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Novel resource allocation algorithms for multiuser downlink MIMO–OFDMA of FuTURE B3G systems

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Abstract

In this paper, subcarrier and power allocation problems for multiuser downlink MIMO–OFDMA of the FuTURE B3G TDD system are investigated. For the reciprocity of the TDD channel, the channel state information can be employed at the transmitter, thus eigen beamforming can be implemented efficiently. With the goal of minimizing the total transmit power under the condition that the QoS requirement of each user can be guaranteed, a novel dynamic resource allocation scheme is proposed to exploit the multiuser diversity gain. The proposed algorithm involves adaptive subcarrier allocation, adaptive modulation and eigen beamforming and achieves significant improvement in overall system performance. Based on the proposed scheme, a modified bit and power allocation is developed. The modified scheme reduces the computational complexity at little expense of system performance. Numerical simulations show that the proposed algorithm and the modified scheme can decrease the total transmit power effectively.

Keywords: Adaptive modulation and coding; Dynamic resource allocation; Eigen beamforming; MIMO–OFDMA

1. Introduction

Future wireless communications are expected to provide high data rates and diverse QoS with limited radio resources and harsh wireless channel conditions. The requirements promote development of dynamic resource allocation which achieves higher resource utilization and better QoS [1]. Dynamic resource allocation assigns subcarriers and bits dynamically for different users according to their instantaneous channel state information (CSI). It will become one of the most promising techniques in future wireless communication systems, as the subscriber population and service demands continue expanding.

OFDMA is an emerging multiple access technology that converts a frequency-selective fading channel into several flat-fading subchannels for mitigating the effects of intersymbol interference. In the multiuser OFDMA system, different users experience different fading at a particular instance of time; thus, multiuser diversity can be exploited by scheduling the data subcarriers to the users depending on the users' channel conditions [2]. Multiuser diversity combined with dynamic resource allocation plays a very important role in enhancing system performance of OFDMA systems, even in the case where hard fairness among users is required [3,4].

MIMO systems motivated by the pioneering work of Telatar [5] and Foschini [6] have attracted significant attention recently in wireless communications [7]. MIMO systems provide enhanced performance improvements in terms of diversity and data rate without increasing the transmit power or bandwidth. A great deal of research work has been devoted to the area of combining MIMO with OFDM systems. In this way, the wideband frequency-selective MIMO channel can be separated into many flat-fading MIMO channels.

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Such systems combine the advantages of MIMO and OFDM, and provide increased data rate and robustness against channel delay spread.

In Refs. [8,9], the multiuser subcarrier and bit assignment problems have been extended to eigen beamforming based MIMO–OFDMA systems. By exploiting the instantaneous CSI at the transmitter, eigen beamforming converts a flat MIMO channel into a bank of scalar channels without crosstalk from one scalar channel to the other. The results have shown that the subcarrier and bit allocation achieved significant reduction in total transmit power. However, the subcarrier and bit allocation considered only the largest one or two spatial subchannels but neglected the other spatial subchannels. They could not efficiently utilize the available spatial degrees of freedom. In fact, more eigen subchannels can be exploited to transmit data.

In this paper, subcarrier and bit allocation is investigated for downlink MIMO–OFDMA of B3G TDD systems. For the reciprocity of the TDD channel, the CSI can be employed at the transmitter; thus eigen beamforming can be implemented efficiently. In order to efficiently utilize the spatial resources, the proposed algorithm extends the data transmission to all the non-zero spatial subchannels. With the goal of minimizing the total transmit power under the condition that users' fairness and QoS requirements are guaranteed, a novel subcarrier assignment scheme is proposed. The subcarriers are assigned according to the instantaneous characteristics of all the spatial subchannels on each subcarrier. Based on the subcarrier assignment, a novel metric for subcarrier and bit allocation is proposed. The proposed algorithm not only satisfies all users' QoS requirements and fairness, but also achieves more multiuser diversity. In order to reduce the computational complexity, a modified bit and power allocation scheme is proposed. The modified scheme divides the spatial subchannels of each user into groups, and the same modulation and coding are used within each group. It significantly reduces the computational complexity at little expense of the system performance.

