A Fairness-based and Adaptive User Grouping and Subcarrier Allocation Algorithm for Grouped MC-CDMA Systems

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Abstract—In this paper, we propose a user grouping and subcarrier allocation algorithm for grouped MC-CDMA systems. Given the fading conditions of the subcarriers of all the users, we first adaptively divide the users into groups according to their overall fading effect and then perform subcarrier allocation to each group. This scheme aims at maximizing total system throughput while guaranteeing bandwidth-fairness among groups. Simulation results are given to demonstrate the performance of the proposed algorithm in terms of time stability, total data rate, spectral efficiency and average user efficiency. We also compare the performance of our algorithm with that of random policy and the optimal scheme. The results show that our scheme outperforms the random policy and has almost the same performance as the optimal one while having considerably low complexity.

I. INTRODUCTION

Recently, Multi-carrier Code Division Multiple Access (MC-CDMA) has drawn a lot of interests from both academia and industries [1]. This powerful transmission technique possesses advantages of both CDMA and OFDM. For example, just like CDMA technology, MC-CDMA is also able to achieve multiple access, to cope with asynchronous nature of multimedia traffic in future wireless network, and to provide higher capacity than conventional access schemes such as time division multiple access (TDMA) and frequency division multiple access (FDMA). MC-CDMA can also achieve high data rate transmission and combat severe channel frequency selectivity, which are the main advantages of OFDM. Meanwhile, by using fast Fourier transform (FFT) and inverse fast Fourier transform (IFFT) devices, the transmitters and receivers of MC-CDMA can be easily implemented without increasing complexity. However, MC-CDMA is not a simple combination of CDMA and OFDM. OFDM can be seen as a special case of MC-CDMA with a spreading factor SF=1. Compared to OFDM, MC-CDMA can not only achieve high data rate transmission (e.g. 1Gb/s), but also have better performance than OFDM since MC-CDMA can get certain channel diversity without complex channel coding schemes [2]. Meanwhile, MC-CDMA can achieve universal frequency reuse [3], which is important for future cellular systems to obtain superior capacity. Furthermore, MC-CDMA is a promising solution scheme to future wireless multimedia packet-switching networks, which require multi-rate access due to the different rate requirement from a variety of applications. Therefore, MC-CDMA has been considered to be a candidate for B3G systems, e.g. for B3G mobile communication systems, B3G wireless consumer networks, and so on.

So far, a lot of research has been done on the performance of MC-CDMA systems [2-7]. Most of the work, to our best knowledge, focuses on physical layer (PHY) design, such as the bit error rate (BER) analysis, receiver design, peak-to-average power ratio reduction, and so on. There has also been some research on medium access control (MAC) layer design. For example, in [10], the authors applied rate compatible punctured turbo (RCPT) coded hybrid automatic repeat request (HARQ) to MC-CDMA systems and showed that the performance of RCPT HARQ MC-CDMA is better than that of OFDM and almost insensitive to channel characteristics.

Even though much research has been done on MC-CDMA, the radio resource management in this system is relatively unheeded, especially when compared with OFDM. In MC-CDMA, the resource of subcarriers is as important as in OFDM. Although there has been much work about subcarrier allocation or subcarrier grouping for OFDM, similar work in MC-CDMA systems is less. However, the use of subcarriers in the two systems is totally different. In OFDM, subcarriers can only be occupied by only one user while they can be shared among a large number of users in MC-CDMA systems. Furthermore, this sharing characteristic makes the allocation of subcarriers more complicated.

In this paper, we will exploit the sharing nature of subcarriers and deal with the user grouping and subcarrier allocation in a grouped MC-CDMA system [8], [9]. A grouped MC-CDMA system is such a system that divides users and subcarriers into several groups. In each group, users are distinguished by their own spreading codes and they share the same set of subcarriers. Different groups have different set of subcarriers. One main advantage of this MC-CDMA architecture is that the number of users in each group is usually small so that it is practically feasible to implement multiuser detection (MUD) per group to mitigate the detrimental effects of multiuser
interference (MUI).

In a grouped MC-CDMA system, not only the users but also the subcarriers will be grouped. The sharing nature of the subcarriers makes this grouping more complicated than in OFDM. In [11], Li and Wang proposed stochastic-ruler based algorithms for subchannel allocation to improve the system throughput. However, the authors just considered the case that each group had only one user, which may reduce the user capacity of MC-CDMA systems. Tabulo and Al-Susa[12] proposed a linear programming algorithm for a grouped MC-CDMA system, aiming at improving BER performance.

In this paper, an adaptive user grouping and subcarrier allocation algorithm is proposed for grouped MC-CDMA systems. Making use of the channel conditions, this scheme aims at maximizing the system throughput while guaranteeing bandwidth fairness among groups. We first divide the users into groups according to their average fading conditions on all subcarriers and then allocate subcarriers to the groups for which they have maximum channel gain. Finally, by way of reallocating subcarriers among groups, we ensure each group has the same number of subcarriers. Therefore, the bandwidth fairness among groups is guaranteed.

