j) = 1 \\ 1 & \text{otherwise} \end{cases} \quad (8)$$

subject to the following constraints

$$C1 : R_m = \sum_{n=1}^N b_{m,n}, \forall m, \quad (9)$$

$$C2 : \sum_{m=1}^M \{ \beta_m(n) + \sum_{k=1}^K \sum_{j=1}^N \alpha_{s_m r_k}(n, j) \} = 1, \forall n, \quad (10)$$

$$C3 : \sum_{m=1}^M \sum_{k=1}^K \sum_{n=1}^N \alpha_{s_m r_k}(n, j) \leq 1, \forall j \quad (11)$$

Note that  $C1$  is the rate constraint,  $C2$  indicates that each subchannel can only be used by one source and relayed by at most one relay at a given time, and  $C3$  means that each subchannel  $j$  in RD links can be used by at most one relay.

### III. CENTRALIZED ALGORITHMS

In this section, we devise centralized algorithms for cooperative OFDMA systems. We first do not consider subchannel permutation. Then, we will employ subchannel permutation to further improve the performance.

#### A. Resource allocation without subchannel permutation

In this case, for subchannel  $n$  in the SR links, the selected relay node also uses subchannel  $n$  in the RD links to retransmit the information. The equivalent channel power gain through relay node  $k$  is determined by the mode in which the subchannel is used. If  $G_{s_m d}(n) < \min\{G_{s_m r_k}(n), G_{r_k d_m}(n)\}$ , the equivalent channel power gain through relay node  $k$  is

$$G_{s_m r_k d}(n) = \frac{G_{s_m r_k}(n)G_{r_k d_m}(n)}{\Delta_{s_m r_k d}(n, n)} \quad (12a)$$

otherwise

$$G_{s_m r_k d}(n) = G_{s_m d}(n) \quad (12b)$$

Each subchannel should be used by the relay node, among the  $K$  nodes, which has the largest equivalent channel power gain to relay the information. Let  $G_{eq,m}(n)$  denote this maximum equivalent channel power gain for user  $m$ , then it can be written as

$$G_{eq,m}(n) = \arg \max_{k=1,\dots,K} G_{s_m r_k d}(n) \quad (13)$$

The optimization problem can be rewritten as

$$P_T = \min_{b_{m,n} \in B} \sum_{m=1}^M \sum_{n=1}^N \frac{P_{req}(b_{m,n})}{G_{eq,m}(n)} \quad (14)$$

In this case, constraint  $C3$  is automatically satisfied, and we only need to consider the rate constraint  $C1$  and the OFDMA orthogonal transmission constraint  $C2$ .

We can see that the optimization problem is similar to that in traditional multiuser OFDMA systems, which has been extensively researched. This optimization problem is an

integer programming (IP) one and has been proved to be NP-hard [13]. A number of suboptimal algorithms have been proposed [14]-[16]. In [14], a Lagrangian relaxation technique is introduced to solve the problem iteratively. Although significant performance gain can be achieved over fixed strategies, high computational complexity prohibits its implementation in practical systems. The optimization problem is formulated as a linear programming in [15]. Better performance is obtained with even higher complexity, compared with the approach in [14].

In [16], the optimization problem is decoupled into three steps. The first step is bandwidth allocation, which determines the number of subchannels needed for each user according to their required data rates and channel gains. Then, subchannel allocation is performed to assign subchannels to each user. Finally, each user independently allocates bit and power to its own assigned subchannels. As shown in [16], a comparable performance can be achieved by this computationally efficient algorithm. As we can see, these algorithms can be easily extended to cooperative systems. The only difference is that we use the equivalent cooperative channel power gains  $G_{eq,m}(n)$  instead of the point-to-point channel gains used in traditional systems.

In this paper, we focus on the performance gain obtained by subchannel permutation. We will modify the practical algorithms in [16] to accommodate subchannel permutation. Specifically, we adopt the simple amplitude-craving greedy (ACG) subchannel assignment. The basic idea of ACG is that, for each subchannel  $n$ , we find and allocate this subchannel to the user which has the maximum channel power gain on this subchannel. For a detailed description, please refer to [16].

Please note, the algorithms in [14]-[15] can also be modified correspondingly to accommodate subchannel permutation.

