Adaptive resource allocation for downlink grouped MC-CDMA systems with power and BER constraints

Yaw-Wen Kuo*, Chun Chieh Lu, Guan-Yi Shen
Department of Electrical Engineering, National Chi Nan University, Puli, Nan-Tou, Taiwan

ARTICLE INFO

Article history:
Received 9 October 2012
Accepted 11 July 2013

Keywords:
MC-CDMA
User grouping
Adaptive modulation
BER

ABSTRACT

This paper proposes a complete solution to adaptively allocate resource for downlink Multi-Carrier Code Division Multiple Access (MC-CDMA) systems with the power and bit error rate (BER) constraints. Under frequency-selective fading channels, the whole spectrum is divided into several groups and each user is allocated to a group based on its channel state information (CSI). After grouping, the adaptive modulation algorithm assigns the bit loading and allocates the transmission power for each user according to its effective channel response. Simulation results show that the proposed solution can achieve high throughput, guarantee the required BER, and reduce the blocking probability.

© 2013 Elsevier GmbH. All rights reserved.

1. Introduction

Multi-Carrier Code Division Multiple Access (MC-CDMA) [1–14] systems have recently been considered potential candidates for next generation wireless communication technology. As described in [3], there are multiple methods of combining the OFDM with CDMA concepts. In MC-CDMA, data symbols are spread by orthogonal codes (e.g., Walsh codes) and mapped into subcarriers. Spreading in the frequency domain can achieve frequency diversity and multiple access operation in the system, which in turn combats frequency selective fading channels and increases spectrum efficiency. In fact, OFDM is a special case of MC-CDMA in which the spreading code length is 1.

Previous studies [7–13] on this topic grouped subcarriers in MC-CDMA systems to improve performance under frequency-selective channels, where users are adaptively grouped and use only some of the subcarriers. The basic idea of user grouping is simple. Carefully allocating users to the group with good channel quality leads to higher throughput. Processing complexity can also be reduced because the data symbol of one user is only spread among some of the subcarriers. Regarding to resource allocation, the power and modulation level of each user should be carefully adjusted to achieve high efficiency according to current channel state information (CSI). Resource allocation has been extensively studied in the literature [7–17] for MC-CDMA or OFDM systems. Many papers on MC-CDMA [7–9] assumed the same modulation, but in principle, an MC-CDMA system can allocate resources (i.e., subcarriers, modulation, and power) to maximize the overall data rate and guarantee the BER target. The authors in [10–12,14,15] focused on the theoretical analysis with system capacity formulated according to Shannon’s capacity. The optimization problem was solved by Lagrange multipliers. In practice, a system can only operate at a fixed set of modulations and its performance depends on the receiver design. Consequently, these results may not be suitable for real systems. In summary, the above-mentioned papers did not consider the adaptive modulation technique adopted in real systems. The algorithms in [13,16,17] jointly determine bit loading and power. The optimization problems were formulated based on a simple BER approximation formula [18,19]. As will be shown in Section 3, the approximation error of that formula is non-ignorable at some cases, resulting in over-allocation in power or insufficient bit loading.

Tang and Stolpman [13] proposed two adaptive modulation algorithms based on an equivalent channel concept. To improve the data rate for frequency selective channels, they divided subcarriers into groups that can be considered logical channels. A user can use all groups and the aggregated power of each user is the same. For a user, the modulation level and power at each group are determined by optimization. If a user has a bad channel response in a group, it cannot transmit in that group, resulting in inefficiency. This paper considers another approach for user grouping. All subcarriers are divided into several equal-size groups and allocate each user to only one group instead of all groups as in [13]. Though the shared data rate per user decreases, the number of users and the overall bit rate increase because of multiuser diversity. Two adaptive modulation algorithms are proposed to allocate the power and bit loading for each user based on the channel quality and BER target. The first algorithm, based on the Lagrange multipliers, optimizes

---

* Corresponding author.
E-mail address: ywkuo@ncnu.edu.tw (Y.-W. Kuo).

