

An Adaptive User Grouping and Subcarrier Allocation Algorithm for Multiuser MC-CDMA Networks

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Abstract

Grouped MC-CDMA is an efficient system with a number of attractive features. In this paper, we treat the multiuser downlink MC-CDMA system and propose a user grouping and subcarrier allocation algorithm. Given the fading conditions of the subcarriers of all the users, we first adaptively divide the users into groups and then perform subcarrier allocation to each group. This scheme aims to maximize the total system throughput while guaranteeing bandwidth-fairness among groups and the rate-fairness among users in the same group. Simulation results are given to demonstrate the performance of the proposed algorithm in terms of stability, spectral efficiency with different number of groups, and BPS(bits per symbol) per user. We also compare the performance of our algorithm with that of random policy. The result shows that our scheme outperforms the random policy.

1. Introduction

The demand for wireless communication services have been growing rapidly since the last decade, and this trend is expected to continue in the future. To meet this demand, future cellular mobile communication systems are expected to achieve high-data-rate transmission. For example, 100Mb/s 1Gb/s class wireless packet access may be necessary for 4G systems [1]. As a candidate for the 4G systems, Multi-Carrier Code Division Multiple Access (MC-CDMA) has drawn a lot of interests from researchers. This powerful transmission technique, representing a combination of frequency domain spreading and multicarrier modulation, can achieve frequency diversity and multiple access operation.

As in CDMA systems, there exists multiuser interference (MUI) in MC-CDMA systems. Although multiuser detection (MUD) can be used to mitigate the detrimental effects

of MUI, the complexity of MUD grows exponentially with the number of users. To alleviate the complexity of MUD, some grouped MC-CDMA schemes are proposed [2][3], in which the users are divided into groups. The number of users per group is small so that it is practically feasible to apply MUD per group. On the other hand, in each group, a set of codes are used to distinguish the users. Different groups can have the same set of codes, and in each group, a set of subcarriers are shared by users. The number of the users per group is small so that it is practical to implement MUD for each group. Much research has shown that such a grouped MC-CDMA system can benefit from carefully designed resource management scheme.

Resource management is another very challenging task in wireless communication systems. A promising resource management scheme should be efficient in utilizing the scarce radio resource, and be fair in scheduling services.

Till now, relative little has been done in the theme of resource management in MC-CDMA systems when compared with similar work in OFDM. Tang and Stolpman [4] proposed the concept of equivalent subcarrier, and implemented two adaptive modulation scheme based on this concept. Li and Wang [5] proposed stochastic ruler based algorithms to allocate subchannels, and thus to improve the system throughput. But 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 [6] proposed a linear programming algorithm for a grouped MC-CDMA system to improve the 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 and the delay tolerance of the non-real-time traffic, this scheme aims to maximize the system throughput. We first adaptively divide the users into groups by their fading conditions, and then allocate subcarriers to the groups for which these subcarriers have maximum channel gain. By way of reallocat-

ing subcarriers among groups, we assure the groups have the same number of subcarriers. therefore, the bandwidth among groups is guaranteed. Furthermore, we also ensure the rate-fairness among users of the same group.

The remainder of this paper is organized as follows. In section 2, we describe the grouped MC-CDMA systems and formulate the problem. Section 3 develops the user grouping and subchannel allocation algorithm. Simulation results are given in section 4, followed by the conclusion in section 5.

2. System model

The transmitter of grouped MC-CDMA systems is shown in fig1. We concentrate on downlink. In the transmitter, first the users are grouped by the multiuser grouping algorithm, which will be described in section 3. And then, the data bits of user are spread by a signature sequence allocated to this user. The chip streams of all users in the same group are summed together 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. By designing the number of users per group relative small, the receiver can implement MUD algorithm to mitigate the effect of MUI.

