Margin Adaptive Optimization in Multi-User MISO-OFDM Systems under Rate Constraint

Chuanming Wei, Ling Qiu, and Jinkang Zhu

Abstract: **In this paper, we focus on the total transmission power minimization problem for downlink beamforming multiple-input multiple-output (MIMO) orthogonal frequency division multiplexing (OFDM) systems while ensuring each user's QoS requirement. Although the linear integer programming (LIP) solution we formulate provides the performance upper bound of the margin adaptive (MA) optimization problem, it is hard to be implemented in practice due to its high computational complexity. By regarding each user's equivalent channel gain as approximate independent values and using iterative descent method, we present a heuristic MA resource allocation algorithm. Simulation results show that the proposed algorithm efficiently converges to the local optimum, which is very close to the performance of the optimal LIP solution. Compared with existing space division multiple access (SDMA) OFDM systems with or without adaptive resource allocation, the proposed algorithm achieves significant performance improvement by exploiting the frequency diversity and multi-user diversity in downlink multiple-input single-output (MISO) OFDM systems.**

Index Terms: **Beamforming, bit error rate (BER), linear integer programming (LIP), margin adaptive (MA), multiple-input single-output orthogonal frequency division multiplexing (MISO-OFDM).**

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is regarded as a promising technology for high speed wireless communication systems due to its ability to divide a frequency selective broadband channel into a number of orthogonal narrowband subchannels. Recent studies have shown that in a multi-user OFDM system, significant performance gain can be obtained by effective resource allocation among different users [1]–[3].

A downlink multi-user multiple-input single-output (MISO) OFDM system with multiple antennas at the base station is considered in this paper. Using space division multiple access (SDMA) technique, multiple users could transmit simultaneously on the same subcarrier, which not only increases the spectral efficiency of the system, but also provides additional resource allocation freedom in spatial dimension. [4], [5] studied power and bit allocation in so-called SDMA-OFDM systems where OFDM is used as a modulation technique and each user's data are transmitted on all subcarriers. The number of users supported in each OFDM symbol is limited by the number of antennas at the base station in SDMA-OFDM systems. For multi-user beamforming MISO-OFDM systems with dynamic subcarrier allocation, [6] and [7] investigated the rate adaptive (RA) resource allocation problem. The objective of RA optimization is to maximize the sum rate of all users in the system with a total transmission power constraint.

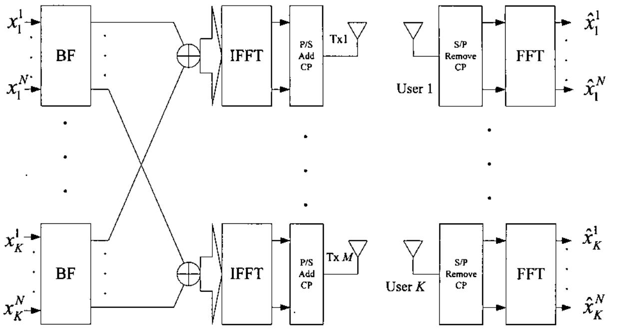

Fig. 1. Block diagram for a multi-user beamforming MISO-OFDM system.

In this paper, we aim at margin adaptive (MA) optimization problem in a downlink beamforming multi-user MISO-OFDM system, which is to minimize total transmission power while fulfilling each user's data rate and bit error rate (BER) requirement. The most difficult part in this problem is that each user's equivalent channel gain is decided by the subcarrier allocation; however, existing MA algorithms require the knowledge of every user's channel gain on different subcarriers. Here, we formulate this problem as a linear integer programming (LIP) problem. Due to the high computational complexity of the optimal LIP solution, we present a heuristic MA algorithm with polynomial complexity. Simulation results show that the performance of proposed algorithm is very close to that of the LIP solution. Compared with nonadaptive SDMA-OFDM systems and SDMA-OFDM systems with bit and power allocation [4], [5] our algorithm achieves significant performance improvement.

The multi-user MISO-OFDM system model is described in Section II. In Section III, the LIP optimization problem is formulated. Our heuristic MA resource allocation algorithm is proposed in Section IV. Simulation results are presented and discussed in Section V. Finally, Section VI contains conclusion remarks.

II. SYSTEM MODEL

In a multi-user MISO-OFDM system with downlink beamforming, the base station is equipped with M transmit antennas while each user is equipped with one receive antenna. The system has N subcarriers and K users (K could be larger than M). The block diagram of our system is shown in Fig. 1.