The rest of the paper is organized as follows. The system model of downlink MIMO–OFDMA is described in Section 2. A novel dynamic subcarrier and bit allocation algorithm and its modified scheme are proposed in Section 3. The simulation results are presented and analyzed in Section 4. Finally, conclusions are drawn in Section 5.

2. System model

The downlink MIMO–OFDMA system model is presented in Fig. 1, equipped with N subcarriers, M_T transmit antennas at the base station, and M_R receive antennas for each of the K users who is served by the base station (BS). The CSI is assumed to be known perfectly at the receiver and transmitter, and the channel changes little during the transmission. At the transmitter, all users' packets are sent to the subcarrier allocation module, which allocates different subcarriers to different users according to the algorithm proposed in this paper. After the power and bits are allocated to different subcarriers according to the algorithm proposed here, the information bits are mapped into every eigen subchannel obtained by the singular value decomposition (SVD)-based eigen beamforming done on every subcarrier. Then, the symbols are sent to the IFFT module to perform OFDM modulation for every transmit antenna. After IFFT processing, cyclic prefix (CP) is added to every OFDM symbol. Finally, the OFDM symbol is transmitted from every antenna. At the receiver, the decoupling operation is performed to decode the information bits for each user.

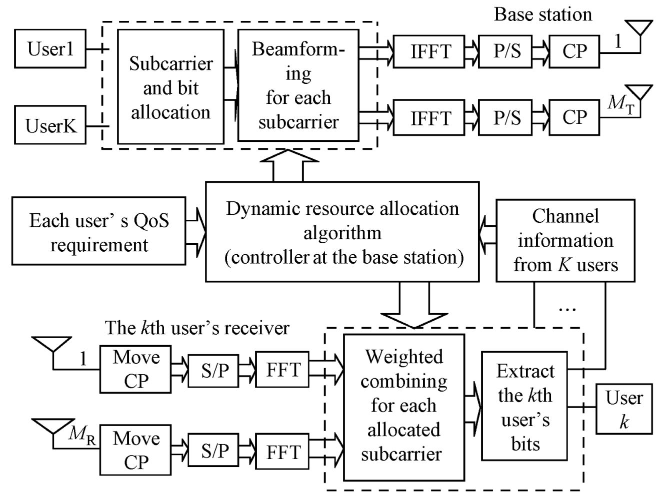

Fig. 1. The system model of MIMO–OFDMA.

The channel gain matrix experienced in subcarrier n of user k is denoted as $\boldsymbol{H}_{k,n}$. Its SVD can be presented as

$$\boldsymbol{H}_{k,n} = \boldsymbol{U}_{k,n}\boldsymbol{S}_{k,n}\boldsymbol{V}_{k,n}^H = \sum_{i=1}^{M} \boldsymbol{u}_{k,n}^i s_{k,n}^i (\boldsymbol{v}_{k,n}^i)^H \tag{1}$$

where $\boldsymbol{U}_{k,n} = [\boldsymbol{u}_{k,n}^1, \boldsymbol{u}_{k,n}^2, \ldots, \boldsymbol{u}_{k,n}^{M_R}]$ and $\boldsymbol{V}_{k,n} = [\boldsymbol{v}_{k,n}^1, \boldsymbol{v}_{k,n}^2, \ldots, \boldsymbol{v}_{k,n}^{M_T}]$ are the singular vectors, $\boldsymbol{S}_{k,n}$ is a matrix with all singular values of $\boldsymbol{H}_{k,n}$ as the diagonal elements, and $M = \mathrm{rank}(\boldsymbol{H}_{k,n})$ is the rank of $\boldsymbol{H}_{k,n}$. Let d_j denote the transmit symbol of the jth stream on subcarrier n and p_j denote the amount of transmit power allocated to d_j. Then, by precoding at the transmitter, the data received by the M_R receive antennas are given by

$$\boldsymbol{r}_{k,n} = [r_1, r_2, \ldots, r_{M_R}]^T = \boldsymbol{H}_{k,n} \sum_{j=1}^{M} \boldsymbol{v}_{k,n}^j \sqrt{p_j} d_j + \boldsymbol{n} \tag{2}$$

where $\boldsymbol{n}$ is the noise vector with i.i.d. complex Gaussian entries, each having variance σ^2.