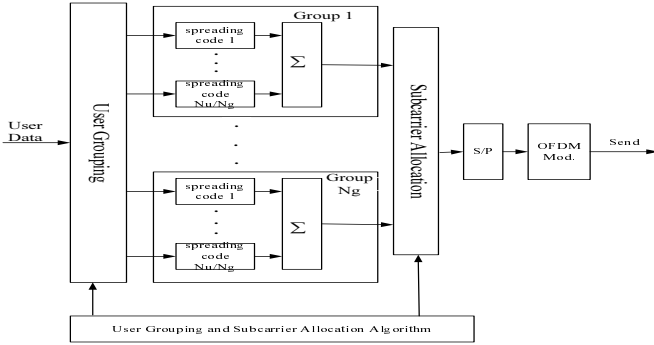


Figure 1. Transmitter of grouped MC-CDMA

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_g , i.e., $\frac{N_c}{N_g}$ is an integer. The noise spectral power density is denoted by N_0 . Thus, each group will have at most $\lceil \frac{N_u}{N_g} \rceil$ 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 $\frac{N_c}{N_g}$ 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. 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

$$S(u) = \sum_{j \in X_g} \frac{P_j}{\frac{N_c}{N_g}N_0B_c} [(h(u, j))]^2 = \sum_{j \in X_g} \frac{N_g P_j}{N_c N_0 B_c} [(h(u, j))]^2$$

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

$$\begin{aligned} \sum_{g=1}^{N_g} \sum_{u \in X_u^g} R(u) &= \sum_{g=1}^{N_g} \sum_{u \in X_u^g} B_c \log(1 + S(u)) \\ &= \sum_{g=1}^{N_g} \sum_{u \in X_u^g} B_c \log\left(1 + \sum_{j \in X_g} \frac{N_g P_j}{N_c N_0 B_c} [h(u, j)]^2\right) \end{aligned}$$

where X_u^g represents the index set of users in the g th group.

We further define the average user efficiency as

$$\frac{\sum_{g=1}^{N_g} \sum_{u \in X_u^g} R(u)}{B_c N_u} = \frac{\sum_{g=1}^{N_g} \sum_{u \in X_u^g} \log(1 + S(u))}{N_u}$$

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

Our objective is to maximize the total system throughput $\sum_{g=1}^{N_g} \sum_{u \in X_u^g} R(u)$, 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

$$\begin{aligned} \sum_{g=1}^{N_g} \sum_{u \in X_u^g} R(u) &= \sum_{g=1}^{N_g} \sum_{u=1}^{N_u} R(u) \rho_{u,g} \\ &= \sum_{g=1}^{N_g} \sum_{u=1}^{N_u} B_c \log\left(1 + \sum_{j=1}^{N_c} \frac{N_g P_j}{N_c N_0 B_c} [h(u,j)]^2 \rho_{u,j} \rho_{j,g}\right) \rho_{u,g} \end{aligned} \quad (1)$$

Finally our problem can be formulated as follows.

$$\max \sum_{g=1}^{N_g} \sum_{u \in X_u^g} R(u) \quad (2)$$

$$s.t. \sum_{u=1}^{N_u} \leq \lceil \frac{N_u}{N_g} \rceil \quad (3)$$

$$\sum_{j=1}^{N_c} \rho_{j,g} = \frac{N_c}{N_g} \quad \forall g = 1, 2, \dots, N_g \quad (4)$$

$$|\rho_{u_1,g} - \rho_{u_2,g}| = |\rho_{u_1,j} - \rho_{u_2,j}| \quad \forall g = 1, 2, \dots, N_g; \forall u_1, u_2, j \quad (5)$$

$$\begin{aligned} \rho_{u,g} &= \rho_{j,g} && \text{when } \rho_{u,j} = 1 \\ \rho_{u,g} &\neq \rho_{j,g} && \text{when } \rho_{u,j} = 0 \end{aligned} \quad (6)$$

$$R(u_i) = R(u_j) \quad \forall u_i, u_j \in \text{the same group} \quad (7)$$

where $\sum_{g=1}^{N_g} \sum_{u \in X_u^g} R(u)$ 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. Condition (7) is to guarantee the equal rates among users in the same group.

3. Our suboptimal algorithm

To get the optimal solution of (1), we should optimize the user grouping and subcarrier allocation simultaneously. This will cause very high computational complexity and so is not easy to implement in practical systems. So, in this section, we will develop a suboptimal algorithm which consists of two stages, namely, user grouping and subchannel allocation, respectively. Note that both steps exploit the subcarrier fading characteristic, which are different from

those in [5], where the multiuser selector does not take these fading information into account.