1434-8411/5 – see front matter © 2013 Elsevier GmbH. All rights reserved.
http://dx.doi.org/10.1016/j.aeue.2013.07.006
the power for each user and has been presented in IEEE TENCON [20]. It differs from the algorithm in Ref. [13], where each user has the same power. Based on the simulation results, we found that over allocation of power occurs because the number of bit loading for each user should be an integer. In addition, the approximation error in the employed BER formula is not negligible. Therefore, the second algorithm is proposed to improve the power efficiency by iteratively allocating the power just required for 1 bit increment to a user. By employing a set of precise BER approximation formulas, the second algorithm can allocate exact amount of resources and the resulting BERs are very close to the desired target.

The rest of this paper is organized as follows: Section 2 presents the system model and describes the instantaneous SNR of each user. Section 3 develops the user grouping and adaptive modulation algorithms. Section 4 presents simulation results and discusses the performance of the proposed solution. Finally, Section 5 draws conclusions and discusses the future work.

2. System model

This study considers a multiuser downlink grouped MC-CDMA system with \( U \) users and \( N \) subcarriers. The \( N \) subcarriers are divided into \( G \) groups. Each user transmits only one symbol over \( L = N/G \) subcarriers, where \( L \) is also the spreading factor of codes. Fig. 1 shows the system model, consisting of one base station and mobile user \( j \). Let \( d_i \) be the data from the \( i \)th user, which is assigned to a suitable group by the user grouping algorithm. After user grouping, the adaptive modulation algorithm calculates each user’s bit loading and transmitting power based on its CSI and the BER target. With an individual spreading code, the modulated data are spread into chips. The chips of all users in the same group are then summed as the input of the OFDM transmitter. The spreading code matrix could be identical for each group because different groups use different subcarriers in the system. Users in the same group are distinguished by their own spreading code. The remaining steps in this process are the same as those in typical OFDM systems. Finally, a cyclic prefix (CP) is inserted in front of every OFDM symbol to avoid inter symbol interference. This study assumes that a control channel exists, such that the base station can broadcast the group assignment to each user and collect the channel status of each user. For convenience, the principal symbols are listed in Table 1.

The signal from the base station is fed into a frequency selective Rayleigh fading channel with additive white Gaussian noise (AWGN). Without loss of generality, let us consider a particular user, which is the \( k \)th user in the first group. The number of users in a group is \( U/G \). Let \( Y^k_i \) be the received signal of user \( k \) at the \( i \)th subcarrier, which can be expressed as the summation of all signals in the same group plus AWGN as Eq. (1) shows:

\[
Y^k_i = \sum_{j=1}^{U/G} X^j_i C^j_i H^k_i + n_i, \quad i = 1, \ldots, L, 
\]

where \( X^j_i \) is the modulated data symbol of the \( j \)th user in this group, \( C^j_i \) is the spreading code of the \( i \)th carrier of the \( j \)th user, \( H^k_i \) is the \( i \)th carrier fading at the \( k \)th user and \( n_i \) is the AWGN component at the \( i \)th subcarrier.

This study assumes that the receiver uses the zero-forcing equalizer. The de-spreading signal of user \( k \) can be expressed as

\[
\hat{X}_k = \frac{1}{L} \sum_{i=1}^{L} \left( \sum_{j=1}^{U/G} X^j_i C^j_i H^k_i + n_i \right) C^k_i \frac{1}{H^k_i} 
\]

\[
= \frac{1}{L} \sum_{i=1}^{L} X^k_i C^k_i + \frac{1}{L} \sum_{i=1}^{L} \sum_{j=1, j \neq k}^{U/G} X^j_i C^j_i + \frac{1}{L} \sum_{i=1}^{L} n_i \frac{1}{H^k_i} 
\]

(2)