At the receiver, by decoding the receive symbol vector $\boldsymbol{r}_{k,n}$ with singular vector $(\boldsymbol{u}_{k,n}^j)^H$, we get the received data symbol on spatial subchannel j.

$$\begin{aligned} y_j &= (\boldsymbol{u}_{k,n}^j)^H \boldsymbol{r}_{k,n} = (\boldsymbol{u}_{k,n}^j)^H \left(\boldsymbol{H}_{k,n} \sum_{j=1}^{M} \boldsymbol{v}_{k,n}^j \sqrt{p_j} d_j + \boldsymbol{n} \right) \\ &= (\boldsymbol{u}_{k,n}^j)^H \left(\sum_{j=1}^{M} \boldsymbol{u}_{k,n}^j s_j (\boldsymbol{v}_{k,n}^j)^H \right) \left(\sum_{j=1}^{M} \boldsymbol{v}_{k,n}^j \sqrt{p_j} d_j \right) + (\boldsymbol{u}_{k,n}^j)^H \boldsymbol{n} \\ &= s_j (\boldsymbol{v}_{k,n}^j)^H \left(\sum_{j=1}^{M} \boldsymbol{v}_{k,n}^j \sqrt{p_j} d_j \right) + (\boldsymbol{u}_{k,n}^j)^H \boldsymbol{n} = s_j \sqrt{p_j} d_j + (\boldsymbol{u}_{k,n}^j)^H \boldsymbol{n} \end{aligned} \tag{3}$$

It can be seen that by precoding the transmit symbol vector at the transmit antennas with the singular vector $\boldsymbol{V}_{k,n}$ and by decoding the receive symbol vector at the receiver using singular vector $\boldsymbol{U}_{k,n}$, up to M parallel SISO channels are constructed. Among the different eigen subchannels, no crosstalk happens when the CSI is known perfectly at the transmitter and receiver. In this paper, only the low mobile speed case is considered. The CSI is assumed to be known perfectly at the receiver and transmitter, and the channel changes little during the transmission.

3. Dynamic resource allocation schemes

In this section, a dynamic subcarrier and bit allocation strategy is presented for downlink MIMO–OFDMA systems, and then a modified bit and power algorithm is shown. At the BS, the packets from different users are buffered in separate queues, which are assumed to have infinite lengths. Within one queue, packets are served in a first-in first-out (FIFO) order. Across the queues, packets are served according to the proposed resource allocation discipline.

3.1. Multiuser subcarrier allocation criterion

In multicarrier systems, minimizing the total transmit power is equivalent to minimizing the power required on each subcarrier. First, we investigate the optimization problem of the single subcarrier MIMO system. Then, we derive the optimal criterion of subcarrier allocation in multiuser scenarios. To avoid severe co-channel interference (CCI), a subcarrier can be occupied by at most one user; so, the system can be viewed as a single user system on each subcarrier. Assuming that subcarrier n is allocated to user k, with channel matrix $\boldsymbol{H}_{k,n}$, the number of spatial subchannels M, the number of bits allocated to the ith spatial subchannel $b^i_{k,n}$ with transmit power $P^i_{k,n}$, and objective bit error rate BER_{target}, the optimization problem of spatial subchannels over one subcarrier can be formulated as

$$\min \sum_{i=1}^{M} P^i_{k,n} \tag{4}$$

subject to

$$\begin{aligned} &\sum_{i=1}^{M} b^i_{k,n} = R_{k,n} \\ &BER^i_{k,n} = BER_{\text{target}} \\ &M = rank(\boldsymbol{H}_{k,n}) \end{aligned} \tag{5}$$