This paper is organized as follows. In Section II, we describe the grouped MC-CDMA systems and formulate the problem. Section III develops the user grouping and subcarrier allocation algorithm. Simulation results are given in Section IV, followed by the conclusion in Section V.

II. SYSTEM MODEL

A typical transmitter of the grouped MC-CDMA system is shown in Fig. 1. At first, the users are grouped by the multiuser grouping algorithm, which will be described in Section III. Then, the data bits \( d_{u,i} \) of user \( u \) are spread by a signature sequence allocated to this user. The chip streams of all users in the same group are summed up and, after subcarrier allocation, are OFDM modulated and sent through the fading channel. At the receiver, we assume that the receiver has knowledge of which group the user belongs to and which subcarriers this group has.

We suppose that there are totally \( N_u \) users and \( N_c \) subcarriers at the base station. The subcarriers are divided into \( N_g \) groups and each subcarrier has a bandwidth of \( B_c \). Both \( N_g \) and \( B_c \) are determined by system designer. For simplicity, we assume \( N_c \) can be divided by \( N_u \), i.e., \( \frac{N_c}{N_u} \) is an integer. The noise spectral power density is denoted by \( N_0 \). Thus, each group will have at most \( \lceil \frac{N_c}{N_u} \rceil \) users, where \( \lceil x \rceil \) indicates that \( x \) is rounded up to the nearest integer. Note that the users in the same group are distinguished by their own signature sequences, but share the same \( \frac{N_c}{N_u} \) subcarriers.

Suppose the channel gain on the \( j \)th subcarrier for user \( u \) is \( h(u,j) \). Then, the equivalent base-band received signal of the \( j \)th subcarrier for user \( u \) can be expressed as

\[
r(u,j) = \sqrt{P_j}h(u,j)c(u,j)d_u + N_j
\]

where \( P_j \), \( c(u,j) \) and \( d_u \) denote the transmitted power of the \( j \)th subcarrier, the \( j \)th chip of user \( u \)’s spreading code and the data bit, respectively. \( N_j \) is the additive white Gaussian noise (AWGN) on the \( j \)th subcarrier.

In grouped MC-CDMA systems, each group is small so that the noise becomes the dominant interference source [8]. Therefore, the interference from other users in the same group can be neglected and the received SINR on subcarrier \( j \) can be given by

\[
S(u,j) = \frac{P_j(h(u,j))^2}{N_0B_c}
\]

Suppose user \( u \) is in group \( g \), then the received SINR of user \( u \) is given by

\[
S(u) = \sum_{j \in X_g} \frac{P_j}{N_uN_0B_c}(h(u,j))^2 = \sum_{j \in X_g} \frac{N_gP_j}{N_cN_0B_c}(h(u,j))^2
\]

where \( X_g \) denotes the index set of subcarriers allocated to the \( g \)th group. Therefore, the achieved data rate of the \( u \)th user is

\[
R(u) = B_c \log(1 + S(u))
\]

and the total system throughput is

\[
\sum_{g=1}^{N_g} \sum_{u \in X_g^g} R(u) = \sum_{g=1}^{N_g} \sum_{u \in X_g^g} B_c \log(1 + S(u)) = \sum_{g=1}^{N_g} \sum_{u \in X_g^g} \frac{N_gP_j}{N_cN_0B_c}(h(u,j))^2
\]

where \( X_g^g \) represents the index set of users in the \( g \)th group. Furthermore, the average user efficiency can be defined as

\[
\frac{\sum_{g=1}^{N_g} \sum_{u \in X_g^g} R(u)}{Bcn_u} = \frac{\sum_{g=1}^{N_g} \sum_{u \in X_g^g} \log(1 + S(u))}{N_u}
\]

which represents the average bits each user transmits in one MC-CDMA symbol.

Our objective is to maximize the total system throughput

\[
\sum_{g=1}^{N_g} \sum_{u \in X_g^g} R(u),
\]

by designing a user grouping and subcarrier allocation algorithm. In order to avoid the case that some groups occupy too much bandwidth, we further provide bandwidth fairness among groups. To formulate this problem intuitively, we introduce three indicators: \( \rho_{u,j} \), \( \rho_{u,g} \) and \( \rho_{j,g} \), where \( u \), \( j \) and \( g \) are the indexes of users, subcarriers and groups, respectively. These three introduced variables can take only integer values of 0 or 1. \( \rho_{u,g} = 1 \) means user \( u \) is in group...
$g$, and $\rho_{u,g} = 0$, otherwise. $\rho_{u,j}$ and $\rho_{j,g}$ have similar meaning as $\rho_{u,g}$. That is, $\rho_{j,g} = 1$ means the $j$th subcarrier is allocated to the $g$th group, and $\rho_{j,g} = 0$, otherwise. $\rho_{u,j} = 1$ denotes user $u$ occupies the $j$th subcarrier, and $\rho_{u,j} = 0$, otherwise. Therefore, the total system throughput can be further expressed by