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It is assumed that the base station can acquire perfect channel state information (CSI). Subcarriers are allocated dynamically to different users. Using beamforming technique, more than one users could transmit simultaneously on the same subcarrier. $\mathcal{U}_n$ represents the combination of users selected on subcarrier n. Since the number of antennas at the base station is M, the maximum number of users each subcarrier can support is M; thus, $\mathcal{U}_n$ has P possible values S_p $(1 \le p \le P)$, where $S_p \subset \{1, 2, \cdots, K\}, 0 \le |S_p| \le M, P = \sum_{l=1}^{M} \binom{M}{l}$.

The received signal of user k $(k \in \mathcal{U}_n)$ on subcarrier n is:

$$y_k^n = \mathbf{h}_k^n \left(\sum_{l \in \mathcal{U}_n} \mathbf{b}_{\mathcal{U}_n,l}^n x_l^n \right) + \eta_k^n \tag{1}$$

where $\mathbf{h}_k^n$ is $1 \times M$ channel fading vector of user k in the frequency domain on subcarrier n, $\mathbf{b}_{\mathcal{U}_n,l}^n$ is $M \times 1$ beamforming vector for user k subject to $\|\mathbf{b}_{\mathcal{U}_n,l}^n\|^2 = 1$, x_1^n is the transmitted data, η_k^n is the normalized additive white complex Gaussian noise. In this paper, beamforming vector is constructed according to the null space method [6]–[8], which means that $\mathbf{b}_{\mathcal{U}_n,l}^n$ is an orthogonal basis for the null space of a matrix with vectors $\mathbf{h}_l^n$ $(l \in \mathcal{U}_n, l \neq k)$ as its rows. So we have $\mathbf{b}_{\mathcal{U}_n,l}^n \mathbf{h}_l^n = 0$, and

$$y_k^n = \mathbf{h}_k^n \mathbf{b}_{\mathcal{U}_n,k}^n x_k^n + \eta_k^n. \tag{2}$$

The equivalent channel gain of user k on subcarrier n is

$$\alpha_{n,k,\mathcal{U}_n} = \mathbf{b}_{\mathcal{U}_n,l}^n \mathbf{h}_k^n. \tag{3}$$

III. PROBLEM FORMULATION AND LIP SOLUTION

The optimization objective in this paper is to minimize the total transmission power while ensuring each user's quality of service requirement including data rate R_k and BER constraint BER_k for user k. This problem is described as follows:

$$\min_{\mathcal{U}_n, c_{n,k}, \rho_{n,k}} \quad P_t = \sum_{k=1}^{K} \sum_{n=1}^{N} \frac{f_k(c_{n,k})}{|\alpha_{n,k,\mathcal{U}_n}|^2} \rho_{n,k} \tag{4}$$

subject to:

$$\text{C1:} \quad R_k = \sum_{n=1}^{N} c_{n,k} \rho_{n,k} \tag{5}$$

$$\text{C2:} \quad \sum_{k=1}^{K} \rho_{n,k} \le M, \forall n \tag{6}$$

$$\text{C3:} \quad \rho_{n,k} \in \{0, 1\}. \tag{7}$$

In the above, $\rho_{n,k} = 1$ means that subcarrier n is allocated to user k. User k transmits c bits on subcarrier n per OFDM symbol and constraint C1 corresponds to each user's required data rate. $f(c)$ represents the needed SNR to transmit c bits while ensuring BER constraint of user k. P_t denotes the total transmission power. The above is a nonlinear optimization problem because $f(c)$ is a nonlinear function. Considering that $c_{n,k}$ takes integer values in practice and $\mathcal{U}_n$ takes P possible values, we convert it into a LIP problem by introducing two dimensions of integer decision variables as below:

$$\min_{\rho_{n,p,k,c}} \ P_t = \sum_{k=1}^{K} \sum_{n=1}^{N} \sum_{p=1}^{P} \sum_{c=1}^{C} \frac{f_k(c)}{|\alpha_{n,k,\mathcal{U}_n}|^2} \rho_{n,p,k,c} \tag{8}$$

subject to:

$$\text{C1:}\ R_k = \sum_{n=1}^{N} \sum_{c=1}^{C} c\rho_{n,p,k,c}, \forall k \tag{9}$$