The greedy water-filling approach is the optimal solution to the optimization problem described above [10]. The approach assigns one bit to the subchannels at a time, and in each assignment, the subchannel that requires the least additional power is selected. The bit allocation process will not be completed until all $R_{k,n}$ bits are assigned. We consider a system that employs M-ary quadrature amplitude modulation (MQAM). Given that the required BER of user k is BER_k, the required receive power for transmitting r bits/symbol reliably at the given BER_k with unity channel gain is [11]

$$f_k(r) = \frac{N_0}{3}\left[Q^{-1}\left(\frac{BER_k}{4}\right)\right]^2 \cdot (2^r - 1) \tag{6}$$

where $Q^{-1}(x)$ is the inverse function of

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-\frac{t^2}{2}}\, dt$$

In order to maintain the required QoS (e.g. BER), the transmit power to transmit $b^i_{k,n}$ data bit on the ith eigen subchannel over the nth subcarrier is given by

$$P^i_{k,n} = \frac{f_k(b^i_{k,n})}{(s^i_{k,n})^2} \tag{7}$$

We define $\Delta P^i_{k,n}$ as the additional power to increment one more bit on the ith spatial subchannel over the nth subcarrier of user k.

$$\Delta P^i_{k,n} = \frac{f_k(b^i_{k,n} + 1) - f_k(b^i_{k,n})}{(s^i_{k,n})^2} \tag{8}$$

The basic procedures of the greedy water-filling algorithm can be described as follows:

Initialization:

For all i, set $b^i_{k,n} = 0$ and $\Delta P^i_{k,n} = \dfrac{f_k(1) - f_k(0)}{(s^i_{k,n})^2}$

Bit assignment iterations:

Repeat the following $R_{k,n}$ times:

$\hat{i} = \arg\min_{i \in \{1,\ldots,M\}} \Delta P^i_{k,n}$

$b^{\hat{i}}_{k,n} = b^{\hat{i}}_{k,n} + 1$

$\Delta P^{\hat{i}}_{k,n} = \frac{f_k(b^{\hat{i}}_{k,n}+1) - f_k(b^{\hat{i}}_{k,n})}{(s^{\hat{i}}_{k,n})^2}$

End;

Finish:

$\{b^i_{k,n}\}_{i=1}^{M}$ is the final optimal bit allocation on all spatial subchannels of the nth subcarrier.

According to the optimal bit allocation result, the corresponding minimum transmit power $J_{k,n}$ for user k on subcarrier n is calculated by

$$J_{k,n} = \min \sum_{i=1}^{M} P^i_{k,n} = \sum_{i=1}^{M} \frac{f_k(b^i_{k,n})}{(s^i_{k,n})^2} \tag{9}$$

Taking multiuser scenarios into consideration and assuming that the required data rate of each user is identical (e.g. R), the required minimum transmit power for each user to transmit R bits can be calculated by Eq. (9). In order to minimize the total transmit power of the whole system, a specified subcarrier n should be allocated to user k whose required transmit power is minimum over subcarrier n. Therefore, the criterion of multiuser subcarrier assignment is

$$k = \arg\min_{i, i \in \{1,\ldots,K\}} (J_{i,n}) \tag{10}$$

3.2. The proposed subcarrier and bit allocation

Let $\rho_{k,n}$ be the subcarrier allocation indicator; $\rho_{k,n}=1$ implies that subcarrier n is assigned to user k; otherwise, $\rho_{k,n}=0$. The optimization problem of multiuser dynamic resource allocation becomes

$$P_T = \min \sum_{n=1}^{N} \sum_{k=1}^{K} \rho_{k,n} J_{k,n} \tag{11}$$

subject to

$$\begin{aligned} &\sum_{k=1}^{K} \rho_{k,n} = 1 \\ &\sum_{n=1}^{N} \rho_{k,n} R_{k,n} = R_k \\ &BER_k = BER_{\text{target}} \end{aligned} \tag{12}$$

The optimization problem mentioned above can be implemented in three steps. The first step is to determine the number of subcarriers N_k required by each user k. The second step is to assign the specified subcarriers to each user according to the proposed subcarrier assignment approach. The last step is to allocate bits and power to all eigen subchannels. The detailed procedures are described as follows:

Step 1: The number of subcarriers N_k for user k is determined. In order to maintain the fairness among different users, the following Eq. (13) is used to initially assign the number of subcarriers for each user.

$$N_k = \left\lfloor \frac{R_k}{R_{\text{aver}}} \right\rfloor, \quad k = 1, 2, \ldots, K \tag{13}$$

where $R_{\text{aver}} = \frac{1}{N}\sum_{k=1}^{K} R_k$ denotes the average number of bits assigned to each subcarrier, when all users' minimum data rates are satisfied.