3.1. 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 \mathbf{H} as $\mathbf{H} = (h_{u,j})_{N_u \times N_c}$, 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.

3.2 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 $\mathbf{B} = (b_{g,j})_{N_g \times N_c}$, 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, $b_{g,j} = \sum_{u \in X_u^g} [h(u,j)]^2$. Next, we introduce some notations. Suppose the number of subcarriers for each group is denoted by $N_i, i = 1, 2, \dots, N_g$. 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.

1, // fill in the group-subcarrier-fading matrix \mathbf{B}

For $j = 1$ to N_c

{

For $g = 1$ to N_g

{

A, find $h(u', j)$ satisfying $h(u', j) = \min h(u, j)$ for the g th group, where u represents the user in the g th group;
 B, fill in B: $b(g, j) = h(u', j)$;
 }
 }

2, // allocate the subcarriers to the groups
 For $j = 1$ to N_c
 {
 Find the g' satisfying $b(g', j) = \max_g b(g, j)$ for all g , then
 allocate this j th subcarrier to the g' th group
 }

3, // subcarrier reallocation
 {
 For all $g \in \Theta_2$, find the group g_2 which has the largest number of subcarriers in Λ_2
 For all $g \in \Theta_1$, find the group g_1 which has the largest number of subcarriers in Λ_1
 Find the subcarrier j' which satisfies: $b(g_1, j') - b(g_2, j') = \min_{j \in g_1} (b(g_1, j) - b(g_2, j))$, where j represents the subcarrier used by group g_1 ; then reallocate this j' th subcarrier to the g_2 th group;
 Update Θ_1 , $\Theta_1 = \Theta_1 - \{g_1\}$ if the number of subcarriers of g_1 th group decreases to N_c/N_g
 Update Θ_2 , $\Theta_2 = \Theta_2 - \{g_2\}$ if the number of subcarriers of g_2 th group increases to N_c/N_g
 }

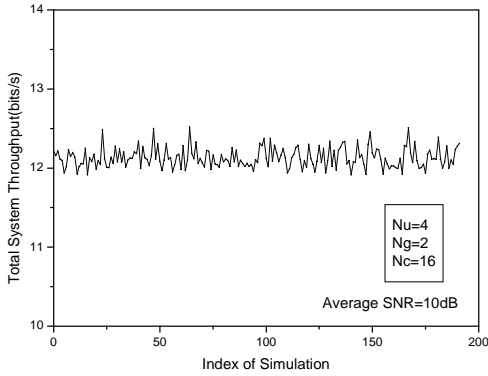


Figure 2. Total system throughput versus simulation times for the case of $N_u = 4$, $N_g = 2$, $N_c = 16$ and average SNR = 10dB

4. Numerical results

In this section, the performance of the proposed algorithm is evaluated. We assume that each user's subcarrier

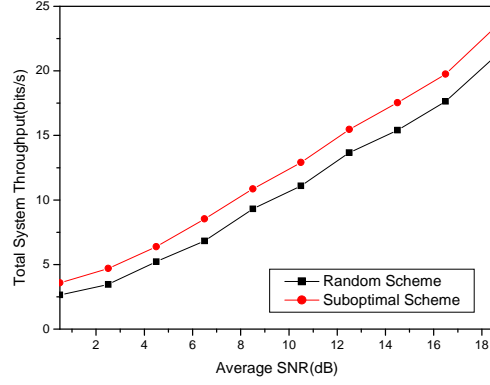


Figure 3. Total system throughput versus average SNR, when $N_u = 4$, $N_g = 2$ and $N_c = 64$

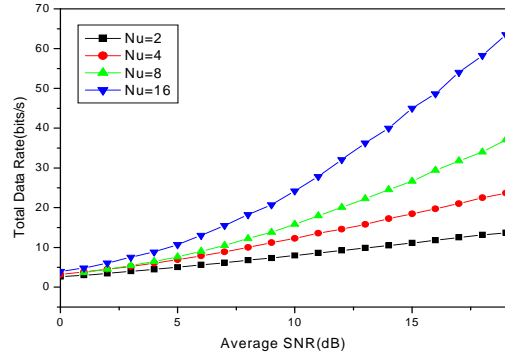


Figure 4. Total data rate with different number of users, when $N_c = 64$, $N_g = 2$

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 $N_u = 4$, $N_g = 2$ and $N_c = 16$, 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 4%, which shows that our algorithm is stable with time.