$$\text{C2:}\ \sum_{c=1}^{C} \rho_{n,p,k,c} \le 1, \forall n, p, k \tag{10}$$

$$\text{C3:}\ \rho_{n,p,k,c} = 0, \text{if } k \in S_p \forall n, p, c \tag{11}$$

$$\text{C4:}\ \sum_{c=1}^{C} \rho_{n,p,k,c} = \sum_{c=1}^{C} \rho_{n,p,l,c} \ \text{ if } k, l \in S_p, k \neq l, \forall n, p \tag{12}$$

$$\text{C5:}\ \sum_{p=1}^{P} \frac{1}{|S_p|} \sum_{k=1}^{K} \sum_{c=1}^{C} \rho_{n,p,k,c} \le 1, \forall n \tag{13}$$

$$\text{C6:}\ \rho_{n,p,k,c} \in \{0, 1\}, \forall n, p, k, c. \tag{14}$$

Here $\rho_{n,p,k,c} = 1$ means the user set on subcarrier n is S_p, and user k in the set transmits c bits on this subcarrier. Constraint C1 and C2 correspond to each user's data rate constraint. Constraint C3 means that users out of set S_p should not transmit any data on subcarrier n. Constraints C4 and C5 limit only one possible user set selected for each subcarrier.

Above problem could be solved by LIP since the objective and constraints are all linear functions of variables $\rho_{n,p,k,c}$. However, the complexity of LIP solution increases exponentially with the number of constraints and variables [2]. It can hardly be implemented if $N \times P \times K \times C$ is large. On the other hand, existing heuristic MA algorithms for multi-user OFDM systems require knowledge of each user's equivalent channel gain on every subcarrier [1]–[3]. However, in our problem user's equivalent channel gain is determined by the user sets selected for each subcarrier. Existing heuristic MA algorithms for multi-user OFDM systems can not be directly applied to our problem. In the following section, we propose an efficient heuristic MA resource allocation algorithm.

IV. HEURISTIC MA RESOURCE ALLOCATION ALGORITHM

Our proposed heuristic MA resource allocation algorithm includes two subsections: The initial user selection and the iterative resource allocation. In the initial user selection, we use the norm of each user's channel fading vector to take the place of their equivalent channel gain, which overcomes the difficulty that we do not know their channel gain before confirming the user sets of every subcarrier. Then, we use a modified subcarrier allocation algorithm to obtain the initial user selection. In the second subsection, we change the user set on each subcarrier iteratively to search for the possible user selection and resource allocation which is close to the optimal LIP solution.

A. Initial User Selection

From (3), we note that the channel gain of user on subcarrier n is determined by the channel vector $\mathbf{h}_k^n$ and the beamforming vector $\mathbf{b}^n_{\mathcal{U}_n,l}$ for user k, while $\mathbf{b}^n_{\mathcal{U}_n,l}$ depends on the user set selected for subcarrier n. $\mathbf{h}^n_k$, which is not very accurate but independent of user selection, can be regarded as an estimation of the equivalent channel gain.

Replace $|\alpha_{n,k,\mathcal{U}_n}|^2$ in (4) with $|\tilde{\alpha}_{n,k}|^2 = |h^n_k|^2$, thus the modified problem becomes:

$$\min_{\rho_{n,k,c}} P_t = \sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{c=1}^{C} \frac{f_k(c)}{|\tilde{\alpha}_{n,k}|^2}\rho_{n,k,c} \tag{15}$$

subject to:

$$\text{C1:} \quad R_k = \sum_{n=1}^{N}\sum_{c=1}^{C} c\rho_{n,k,c} \forall k \tag{16}$$

$$\text{C2:} \quad \sum_{c=1}^{C} \rho_{n,k,c} \leq 1, \forall n, k \tag{17}$$

$$\text{C3:} \quad \sum_{k=1}^{K}\sum_{c=1}^{C} \rho_{n,k,c} \leq L, \forall n \tag{18}$$

$$\text{C4:} \quad \rho_{n,k,c} \in \{0, 1\}, \forall n, k, c \tag{19}$$

where $\rho_{n,k,c} = 1$ means that user k transmits c bits on subcarrier n. In constraint C3, $L = \min(K, M)$ denotes the largest number of users supported on each subcarrier.

Since user's channel gain in above problem is independent of user selection, problem (15) can get resolved using MA algorithms for single antenna OFDMA systems [1]–[3]. Notice that the number of users supported on each subcarrier in above problem becomes L which is 1 in single antenna OFDMA systems. So existing MA algorithms should be modified as below.