$$\sum_{g=1}^{N_g} \sum_{u \in \mathbb{X}_g^u} R(u) = \sum_{g=1}^{N_g} \sum_{u = 1}^{N_u} R(u) \rho_{u,g}$$

\[
= \sum_{g=1}^{N_g} \sum_{u = 1}^{N_u} B_c \log(1 + \frac{N_g P_j}{N_c N_0 B_c} [h(u,j)]^2 \rho_{u,j} \rho_{j,g}) \rho_{u,g}
\]

(1)

Finally our problem can be formulated as follows.

$$\max_{g = 1}^{N_g} \sum_{u \in \mathbb{X}_g^u} R(u)$$

s.t. \(\sum_{u = 1}^{N_u} \rho_{j,g} = \frac{N_c}{N_g} \forall g = 1,2,\ldots,N_g\)

\(\rho_{u,g} = \rho_{u,j} = \rho_{j,g} \quad \text{when} \quad \rho_{u,j} = 1\)

\(\rho_{u,g} \neq \rho_{j,g} \quad \text{when} \quad \rho_{u,j} = 0\)

(2)

(3)

(4)

(5)

(6)

where $\sum_{g=1}^{N_g} \sum_{u \in \mathbb{X}_g^u} R(u)$ is given by (1). Condition (3) ensures that there are at most $\lceil \frac{N_u}{N_g} \rceil$ users in each group. Condition (4) means that each group will be allocated $\frac{N_c}{N_g}$ subcarriers, which assures bandwidth fairness. Condition (5) indicates the users in the same group share the same set of subcarriers. Condition (6) reveals the relation of $\rho_{u,j}$, $\rho_{u,g}$ and $\rho_{j,g}$. When $\rho_{u,j}$ is equal to 1, which indicates user $u$ is assigned the $j$th subcarrier, then this user and the subcarrier should belong to the same group, otherwise they are not in the same group.

III. OUR SUBOPTIMAL ALGORITHM

To get the optimal solution, we should optimize the user grouping and subcarrier allocation simultaneously. This will cause high computational complexity and is not easy to be implemented in practical systems. In this section, we will develop a suboptimal algorithm which consists of two stages, namely, user grouping and subcarrier allocation, respectively. Note that both stages exploit the subcarrier fading characteristic, which is different from that in [11], where the multuser selector does not take the fading information into account.

A. User Grouping

Certain user grouping algorithm should be able to reflect users’ channel conditions to some extent and should not be too complex. Our user grouping algorithm is based on the intuition that the data rate is dependent on the channel fading gains when the transmission power of all users is the same. In order not to hold back the data rate of the group due to the large difference of channel conditions among users, we propose to put those users who have similar fading conditions into a group. The measurement we used for users’ similarity on channels conditions is their overall average fading effect.

Define a user-subcarrier-fading matrix $H = (h_{u,j})_{N_u \times N_c}$, where $h_{u,j} = h(u,j)$ is the channel gain on the $j$th subcarrier for user $u$. Our user grouping algorithm can be described as follows.

STEP 1: For each user, calculate the mean value of his channel fading on all $N_c$ subcarriers, that is, $\sum_{j=1}^{N_c} h_{u,j}/N_c$. It can roughly reflect the fading condition of the user.

STEP 2: Sort $\sum_{j=1}^{N_c} h_{u,j}/N_c$ by $u$ in descending order and then, allocate the users to the groups one by one. When a group has reached its maximum user capacity $N_u/N_g$, the following user is allocated to the next group. By this way, we finished the user grouping.

B. Subcarrier Allocation

After the user grouping has finished, the second stage deals with subcarrier allocation, that is, allocate subcarriers to the groups one by one. First, we define a group-subcarrier-fading matrix $B = (b_{g,j})_{N_g \times N_c}$, which is a $N_g \times N_c$ matrix and whose element $b_{g,j}$ is to reflect the $j$th subcarrier’s overall fading effect for the $g$th group. The key point is to find a proper expression for $b_{g,j}$ and we propose to use the sum of the square of the users’ fading within the same group, that is, $b_{g,j} = \sum_{u \in \mathbb{X}_g^u} [h(u,j)]^2$. Next, we introduce some notations. Suppose the number of subcarriers for each group is denoted by $N_i, i = 1,2,\ldots,N_g$. Let $\Theta_1$ be the index set of the groups which have more than $N_c/N_g$ subcarriers and $\Theta_2$ be the index set of the groups which have less than $N_c/N_g$ subcarriers. Our proposed subcarrier allocation algorithm can be described in details as follows.