In figure 3, the system throughput normalized by the total bandwidth versus average SNR is depicted, when $N_u = 4$, $N_g = 2$ and $N_c = 64$. To evaluate the performance of our proposed scheme, we compare it with the random policy described in [6]. This random policy is to allocate the subcarrier randomly regardless of channel information, which is concluded in [6] to be the best algorithm to get

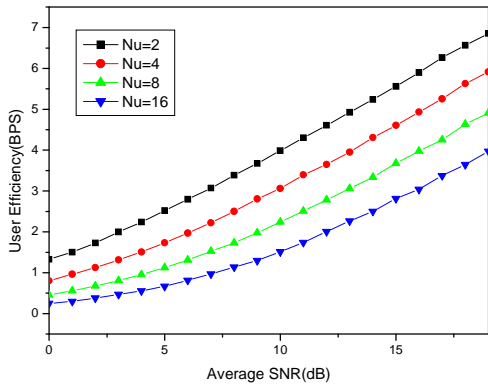


Figure 5. User efficiency versus average SNR, when $N_c = 64$, $N_g = 2$

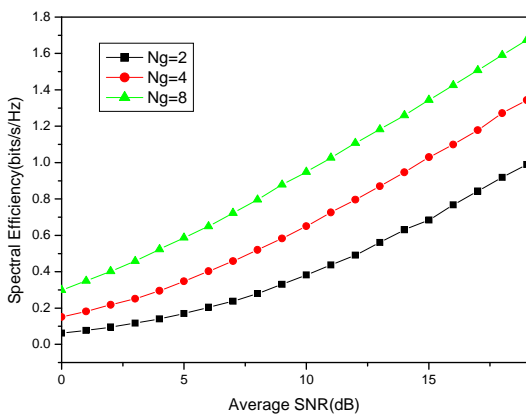


Figure 6. Spectral efficiency for different number of groups, when $N_c = 64$, $N_u = 16$

better BER performance. From Fig. 3, we can see that the total system throughput for both scheme increases with the average SNR, but our proposed method significantly outperforms the random-allocation policy. It is interesting that the difference is almost constant, regardless of the SNR.

Fig. 4 depicts the total data rate versus the average SNR for different number of users. From this figure, it is easy to see the data rate increases with the SNR. The more users the system has, the higher its data rate is. However, when the user's efficiency is taken into account, it is a different case. Fig. 5 shows the user efficiency for these systems with different number of users. This figure indicates when the system has fewer users, its user efficiency is higher, although it has lower total data rate. The reason may be that when the system has fewer users, the rate-fairness constraint among users will become slacker. For example, when each group has only one user, this user's rate will not be constrained by the other. So he can transmit at his maximum rate. So there

should be some trade-off between user efficiency and total system data rate.

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 the same as above. Given the same number of users, the more groups the system is divided into, the fewer users each group will have. Then the constraint of rate-fairness among users is slacker. Therefore, the system throughput can be improved significantly. Another reason may lies in that there will be fewer subcarriers per group when the number of groups increases. And 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 contributes to the improvement of the system throughput.

5. Conclusion

In this paper, we develop a suboptimal user grouping and subcarrier allocation algorithm for multiuser grouped MC-CDMA systems. Given the users's fading conditions on the subcarriers, we adaptively assign users into groups and then deal with subcarrier allocation. Our scheme aims to maximize the system throughput while guaranteeing the bandwidth-fairness among groups and the rate-fairness among users in the same group. Simulation results have shown this proposed scheme outperforms the random-allocation policy significantly and is 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 (denoted by BPS) decreases with that. So there exists some trade-off between them.

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