Replace every subcarrier in above problem using its L copies. Each user's channel gain on the duplicated subcarriers is the same as that on the original subcarrier. Allocate $N \times L$ subcarriers in the modified system to each user according to existing MA algorithms. Remember that if one duplicated subcarrier is employed by a user, other $L - 1$ duplicated subcarriers can not be allocated to this user. Bit and power allocation on all L duplicated subcarriers for each user is the solution of problem (15).

B. Iterative Resource Allocation

It is obvious that solution of problem (15) is not optimal for problem (4). In this step, iterative resource allocation based on the initial user selection result is performed for each subcarrier to improve the system power efficiency. This idea comes from the Bit-swapping method which is widely adopted to update bit loading in DSL systems [10], single-user OFDM systems [11], and uplink MIMO-OFDM systems with multi-user detection (MUD) [12]. Here, we apply the descent method to the user set selection for each subcarrier.

According to last step, we can get initial values of $\mathcal{U}_n$ $(1 \leq n \leq N)$. Then, construct each user's beamforming vector to get the equivalent channel gain on different subcarriers. Transmission rate and power for each user are allocated to every subcarrier using greedy approach [1]. Denote the total transmission power as P'_t.

Step 1. Use Ind to indicate if $\mathcal{U}_n$ has been changed. Set $Ind = 0$.

Step 2. For $n = 1$ to N:

- Change $\mathcal{U}_n$ to other P possible values.
- Reallocate the transmission rate and power of related users during each user set change.
- Recalculate the total transmission power for different $\mathcal{U}_n$.
- Choose the user set with the minimum power P''_t.
- If $P''_t < P'_t$, update the resource allocation and set $P'_t = P''_t$, $Ind = 1$.

Step 3. Repeat above steps until $Ind = 0$ after *Step 2*.

C. Convergence Analysis

During each iteration, a resource allocation scheme which requires less power is selected. Thus, the proposed algorithm converges because the total transmission power is always decreased during the iterative resource allocation subsection. Although it is just a local optimum, simulation results show that the performance of the proposed algorithm is very close to that of the global optimal solution gotten from LIP approach.

D. Complexity

Using subcarrier allocation algorithm proposed in [3], the initial user selection subsection needs $\mathcal{O}(NLK)$ calculations. $\mathcal{O}(NLB)$ calculations are required every time Greedy approach is performed, where B is determined by each user's transmission rate and the number of bits added to a subcarrier at one time in Greedy approach. Thus, the complexity of our proposed algorithm is $\mathcal{O}(IPN^2LB + NLK)$ where I denotes the number of needed iterations and is set to be less than 10 in our simulation. It is polynomial and much lower than the complexity of the optimal LIP solution.

V. SIMULATION RESULTS

The performance of the proposed MA algorithm is investigated in this section. An OFDM system with 64 subcarriers is considered. The channel model is a 5-path Rayleigh fading channel with an exponential delay profile. For adaptive bit loading, QPSK, 16QAM, 64QAM, and no data transmission are adopted here. When uncoded 2^c-ary QAM is empolyed, the required SNR function can be tightly approximated as $f_k(c) = (1 - 2^c)(\log 5\,\mathrm{BER}_k)/1.6$ [9]. The subcarrier allocation algorithm in [3] is employed to obtain the initial allocation.

In Figs 2 and 3, the performance of our proposed heuristic MA resource allocation algorithm is compared with the optimal LIP solution. Due to the complexity of the LIP approach, we consider only 2 antennas at the base station in this scenario. For cases with different number of users, the total transmission rate is fixed at 256 bits per OFDM symbol. The rate constraints for every user are the same.

Fig. 2 illustrates the convergence process of our proposed MA heuristic algorithm. We restrict the iteration number in the iterative resource allocation subsection and observe the required transmission power which is denoted as the SNR value per OFDM symbol. The BER requirement is set to 10^{-3}. The dashed line and the dash-dot line represent the transmission power of LIP solution for 2 users and 4 users, respectively. As the iteration number increases, our algorithm approaches the

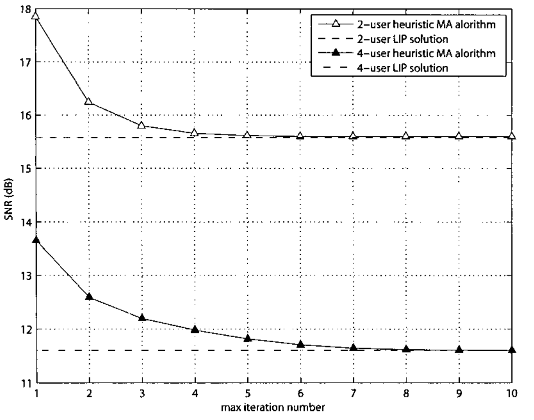

Fig. 2. Influence of the iteration number to the required transmission power of the system.