#### B. Subchannel permutation

In this subsection, we consider subchannel permutation to further save transmission power. We will reallocate the subchannels used for transmission in the RD links. In [10], we have shown that for the single-user scenario, the subchannel permutation gives a 2-dB performance gain even with a large number of relay nodes. Here, with more than one user, the same performance gain is expected. With subchannel permutation, the optimization problem (10) becomes a combinatorial problem and is difficult to solve. Exhaustive search can obtain the optimal solution; however, the computational complexity is prohibitive. Here, we propose two suboptimal algorithms, which are more efficient, but which still give significant performance gains.

The three-step resource allocation algorithm in [16] is adopted. We first perform bandwidth allocation, which determines  $sc_m$ , the number of subchannels required for user  $m$ . Then, a subchannel allocation and permutation algorithm is used to allocate and pair source subchannels and relay subchannels. Lastly, bit and power allocation is performed for each user using the algorithm proposed in [10].

One straightforward algorithm is that, after subchannel allocation, each user performs subchannel permutation within

its own source subchannels and relay subchannels. Each user can adopt the proposed subchannel permutation algorithm in [10]. In this way, after subchannel permutation, the transmission of the source subchannels and the transmission of the relay subchannels remain orthogonal, respectively. This algorithm is referred to as ACGSP in the following discussion. Obviously, separation of subchannel allocation and subchannel permutation is a simple but not optimal algorithm. To achieve better performance, subchannel permutation should also be considered when we allocate subchannels to each user. In the following, we propose a joint subchannel allocation and subchannel permutation algorithm, which is referred to as JSASP (joint subchannel allocation and subchannel permutation).

In JSASP, we first find the pair of source and relay subchannel that maximizes the cooperative channel gains of each user; then, we compare these maximum cooperative channel gains among users, find the maximum one and allocate the corresponding source subchannel and relay subchannel. Notice, each user can only get  $s_{c_m}$  subchannels, and  $s_{c_m}$  is determined by the bandwidth allocation algorithm in [16]. The algorithm is outlined as following:

- Step 1: For user  $m$ , if it has been allocated  $s_{c_m}$  subchannels, set  $G_{s_m} = 0$ ; otherwise, go to Step 2.
- Step 2: For user  $m$ , find the pair of source and relay subchannel that maximizes the equivalent cooperative channel gains  $G_{s_m}$ ; denote the corresponding source subchannel and relay subchannel as  $s_i(m)$  and  $r_i(m)$ , respectively.
- Step 3: Find the user  $\hat{m}$  which has the maximum equivalent cooperative channel gain  $G_{s_m}$  among  $M$  users. Allocate the corresponding source subchannel  $s_i(\hat{m})$  and relay subchannel  $s_i(\hat{m})$  to user  $\hat{m}$  and pair those subchannels.
- Step 4: Set the gains of the source subchannel  $s_i(\hat{m})$  and the relay subchannel  $s_i(\hat{m})$  of all sources and relay nodes to zero.
- Step 5: If all the subchannels are allocated and paired, the subchannel allocation and permutation operation is complete. Otherwise, go to Step 1.

JSASP is obviously more complex than ACGSP, so better performance is expected. After allocating and pairing subchannels, the bit-loading algorithm is performed to allocate the power and bits.

#### IV. DECENTRALIZED ALGORITHMS

In the previous section, a central controller is assumed to collect all the channel gains and perform resource allocation. This assumption is valid for an infrastructure-based network. For ad-hoc networks, decentralized algorithms might be more attractive. Here, we propose a decentralized resource allocation algorithm for ad-hoc networks.

In an ad-hoc network,  $M$  source nodes want to transmit to their destination nodes respectively. Each source will first send a RTS (Request to Send) signal to inform the destination node. The relay nodes and the destination can measure the SR and SD links by listening to the RTS signal, respectively. Then, the destination node sends a CTS (Clear To Send) signal to tell the source node that the channel is ready. We can put the

channel gains of the SD link in the CTS signal so that the relay nodes can obtain them. The relay nodes can measure the RD links by listening to the CTS signal. After all the sources and destinations exchange these control signals, each relay node obtains the channel gains of its own SR, RD links and the SD links from all the sources and destinations. Hence, each relay node can perform resource allocation and calculate the total minimum transmission power. A similar decentralized relay selection algorithm as in [17] can be adopted here. In this algorithm, each relay sets a timer based on its calculated total transmission power. The smaller the total transmission power, the shorter the timer should be. In this way, the timer of the relay with the smallest total transmission power will expire first. That relay then sends a flag signal with the resource allocation information. All other relays, while waiting for their timer to reduce to zero, are in listening mode. As soon as they hear the flag signal, they back off. So, the relay node which has minimum total transmission power will participate in the cooperative transmission between the source nodes and the destination nodes.