![Fig. 1. System model.](image-url)
Table 1  
Glossary of principal symbols.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>The number of users</td>
</tr>
<tr>
<td>N</td>
<td>The number of subcarriers</td>
</tr>
<tr>
<td>G</td>
<td>The number of groups in system</td>
</tr>
<tr>
<td>L</td>
<td>The spreading factor</td>
</tr>
<tr>
<td>d_j</td>
<td>The data of user j</td>
</tr>
<tr>
<td>y_i</td>
<td>The received signal of user k at the ith subcarrier</td>
</tr>
<tr>
<td>X_k</td>
<td>The modulated signal of the jth user</td>
</tr>
<tr>
<td>C^j</td>
<td>The jth chip of the jth user’s spreading code</td>
</tr>
<tr>
<td>L_k</td>
<td>User k’s channel response at the ith subcarrier</td>
</tr>
<tr>
<td>n_i</td>
<td>The AWGN component at the ith subcarrier</td>
</tr>
<tr>
<td>X_k</td>
<td>The de-spreading signal of user k</td>
</tr>
<tr>
<td>σ_k^2</td>
<td>The noise power of each subcarrier</td>
</tr>
<tr>
<td>P_i</td>
<td>The total power of the modulated data symbol</td>
</tr>
<tr>
<td>P_eff</td>
<td>The effective channel response</td>
</tr>
<tr>
<td>m_i</td>
<td>The average effective channel response for user j over all subcarriers</td>
</tr>
<tr>
<td>h_j,g</td>
<td>The effective channel response for user j at group g</td>
</tr>
<tr>
<td>Θ_d</td>
<td>The set of groups not fully filled</td>
</tr>
<tr>
<td>Θ_a</td>
<td>The set of unassigned users</td>
</tr>
<tr>
<td>P_max</td>
<td>The total maximum power in the system</td>
</tr>
<tr>
<td>P_j</td>
<td>The power allocated to user j</td>
</tr>
<tr>
<td>b_j</td>
<td>The bit loading for user j</td>
</tr>
<tr>
<td>ε_j</td>
<td>The BER target for user j</td>
</tr>
<tr>
<td>ε_a</td>
<td>The actual BER of user j</td>
</tr>
<tr>
<td>A</td>
<td>The set of unassigned users</td>
</tr>
<tr>
<td>SNR(h_j)</td>
<td>The required SNR of user j</td>
</tr>
<tr>
<td>P_j(h_j)</td>
<td>The required power of user j when loading b_j bits with the BER target ε_j</td>
</tr>
</tbody>
</table>

Eq. (2) consists of three terms representing user k’s data symbol, other users’ interference, and the enhanced noise term, respectively. Because the zero-forcing equalization and synchronized de-spreading can preserve the orthogonality, we have

\[\sum_{i=1}^{L} C^j C^k = \begin{cases} 1 & j = k, \\ 0 & j \neq k. \end{cases}\]  

(3)

Then, Eq. (2) can be rewritten as

\[\hat{X}_k = X_k + \frac{1}{L} \sum_{i=1}^{L} C^j n_i L_k.\]  

(4)

The power of the enhanced noise term becomes

\[\text{Noise power} = \sigma^2 \sum_{i=1}^{L} \frac{1}{|H^i_k|^2}.\]  

(5)

where \(\sigma^2\) is the noise power of each subcarrier. Let \(P_s = E[X_k^2 X_k]\) be the power of the modulated data symbol. Because \(L\) subcarriers are present, the total transmitting power of user \(k\), denoted by \(P\), is equal to \(LP_s\). The instantaneous SNR at receiver is given by

\[\text{Instantaneous SNR} = \frac{P_s}{\left(\sigma^2/L^2\right)\sum_{i=1}^{L} 1/|H^i_k|^2} = \frac{P}{\sigma^2} \times \frac{L}{\sum_{i=1}^{L} 1/|H^i_k|^2}.\]  

(6)

Fig. 2(a) shows a simplified version of the MC-CDMA block diagram. The design objective of this paper is to select a proper modulation scheme that still satisfies the BER target constraint. To simplify the computation, this study applies the method in [13], which approximates an MC-CDMA system by a simple M-QAM system over a channel with response \(H^e_k\), as shown in Fig. 2(b). Consider Eq. (6). The first term is the SNR at the transmitter, and the second term can be considered as the loss of an effective channel. Therefore, the effective channel response, denoted by \(H^e_k\), is set as follows:

\[|H^e_k|^2 = \frac{L}{\sum_{i=1}^{L} 1/|H^i_k|^2}.\]  

(7)

A dedicated simulation test was performed to verify this approximation. Results show that the BER of an MC-CDMA system is close to that of the equivalent system and we conclude that this model is effective, but space limitations prevent their inclusion in this paper. Combined with a set of BER approximation formulas presented in Section 3.2.2, the proposed solution provides satisfied results as will be shown in Fig. 7 because the actual BERs are very close to the corresponding BER targets.