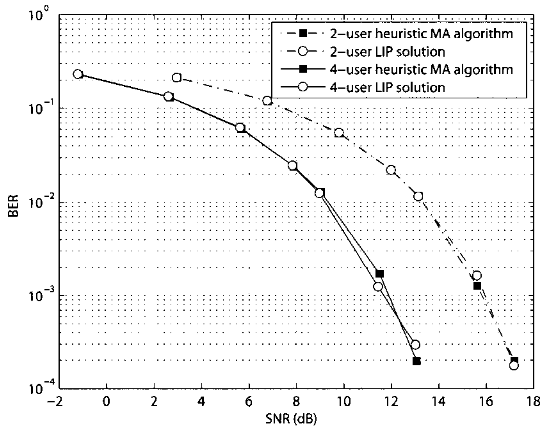

Fig. 3. Performance comparison of the proposed heuristic MA algorithm with the optimal LIP solution.

performance of the optimal solution. There is very little gap between the convergence value of the proposed MA heuristic algorithm and the optimal value. That is because our algorithm can not guarantee convergence to the global optimum every time. It is also worthwhile to note that more iterations are required while increasing the number of user in the system.

Fig. 3 compares the BER versus SNR curves of the MA heuristic algorithm and the optimal LIP solution. We obtain the BER curves by calculating needed transmission power for different resource allocation algorithms given several BER requirements. As can be seen, their performances are very close. Notice that since dynamic subcarrier allocation may efficiently exploit the multi-user diversity in beamforming MIMO-OFDM systems, increasing the number of users leads to better performance (about 4 dB multi-user gain in this case).

We consider a nonadaptive SDMA-OFDM system and another adaptive SDMA-OFDM system with bit and power allocation [5]. There are 4 antennas at the base station. Neither of the two systems adopts subcarrier allocation. When the number of users in these systems exceeds the transmit antennas number at the base station, users are selected as Round-Robin fashion for each subcarrier. For example, user set $\{1, 2, 3, 4\}$ is selected on the first subcarrier and user set $\{5, 6, 1, 2\}$ is selected on the next subcarrier, etc. There is no power control in the nonadaptive SDMA-OFDM system and each subcarrier employs QPSK modulation. A bit and power loading algorithm proposed in [5] is used in the adaptive SDMA-OFDM system. The major differences among these systems and the system discussed in this paper are illustrated in Table 1.

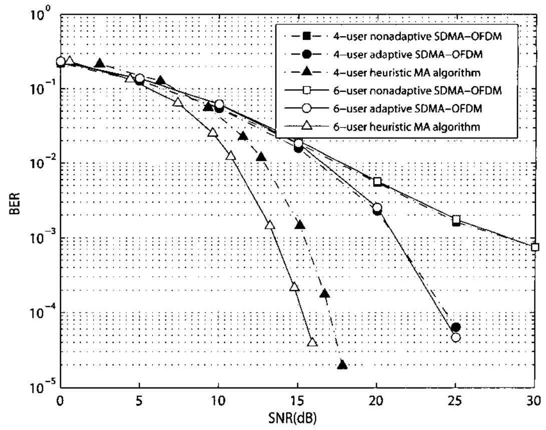

Fig. 4. Performance comparison of the proposed algorithm with existing systems.

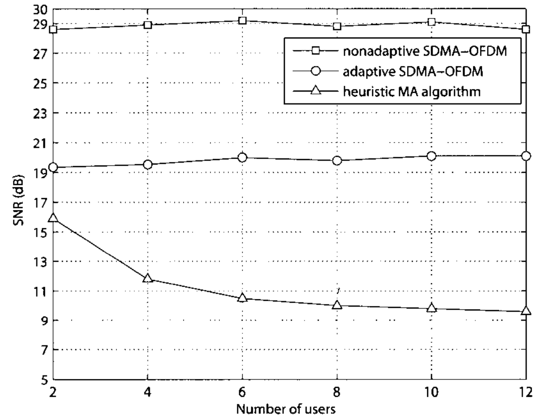

Fig. 5. The number of users versus required transmission power for different systems.