Step 2: Allocate the N_k specified subcarrier for each user k. Assuming that the data rate $R_{k,n}$, $k=1,\ldots,K$ on each subcarrier n is constant, $J_{k,n}$, $k=1,\ldots,K$ can be easily calculated according to (9). The specified subcarrier n is assigned to user k according to the following equation:

$$\rho_{k,n} = \begin{cases} 1, k = \underset{i, i\in\{1,\ldots,K\}}{\arg\min}(J_{i,n}) \\ 0, \text{otherwise} \end{cases} \tag{14}$$

The remaining subcarriers are assigned to users one by one in the same way until each user k obtains N_k subcarriers.

Step 3: After all the subcarriers are assigned to the users, the greedy algorithm is used to allocate bits and power on the eigen subchannels for each user.

3.3. The modified bit and power allocation

In this subsection, we consider only the bit and power allocation and present a modified scheme for bit and power allocation which significantly reduces the computational complexity at little expense of system performance.

As a large number of subcarriers (e.g. 2048) are usually used in MIMO–OFDMA systems, a user will get a large number of subcarriers for high-rate applications. The computational complexity of the proposed subcarrier and bit allocation is prohibitive at the transmitter. In order to reduce the computational complexity, the set of available eigen subchannels for each user can be divided into M groups, with the first group containing the best spatial subchannel on each subcarrier and the second group containing the second best spatial subchannels; the remaining groups can be obtained in a similar way. Taking user k as an example, the concrete grouping process is described in detail as follows:

Assuming that user k is allocated N_k subcarriers, the spatial subchannel matrix of user k on N_k subcarriers can be represented as

$$\boldsymbol{H}_k = \begin{bmatrix} s_{k,1}^1 & s_{k,2}^1 & \cdots & s_{k,N_k}^1 \\ s_{k,1}^2 & s_{k,2}^2 & \cdots & s_{k,N_k}^2 \\ \vdots & \vdots & \vdots & \vdots \\ s_{k,1}^M & s_{k,2}^M & \cdots & s_{k,N_k}^M \end{bmatrix} \tag{15}$$

where $s_{k,n}^1 \geqslant s_{k,n}^2 \geqslant \cdots \geqslant s_{k,n}^M$.

We divide spatial subchannels into M groups:

$$\begin{aligned} &G_1 = \{s_{k,1}^1, s_{k,2}^1, \ldots, s_{k,N_k}^1\} \\ &G_2 = \{s_{k,1}^2, s_{k,2}^2, \ldots, s_{k,N_k}^2\} \\ &\vdots \\ &G_M = \{s_{k,1}^M, s_{k,2}^M, \ldots, s_{k,N_k}^M\} \end{aligned} \tag{16}$$

The average CSI within each group is used to replace the CSI of each spatial subchannel within a group and can be calculated by

$$\text{chG}_m = \left[\sum_{i=1}^{N_k} (s_{k,i}^m)^2\right] \Big/ N_k \tag{17}$$

With the CSI, data bits for different users can be allocated to their spatial subchannels based on groups using the above-mentioned greedy algorithm. Within each group, the same modulation and coding for different spatial subchannels are used. The channel gain of each spatial subchannel within a group is equal to the average gain of all the spatial subchannels in the group. Then, bit and power allocation is implemented by the greedy algorithm based on groups. That is, we can adaptively allocate bit and power between M clusters similar to the subbands in the OFDM systems mentioned in [12].

Assuming that user k obtains N_k subcarriers and there are M parallel SISO channels on each subcarrier, we only need to allocate R_k bits between M groups, calculate the additional power M times and perform $M-1$ comparisons for assigning one bit. However, for the scheme proposed in Section 3.2, we need to calculate the additional power N_kM times and perform N_kM-1 comparisons for assigning one bit. So the computational complexity of the modified scheme is significantly decreased, especially when the number of subcarriers assigned to a user is very large. We conclude this subsection by pointing out that the advantage of the proposed approach is obtained at the expense of a slight decrease in system performance.