STEP 1: For each subcarrier $j = 1,2,\ldots,N_c$, find $g'$: $g' = \arg\max_{g \in \{1,\ldots,N_g\}} b(g,j)$, then allocate this $j$th subcarrier to the $g'$th group.

STEP 2: If $\Theta_2 = \emptyset$, repetition terminated; otherwise, go to step 3.

STEP 3: Find $g_1$: $g_1 = \arg\max_{i \in \Theta_1} N_i$ and $g_2$: $g_2 = \arg\max_{i \in \Theta_2} N_i$, respectively. Get the subcarrier $j'$: $j' = \arg\min_{j \in \mathbb{X}_{g_1}} (b(g_1,j) - b(g_2,j))$, then remove this $j'$th subcarrier from group $g_1$ and reallocate it to group $g_2$. Set $N_{g_1} = N_{g_1} - 1, N_{g_2} = N_{g_2} + 1$.

STEP 4: If $N_{g_1} = N_c/N_g$, set $\Theta_1 = \Theta_1 \setminus \{g_1\}$; if $N_{g_2} = N_c/N_g$, set $\Theta_2 = \Theta_1 \setminus \{g_2\}$; go to step 2 and repeat.
Note that after the first step, the number of subcarriers among different groups may be different. Thus in the following steps, we make subcarrier reallocation to assure bandwidth fairness among groups. The rationale behind step 3 is that the subcarrier which will be exchanged from one group to another should be the one which has the minimum difference of fading between these two groups. By this way, we keep the system throughput as large as possible. Meanwhile, it is easy to see that the algorithm has time complexity $O(N)$.

IV. SIMULATION RESULTS AND DISCUSSION

In this section, the performance of the proposed algorithm is evaluated. We assume that each user’s subcarrier signal undergoes identical Rayleigh fading independently. We also assume that equal transmission power is allocated for each subcarrier. Both the bandwidth of each subcarrier $B_c$ and the noise spectral power density $N_0$ are normalized to 1.

Fig. 2 shows the stabilization of our algorithm. It depicts the total system throughput versus simulation times for the case of $N_u = 8$, $N_g = 4$ and $N_c = 64$ while the average SNR is set to 10dB. From Fig. 2, we can see that the system throughput for this algorithm can keep a stable value regardless of simulation times. The variance of the throughput is no more than 0.6%, which shows that our algorithm is stable with time.

In figure 3, the system throughput versus average SNR is depicted, when $N_u = 8$, $N_g = 2$ and $N_c = 16$. To evaluate the performance of our proposed scheme, we compare it with the optimal solution and the random policy described in [12]. The optimal scheme is derived by searching all the possible solutions and this random policy is to allocate the subcarrier randomly regardless of channel conditions. From Fig. 3, we can see that the total system throughput for all the three schemes increases with the average SNR. The performance of our scheme is almost the same as that of optimal one, with considerably low complexity. Both of them outperform the random scheme.

Fig. 4 depicts the total data rate versus the average SNR for different number of users. From this figure, it is easy to see users’ data rate increases with the SNR. The more users the system has, the higher its data rate is. On the other hand, since total data rate reflects the performance of the system as a whole, the user efficiency describes the transmission efficiency of each user from an individual point of view. Fig. 5 shows the user efficiency for the systems with different number of users. This figure indicates when the system has fewer users, its user efficiency is higher, i.e., users transmit more information during one MC-CDMA symbol. However, the difference is small and negligible. Therefore, from Fig. 4 and Fig. 5, we conclude that this system enjoys higher throughput with more users while keeping the user efficiency almost constant.

In Fig. 6, the spectral efficiency versus the average SNR for different number of groups is depicted. This figure shows that the performance of the system with more groups is much better than that having fewer groups. One reason may be that there will be fewer subcarriers per group when the number of groups increases. In MC-CDMA, the subcarriers within a group carry the same information to get frequency diversity. Therefore, when the number of subcarriers per group becomes
smaller, the total subcarriers can carry more information bits, which contribute to the improvement of system throughput.

V. CONCLUSION

In this paper, we develop a suboptimal user grouping and subcarrier allocation algorithm for multiuser grouped MC-CDMA systems. Given the users’ fading conditions on the subcarriers, we adaptively assign users into groups and then deal with subcarrier allocation one by one. Our scheme aims at maximizing the system throughput while guaranteeing the bandwidth-fairness among groups. Simulation results have shown this proposed scheme outperforms the random-allocation policy and has negligible performance gap with the optimal scheme, while having rather low time complexity. This algorithm is also stable with time. It also shows that the spectral efficiency is higher when the system has more groups.

The total data rate increases with the number of users while each user’s efficiency keeps almost invariable.

REFERENCES