Table 1. Comparison for different resource allocation schemes.

Resource allocation	Nonadaptive SDMA -OFDM[5]	Adaptive SDMA -OFDM[5]	Heuristic MA algorithm
Beam	fixed	fixed	dynamic
Subcarrier	fixed	fixed	dynamic
Bit	fixed	dynamic	dynamic
Power	fixed	dynamic	dynamic

Performance comparison of our proposed algorithm with adaptive and nonadaptive SDMA-OFDM systems is shown in Fig. 4. The total transmission rate is fixed at 512 bits per OFDM

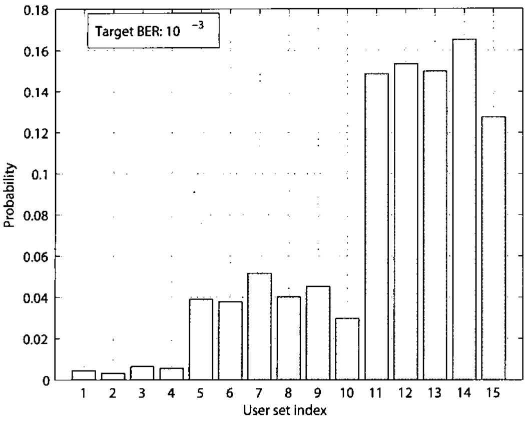

Fig. 6. Each possible user set's probability of being selected on every subcarrier in a 4-antenna 4-user beamforming MISO-OFDM system.

symbol. The dashed lines are for 4-user case and the solid lines are for 6-user case. It is easy to see that the nonadaptive system has the worst performance. The adaptive SDMA-OFDM system has better performance than the nonadaptive one due to bit and power allocation. Using user selection (dynamic subcarrier allocation) and resource allocation, our proposed algorithm achieves significant performance improvement by exploiting the frequency diversity and multi-user diversity in the system. Also notice that the performances of SDMA-OFDM system for 4-user case and 6-user case are almost the same. However, about 2 dB multi-user gain can be obtained using our algorithm.

Fig. 5 compares required transmission power for the proposed heuristic MA algorithm and SDMA-OFDM systems. The number of antennas at the base station is 2 and the total transmission rate is 256 bits per OFDM symbol. The number of users varies from 2 to 12 and each user's BER requirement is 10^{-3}. Obviously, without dynamic subcarrier allocation among different users, SDMA-OFDM systems in [5] could hardly achieve any multi-user gain while the required transmission power in the proposed algorithm is reduced as the number of users increases.

Consider a downlink 4-user beamforming MISO-OFDM system with 4 antennas at the base station. Fig. 6 shows each possible user set's probability of being selected on a subcarrier in our proposed algorithm. The user set indices in Fig. 6 denote the 15 possible user combinations in sequence: $\{1\}$, $\{2\}$, $\{3\}$, $\{4\}$, $\{1,2\}$, $\{1,3\}$, $\{1,4\}$, $\{2,3\}$, $\{2,4\}$, $\{3,4\}$, $\{2,3,4\}$, $\{1,3,4\}$, $\{1,2,4\}$, $\{1,2,3\}$, $\{1,2,3,4\}$. Their probabilities are calculated over 1000 channel realizations. As the figure illustrates, although the system can support up to 4 users transmitting simultaneously on each subcarrier, user sets with 3 users (indices 11 to 14 in Fig. 6) have more chances to be selected. This is due to the fact that when the number of users on a subcarrier is less than the base station antenna number, the interferences between users may be decreased and more transmission diversity gain is achieved. Also, the MISO-OFDM system allows the unselected users to transmit on other subcarriers. Such character might be valuable in the design of practical beamforming MISO-OFDM systems.

VI. CONCLUSION

In this paper, a downlink multi-user beamforming MISO-OFDM system was considered. We aimed at the margin adaptive optimization problem, which was to minimize total transmission power given each user's data rate and BER constraints. This problem was formulated as a LIP problem in our paper. Since the optimal solution could hardly be implemented due to its high computational complexity, we presented a heuristic MA resource allocation algorithm with polynomial complexity. Simulation results showed that compared with existing SDMA-OFDM systems with or without resource allocation, our algorithm achieved significant performance improvement. The performance of the proposed algorithm was very close to that of the optimal solution.

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