Before leaving this section, let us have a quick performance review of an MC-CDMA system. Because the channel characteristic plays an important role in the performance of a wireless communication system, adaptive modulation is an important technique to adjust the bit loading based on current channel responses. Fig. 3 shows the BER performance of an MC-CDMA system under BPSK and 64-QAM modulations in a frequency-selective fading (Rayleigh) channel without grouping. Suppose the BER target is \(10^{-3}\), the required SNR exceeds 25 dB even for the BPSK modulation. According to the simulation results in Section 4, it only requires <10 dB to achieve the same capacity. The benefit of user grouping is significant an MC-CDMA system. The major contribution of this paper is presenting a complete solution of resource allocation, which includes user group and adaptive modulation algorithms.
3. User grouping and adaptive modulation

After receiving the channel response of all users, the base station first allocates each user to a suitable group. The base station then calculates the bit loading for each user and the corresponding power to meet the BER target.

3.1. User grouping

The total power of the system is fixed. To improve spectrum efficiency, the system sacrifices some users with extremely bad channels, and allocates no power to them. As a result, it is important to assign a user to a proper group. A straightforward strategy for high spectrum efficiency is to assign the user with the best average channel first (BACF) scheme. However, because it is easier to find a suitable group for users with good average channels, this study proposes another strategy of assigning the user with the worst average channel first (WACF) scheme. According to the simulation results presented in Section 4, the WACF strategy can reduce the blocking probability while providing almost similar capacity.

The WACF grouping algorithm assigns one user to a proper group iteratively according to the current channel responses of all subcarriers. Let $\Theta_{Uj}$ and $\Theta_{g}$ be the set of unassigned users and the set of groups not fully filled, respectively. Let $n_j$ be the number of users in group $j$. The channel response on the $j$th subcarrier for $U$ users is denoted by $H_{Uj}$. Let $m_j$ and $h_{jg}$ be the average effective channel response for user $j$ over all subcarriers and the effective channel response for user $j$ at group $g$, respectively. This leads to

$$m_j = \frac{N}{\sum_{i=1}^{N} 1/|H_{Uj[i]|^2}},$$

$$h_{jg} = \frac{L}{\sum_{i \in \text{group } g} 1/|H_{Uj[i]|^2}}.\quad (9)$$

The WACF user grouping algorithm is shown as follows:

Step 1: Calculate $m_j$ and $h_{jg}$ for $0 \leq j \leq N$ and $0 \leq g \leq U$.
Step 2: Find the user $j^*$ that has the smallest average channel response and $j^* = \arg \min_j m_j \{m_j\}$. Then, find the group $g^*$ where user $j^*$ has the best effective channel response and $g^* = \arg \min_{g \in \Theta_{g}} \{h_{j^*g}\}$. Assign user $j^*$ to group $g^*$.

Step 3: Remove user $j^*$ from $\Theta_{Uj}$, and $n_{g^*} = n_{g^*} + 1$. If $n_{g^*} = L$, remove group $g^*$ from the set $\Theta_{g}$.
Step 4: If $\Theta_{Uj} = \emptyset$, end the algorithm; otherwise, return to Step 2.

The BACF algorithm is similar to the WACF one except that it selects the user with the best average channel response in Step 2.