In this decentralized algorithm, only one relay node is selected to cooperate, that is, all the subchannels are relayed by the same relay node. In the centralized algorithm, however, each subchannel may be relayed by different relay nodes, and all the relay nodes may cooperate. Obviously, the centralized algorithm performs better than the distributed algorithm, at the expense of more communications overhead.

#### V. SIMULATIONS RESULTS

In this section, we present simulation results to compare the performance of the different resource allocation algorithms. Consider multiple source-destination pairs in an OFDMA cooperative network with  $M$  sources and  $K$  relay nodes. In each node, an OFDMA transceiver with  $N = 64$  subchannels is employed. We assume that the distances from all the sources to all the relay nodes and the distances from all the relay nodes to all the destinations are the same and normalized to one. The distance from each source to its corresponding destination is normalized to two; the path loss exponent is 4. Shadowing is not considered. We assume that the channels between each source and each relay and the channels between each relay and each destination are independent. The power delay profile is assumed to be exponential with a root-mean-square delay spread  $\tau_{rms} = \eta T$ , where  $T$  is the time duration of one OFDMA symbol (block),  $T = NT_s$ , where  $T_s$  is the time duration of one sample, and  $0 < \eta \leq 0.1$ . In the simulation, we use a discrete-time model with an impulse response limited to 16 samples spaced by  $T_s$ . This is sufficient to encompass all of the paths with significant energy.

We assume the total target bit rate of the system is such that there are 128 bits per OFDM symbol. Each user has the same target rate, that is,  $R_m = 128/M$ , and  $b_{m,n}$  can take values in the set  $B = \{0, 1, 2, 3, 4\}$ . Without resource allocation, each user will be allocated  $64/M$  subchannels and a subchannel will transmit 2 bits per OFDM symbol; we call this Fixed Subchannel and Bit Allocation (FSBA).

In Fig. 2, we compare the average required transmission power for FSBA, and resource allocation with and without

subchannel permutation. We assume there is two sources and one relay node, i.e.,  $M = 2$  and  $K = 1$ . We notice that the required transmission power for ACG and ACGSP decreases with an increase in the delay spread,  $\tau_{rms}$ . This is because an increase in delay spread corresponds to more available frequency diversity, and hence greater gains can be achieved. The performance of FSBA is not good because frequency diversity and multiuser diversity are not exploited. Compared to FSBA, a 5.5-dB power saving can be achieved by ACG. With subchannel permutation, the required transmission power can be further reduced by 2 dB.

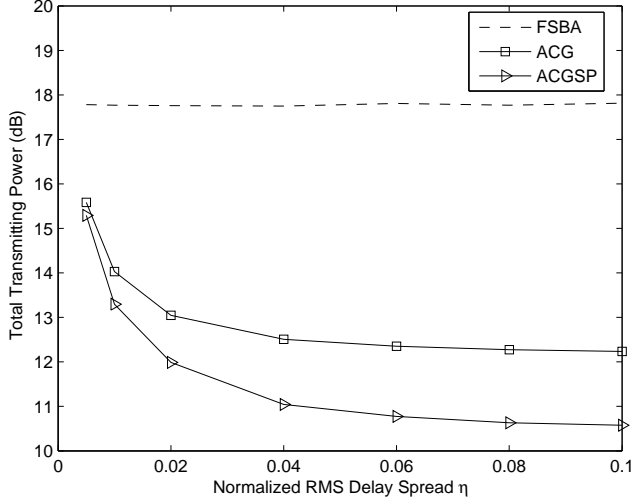


Fig. 2. Average transmission power required for different resource allocation algorithms with  $M = 2$  and  $K = 1$ .