4. Simulation results

In this section, we present some simulation results and comparisons that demonstrate the potential of our proposed schemes. We consider only the subcarrier and bit allocation for MIMO–OFDMA systems in a single-cell scenario. Inter-cell interference is not considered. The system parameters are shown in Table 1. These parameters are chosen for the purpose of demonstrating the numerical results only.

We simulate four MIMO–OFDM resource allocation schemes, namely, fixed subcarrier allocation (FSA), dynamic subcarrier allocation with only the best eigen subchannels used (DSA-BES), proposed algorithm (PA) and modified algorithm (MA).

Figs. 2 and 3 show the performance of the four resource allocation schemes versus the number of users with two receive antennas and four transmit antennas. It can be seen from Figs. 2 and 3 that the proposed scheme achieves the best performance, especially when the number of users is large. The reason is that it not only employs dynamic resource allocation, but also exploits all the spatial subchannels which result in the increase in multiuser diversity. It can also be seen that the modified scheme is a little worse than the proposed scheme. The reason is that the MA does not use the multiuser diversity efficiently because of the grouping mechanism of spatial subchannels.

Table 1
Simulation parameters.

Parameters	Value
Carrier frequency	2 GHz
System bandwidth	2.5 MHz
Number of data subcarriers	128
Cell radius	1 km
User distribution	Uniform
Number of users	2–24
Number of transmit bits for each user	48
Required BER of each user	10^{-3}
Number of transmit antennas	4
Number of receive antennas	2, 4

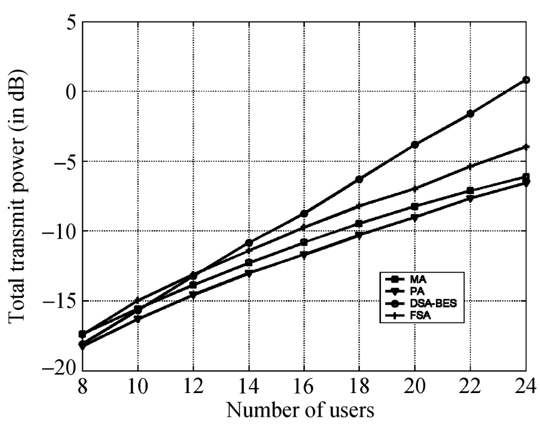

Fig. 2. Total transmit power versus the number of users for different algorithms.

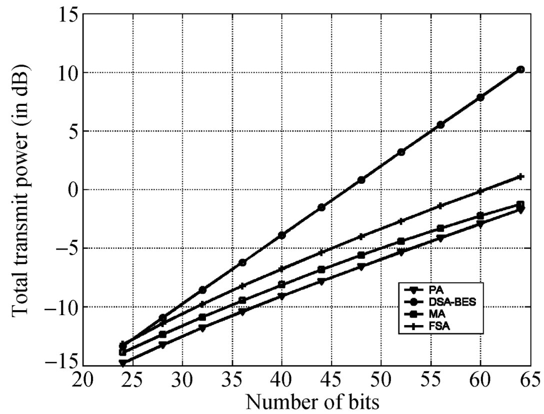

Fig. 3. Performance comparisons of different algorithms versus the number of bits transmitted for a user in each OFDM symbol with 24 users.

Fig. 4 shows the performance comparisons of the PA and the FSA scheme with two and four receive antennas, respectively. Simulation results demonstrate that the required transmit power is decreased as the number of receive antennas is increased, and the relative gain of each scheme is increased as the number of users is increased. This is because the increase in the spatial resources brings more performance gain and multiuser diversity gain.

Fig. 5 and 6 show the total transmit power of the PA and the MA, respectively, versus the number of users with different BERs. From Figs. 5 and 6, it can be seen that the required total transmit power is decreasing with the increase in the BER constraint; moreover, as the exponent of the BER increases, the relative increment of total transmit power required decreases gradually.