3.2. Adaptive modulation algorithm

Under a frequency-selective fading channel, the BER is high if a high order modulation is used for a bad channel. Conversely, if a low order modulation is used for a good channel, the spectrum efficiency is low. Adaptive modulation techniques \cite{18,19} are commonly used to solve this problem. An adaptive modulation algorithm uses the instantaneous channel response to adjust the output power and the bit loading for each user to satisfy the BER target. Although the data rate increases with transmission power, regulations limit the total power of a BS. Let $P_{\text{total}}$, $P_j$, and $\bar{H}_j$ be the total maximum power in the system, the power allocated to user $j$, the bit loading for user $j$, and the BER target, respectively. In the investigated system, $P_{\text{total}}$ is fixed according to communication regulations and $\bar{H}_j$ is given. The design objective is to calculate $P_j$ and $b_j$ for all $j$ to maximize the overall system throughput. The optimization problem can be stated as

$$\begin{align*}
\text{maximize} & \quad \sum_{j=1}^{U} b_j, \\
\text{subject to} & \quad (a) \sum_{j=1}^{U} P_j - P_{\text{total}} \leq 0, \\
& \quad (b) \bar{H}_j - \bar{H}_j \leq 0 \text{ for } j = 1, 2, \ldots, U.
\end{align*}$$

The following discussion presents two adaptive modulation algorithms based on different approaches.

3.2.1. Lagrange optimization (10) adaptive modulation algorithm

Chung et al. \cite{18} derived a BER approximation formula for M-QAM communication systems by

$$\bar{e}_j = 0.2 \exp \left( \frac{-1.6 |H_{eff}^k|^2 P_j}{(2^k - 1) \sigma^2} \right),$$

where $\bar{e}_j$ denotes the resulting BER. After rearranging Eq. (11), the bit loading is given by

$$b_j = \left\lfloor \log_2 \left( \frac{1 - 1.6 |H_{eff}^k|^2 P_j}{\sigma^2 \ln (2 |\bar{e}_j/0.2|)} \right) \right\rfloor \text{ for } \bar{e}_j < 0.2. \quad (12)$$

Lagrange multipliers can be used to find the solutions of user powers for Eq. (10), as follows:

$$P_j = \frac{\sigma^2 \ln (\bar{e}_j/0.2)}{1.6 |H_{eff}^k|^2} + \frac{P_{\text{total}} - \sum_{k=1}^{U} \sigma^2 \ln (\bar{e}_k/0.2)}{1.6 |H_{eff}^k|^2}. \quad (13)$$

After solving $P_j$, the bit loading for user $j$ can be calculated by substituting Eq. (13) into Eq. (12). If some users experience deep fading on all groups, Eq. (13) likely produces negative or small values. If this occurs, it is necessary to iteratively remove these users from the algorithm because it is nonsensical to allocate power to them. Thus, service to users with bad channel responses are suspended temporarily until their channel recovers. Let $\Theta_{A}$ be the set of unassigned users and let $A$ be the number of users in $\Theta_{A}$. Initially, $\Theta_{A}$ contains all users. The complete algorithm is described as follows:
Step 1: Find each user’s power in $\Theta_A$ by

$$P_j = \frac{\alpha^2 \ln \left( \frac{\hat{e}_j/0.2}{1.6 [H_{eff,j}]} \right)}{\frac{1}{A} + \frac{\alpha^2 \ln \left( \frac{\hat{e}_j/0.2}{1.6 [H_{eff,k}]} \right)}{\sum_{k \in \Theta_A} \frac{1}{A}}}, \quad (14)$$

Step 2: Find user $i$ with the smallest power value by $i = \arg \min_{\Theta_A} (P_i)$. Calculate its bit loading $b_i$.

Step 3: If $P_i \leq 0$ or $b_i < 1$, set the transmitting power of user $i$ to zero, remove user $i$ from $\Theta_A$, and go to Step 1; otherwise, go to Step 4.

Step 4: Use Eq. (12) to calculate the bit loading for each user in $\Theta_A$.

The LO algorithm has two major issues. First, because the number of bits allocated should be an integer, the LO algorithm may over-allocate power to some users. Second, the BER approximation formula is only valid for $b_j = 2, 4, 6$, and the errors are large for $b_j = 1, 3, 5$. Due to these limitations, this study proposes an iterative adaptive modulation scheme to improve power efficiency.

### 3.2.2 Least Required Power First (LRPF) adaptive modulation algorithm

This subsection presents a different approach to find the solution for Eq. (10). The basic concept of this algorithm is to allocate power as efficiently as possible. Initially, $b_j = 0$ for all $j$. The proposed algorithm first calculates the required powers for all users with increments of 1 bit, and then selects the user with the smallest power requirement for allocation. As a result, this algorithm is called the Least Required Power First (LRPF) adaptive modulation algorithm.