In the following simulation, we assume  $\tau_{rms} = 0.1T$ , which is a reasonable delay spread for practical systems. Fig. 3 presents the outage performance with different numbers of relay nodes. The outage is defined as the total required transmission power is greater than the available transmission power. We compare the performance of FSBA and ACG. We can see that the performance gains of ACG over FSBA decrease with an increase in  $K$ , the number of relay nodes. For  $\tau_{rms} = 0.1T$ , the power saving of ACG decreases from 6-dB with one relay node to 2-dB with four relay nodes. The main reason is that, for each subchannel, we compare the subchannel gains of  $K$  relay nodes and select the best one. The more relay nodes, the less subchannel gain variation after selection, and the less frequency diversity.

In Fig. 4, we present the performance of the resource allocation algorithms using subchannel permutation with  $K = 1, 2,$  and  $4$  relay nodes, respectively. Compared with FSBA, a dramatic performance gain can be achieved by ACG with SP, even in the case when four relay nodes are employed. For a 10% outage, the performance gain is 4dB with 4 relay nodes. In Fig. 5, we compare the performance of two resource allocation algorithms with subchannel permutation. We can see that JSASP is about 0.5-dB better than ACGSP, where subchannel allocation and subchannel permutation are separated, at the expense of more complexity. A good complexity-performance tradeoff can be achieved by using the ACGSP.

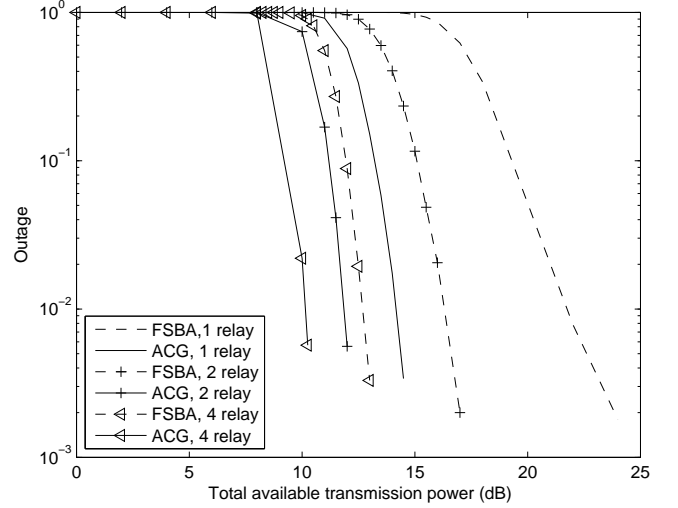


Fig. 3. Outage of FSBA and ACG with  $M = 2$  and  $K = 1, 2, 4$ .

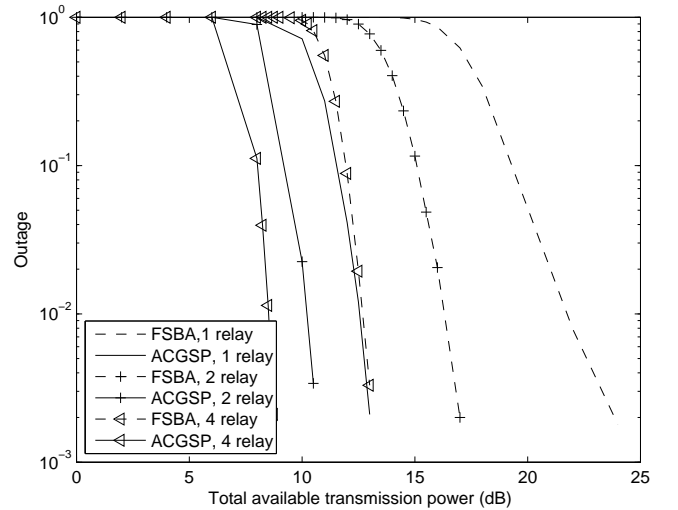


Fig. 4. Outage of FSBA and ACGSP with  $M = 2$  and  $K = 1, 2, 4$ .