The required CPU runtime of the PA and the MA for executing an assignment process versus the number of users with four transmit antennas and two receive antennas is shown in Fig. 7. According to the results, the runtime

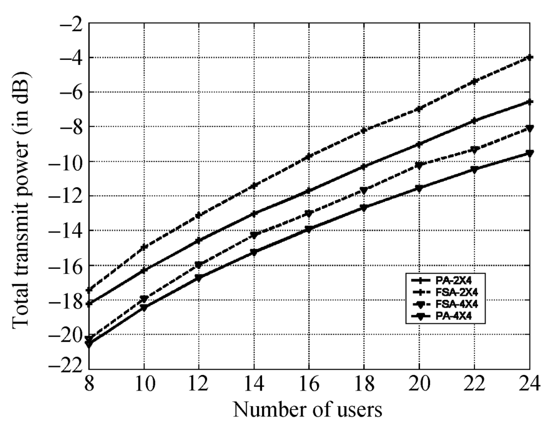

Fig. 4. Performance of the proposed algorithm with different receive antennas.

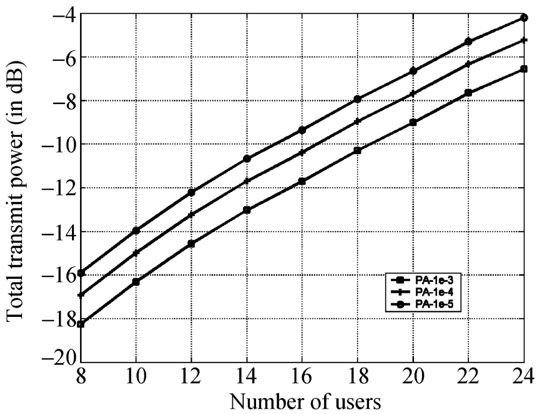

Fig. 5. Performance of the proposed algorithm with different BERs.

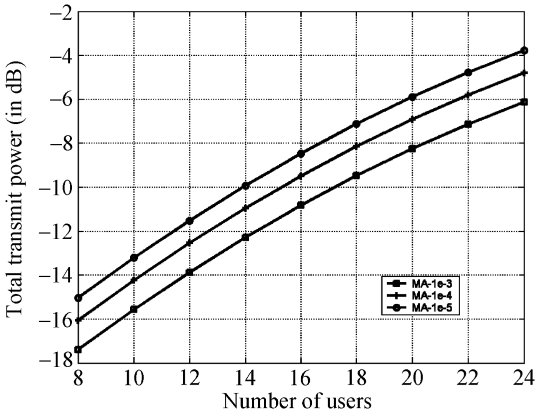

Fig. 6. Performance of the modified algorithm with different BERs.

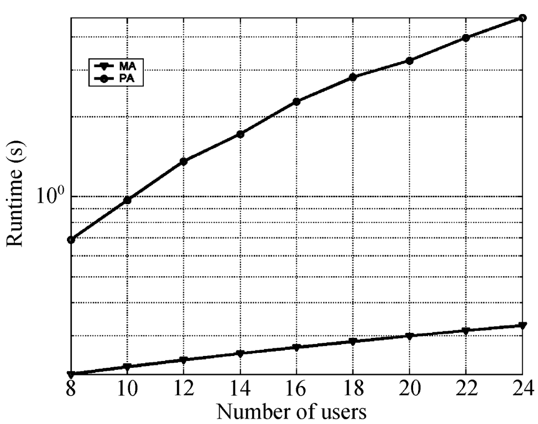

Fig. 7. The required runtime versus the number of users for the proposed algorithm and the modified algorithm.

required by the MA is much less than the PA. This proves that the computational complexity of the MA is significantly reduced.

5. Conclusions

The problems of resource allocation are considered for multiuser downlink MIMO–OFDM TDD systems. A novel dynamic resource allocation scheme is proposed. The proposed algorithm minimizes the required total transmit power under the condition that the fairness and the QoS requirements (i.e. user data rate and BER requirements) are guaranteed. In the novel scheme, a new dynamic subcarrier assignment approach based on CSI is proposed. The new scheme exploits all the eigen subchannels and allocates the bits to all the eigen subchannels of one user simultaneously, which can provide more multiuser diversity. In order to reduce the computational complexity, a modified bit and power allocation algorithm is proposed. The modified algorithm significantly reduces the computational complexity at little expense of the system performance. Simulation results demonstrate that the proposed and modified algorithms minimize the required total transmit power under the condition that the fairness and QoS requirements are guaranteed.

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