As mentioned earlier, the approximation error of the BER formula in Eq. (11) is non-ignorable for some cases. Before introducing the proposed algorithm, we give a short review of BER formulas. Let $\gamma_m$ be the received average SNR per symbol for a QAM system. According to [21], the BERs for $2^b$-QAM are given as below:

$$\epsilon_j = \begin{cases} 
Q\left(\sqrt{2\gamma_m}\right), & b_j = 1, \\
\left(1 - (1 - SE_{1/3})(1 - SE_{2/3})\right), & b_j = 3, \\
\left(1 - (1 - SE_{1/2})^2\right), & b_j = 2, 4, 6, \\
4b_jQ\left(\sqrt{\frac{3}{2^{b_j} - 1}\gamma_m}\right), & b_j = 5, 7, 9, \\
& \ldots.
\end{cases} \quad (15.1)$$

where

$$SE_n = \frac{2(2^{b_j} - 1)}{2^{b_j}}Q\left(\sqrt{\frac{6n}{2^{b_j} - 1}\gamma_m}\right), \quad n = 0, 1, 2, 3, \ldots.$$  

Eq. (15.1) is the BER for a BPSK system. Eq. (15.3) approximates the BER well for even $b_j$, as Fig. 4(a) shows. Fig. 4(b) shows the BERs for odd $b_j$. When $b_j > 3$, Eq. (15.4) yields a good approximation. However, the error is unacceptable for $b_j = 3$ when the SNR exceeds 9 dB. As a result, we decompose 8-QAM into two PAM systems (2-PAM and 4-PAM) and derive the BER as shown in Eq. (15.2). Fig. 4(b) shows that Eq. (15.2) provides a better approximation. Given the BER target $\epsilon_i$, the required SNRs, denoted by $\text{SNR}(b_j)$, at the receiver for different $b_j$ can be calculated using the bisection method based on Eq. (15). Table 2 shows the results for different BER targets. Let $P_n$ and $P_j(b_j)$ be the noise power and the required power for user $j$ to achieve $\epsilon_j$ with $b_j$ bits, respectively. This leads to

$$P_j(b_j) = \frac{\text{SNR}(b_j)}{H_{eff}}P_n. \quad (16)$$

Finally, the detailed procedure of the LRPF algorithm is shown as follows:

Step 1: Initially, $b_j = 0$ for all $j$. The remaining power, denoted by $P_n$, is equal to $P_{total}$.

Step 2: Find user $i$ with the least required power for the increment of 1 bit by $i = \arg \min_{\Theta_A} (P_j(b_j + 1) - P_j(b_j))$.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>The required SNR at receiver for different BER targets.</th>
</tr>
</thead>
<tbody>
<tr>
<td>BER = 0.01</td>
<td>BER = 0.001</td>
</tr>
<tr>
<td>SNR(1)</td>
<td>2.72</td>
</tr>
<tr>
<td>SNR(2)</td>
<td>5.43</td>
</tr>
<tr>
<td>SNR(3)</td>
<td>15.3</td>
</tr>
<tr>
<td>SNR(4)</td>
<td>24.6</td>
</tr>
<tr>
<td>SNR(5)</td>
<td>53</td>
</tr>
<tr>
<td>SNR(6)</td>
<td>94.27</td>
</tr>
<tr>
<td>SNR(7)</td>
<td>190</td>
</tr>
<tr>
<td>SNR(8)</td>
<td>349.22</td>
</tr>
<tr>
<td>SNR(9)</td>
<td>664.87</td>
</tr>
<tr>
<td>SNR(10)</td>
<td>1288.8</td>
</tr>
</tbody>
</table>
Step 3: If $P_i < P_i(b_i + 1) - P_i(b_i)$, end the algorithm.
Step 4: $b_i = b_i + 1$ and $P_i = P_i - (P_i(b_i + 1) - P_i(b_i))$. If $b_i = b_{\text{max}}$, remove user $i$ from $\Theta_A$, where $b_{\text{max}}$ is the maximum number of bits in the system profile.
Step 5: If $\Theta_A = \emptyset$, end the algorithm; otherwise, return to Step 2.