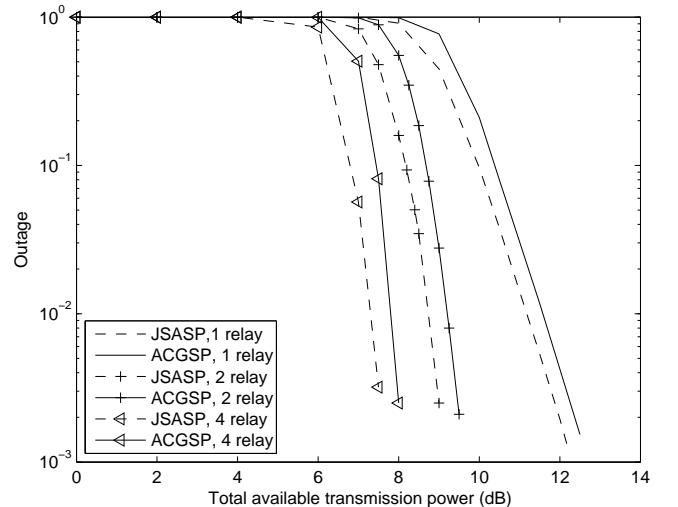


Fig. 5. Outage of two resource allocation algorithms with subchannel permutation,  $K = 1, 2, 4$ .

From these results, we can see that resource allocation can provide a significant savings in transmission power, especially when the number of relays is small. A small number of relays on their own does not provide enough space diversity. So, even simple resource allocation without SP can provide significant gains compared to fixed resource allocation. With an increase in the number of relays, however, space diversity can provide good performance improvement; thus, subchannel permutation is required to obtain additional performance gains.

In the following, we compare the performance of the decentralized adaptive resource allocation and the decentralized fixed resource allocation. For the decentralized fixed allocation, the same process as the decentralized adaptive resource allocation is performed. Only one relay node is selected to relay the information and all the subchannels have the same number of bits. The ACGSP is employed in the decentralized adaptive resource allocation algorithm. As shown in Fig. 6, the decentralized ACGSP algorithm significantly outperforms the decentralized fixed allocation algorithm (FSBA), even with four relay nodes. Compared with the centralized ACGSP algorithm, a 2.5-dB performance degradation is observed with 4 relay nodes; the main reason is that only one relay node is selected in the decentralized algorithm.

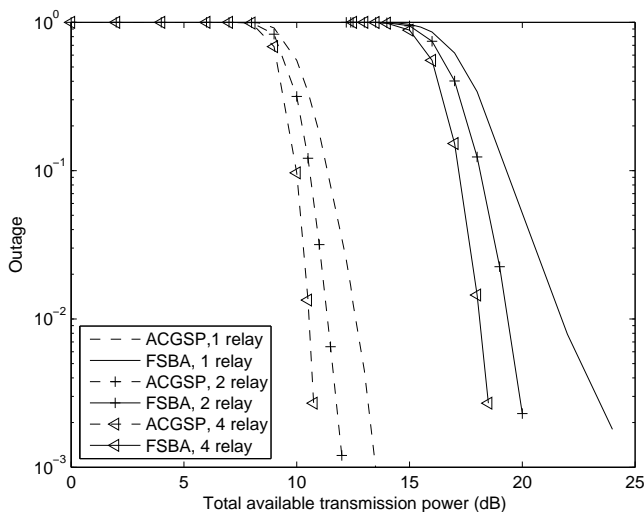


Fig. 6. Outage of decentralized resource allocation algorithms with  $M = 2$  and  $K = 1, 2, 4$ .

## VI. CONCLUSIONS

In this paper, we investigated multiuser resource allocation for cooperative OFDM systems. Aiming at minimizing the total two-stage transmission power for a given transmission rate for each user, we formulated the optimization problem and proposed several resource allocation algorithms. First, without considering subchannel permutation, we showed that the optimization problem is similar to the one for point-to-point OFDM systems. To further improve the performance gain, we considered reallocating subchannels in the RD links, called subchannel permutation. Two subchannel permutation algorithms were proposed. Simulation results show that the

simple algorithm, ACGSP, can further improve the performance by at least 2dB. Even with four relay nodes, the resource allocation with subchannel permutation still outperforms fixed resource allocation by about 4dB when there are two users. The joint subchannel allocation and subchannel permutation algorithm performs a little better than ACGSP at the expense of computational complexity. The decentralized resource allocation algorithm is also considered and the simulation results demonstrate its good performance.

In this paper, we focused on low complexity and efficient algorithms. The optimal resource allocation with subchannel permutation is needed to serve as the performance bound and is the focus of our current work. Also, an investigation of some of the practical issues, such as timing and frequency synchronization, is warranted.

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