4. Simulation results

This section evaluates the performance of the proposed solution. Simulations were conducted under a multuser single-cell downlink scenario with Rayleigh and distant fading. Distant fading was uniformly distributed between 0 dB and −7 dB. There were 48 users in an MC-CDMA system with 48 subcarriers divided into 12 groups of four subcarriers. Therefore, the length of Hadamard Walsh code was 4. The BER target in the simulation was $10^{-3}$. The possible bit loading, $b_i$, is from 0 to 6. Two metrics were evaluated, including the resulting BER and the bits per OFDM symbol (BPS). In addition to the proposed solution, we also conducted simulations for the reference algorithm [13].

Fig. 5 shows a comparison of the BERs against SNR. The WACF grouping algorithm is used for the proposed solution. All schemes can satisfy the BER target, but the reference algorithm and the LO algorithm show increasing gaps between the resulting BERs and the BER target ($10^{-3}$). Fig. 6 shows a comparison of the BPSs against SNR for the three algorithms. With 48 users, the BPS with fixed BPSK modulation is also 48. The required SNR to achieve BPS higher than 48 is <10 dB. Compared with 25 dB in the non-grouping case in Fig. 3, the benefit of user grouping is significant. Regarding to performance comparison between different algorithms, the LRPF algorithm performs best because its BER approximation is more accurate. The fundamental issue of the reference algorithm is that the system power is not efficiently utilized because the total power is equally distributed to all users. The proposed LO algorithm can allocate different powers to users according to their effective channel responses, resulting in higher BPS. The LO algorithm and the reference algorithm rely on the closed form of BER formula in Eq. (11). Unfortunately, this is not valid for some cases. These two algorithms also determine power first. Because the bit loading must be an integer, the floor function in Eq. (12) implies the over-allocation in power. Conversely, because the LRPF determines the amount of power required to allocate one more bit at each iteration, there is no waste in power allocation.

Figs. 7 and 8 show the BPS and the resulting BER for the LRPF algorithm at different BER targets. As expected, Fig. 8 shows that the proposed solution can effectively adjust the modulation level and power to meet the BER targets. In other words, the approximations, including the equivalent system and BER formulas, used in this paper are reasonable. Fig. 8 shows that the BPS decreases as the BER target decreases, implying that operators must make a tradeoff between the BER target and system throughput.

In the last experiment, we simulated different user grouping algorithms with the LRPF algorithm to evaluate the impact of grouping. In addition to the BACF and WACF algorithms, the scenarios for “no grouping” and “random grouping” were also evaluated. As shown in Fig. 9, we can see that the improvements in BPS by grouping are significant. As mentioned before, it is interesting that the WACF grouping algorithm can provide almost the same BPS as the BACF algorithm does. Fig. 10 shows the blocking probability which denotes the probability that a user receive no service ($P_i = 0$) in a frame. Again, the blocking probability decreases thanks to the grouping algorithm. Because a user with
a bad average channel response has a higher priority by the WACF algorithm, it has a higher chance to find a relative good group, resulting in less block probability. In summary, the WACF grouping algorithm, achieving a good balance between system capacity and blocking probability, is the final solution proposed in this paper.

5. Conclusions

This study proposed user grouping algorithms and adaptive modulation algorithms to improve the system performance of multiuser downlink MC-CDMA systems. Simulation results show that the proposed solutions outperform the reference scheme and can achieve high efficiency with BER and power constraints.

Unlike the reference algorithm, the proposed solution assigns a user to a group for higher efficiency. It is easy to extend the proposed solution to the case in which a user requires a high data rate by assigning this user to multiple groups. In the future, we plan to investigate a system with the minimum mean square error (MMSE) equalizer to improve performance at low SNR, where one should consider the interference between users and possibly a different design strategy is required.

Acknowledgment

This work was supported in part by the National Science Council, Taiwan, under Grant NSC101-2221-E-260-003.

References


