An Adaptive Grouped-Subcarrier Allocation Algorithm Using Comparative Superiority

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ABSTRACT

In this paper, an adaptive grouped-subcarrier allocation algorithm using comparative superiority is proposed for the enhancement of system capacity and its simple implementation in a multiuser OFDM system. Since the computational complexity of the optimal subcarrier allocation algorithm based on the each subcarrier is extremely high, various sub-optimal algorithms have been developed for the realization of adaptive subcarrier allocation algorithm with the reduced complexity. Some of the promising sub-optimal algorithms are the blockwise [1] and the decentralized allocation algorithms [2], which allocate subcarriers in groups instead of each subcarrier. The proposed algorithm is similar to the blockwise or the decentralized subcarrier allocation algorithm but all subcarriers are grouped according to the coherence bandwidth for the enhancement of system capacity. In addition, the proposed algorithm provides a simple solution for the conflict problem among users by reallocating only the conflicted groups and unassigned groups instead of reallocating entire groups. Furthermore, the comparative superiority concept, which swaps the groups between users if the system capacity is increased, is adopted in the re-allocation process for the enhancement of system performance. Simulation results demonstrate that the proposed algorithm increases the system capacity effectively over a static, an adaptive blockwise, and a decentralized subcarrier allocation algorithms.

I. Introduction

Orthogonal Frequency Division Multiplexing (OFDM) is a promising multicarrier transmission technique because it not only provides high data rates but also mitigates intersymbol interference (ISI) in broadband transmission over wireless multipath fading channels [3]. Multiuser OFDM is a multiple access technique efficiently exploiting the limited resources such as bandwidth and transmit power. In traditional multiuser OFDM-TDMA or OFDM-FDMA systems, the predetermined subcarriers are assigned to each user [4]. However, since different users experience mutually independent fading, adaptive multiuser subcarrier allocation algorithms, which assign subcarriers to each user based on channel state information (CSI), have been developed for the enhancement of system performance [5]-[11].

There are two major problems for optimal bit loading and subcarrier allocation in multiuser OFDM systems: minimization of the overall transmit power under the data rate constraints [6][7][8] and maximization of the data rate under power constraints [2][5][9]. Many papers have suggested solutions for these problems and the enhancement of system performance has been demonstrated by adopting adaptive modulation techniques [10][11]. Furthermore, in multiuser environment, a wide range of data rates would be required by many different users. Thus, an efficient resource allocation strategy among users becomes an important issue and the system performance can be significantly improved by employing an adaptive subcarrier, bit, and power allocation algorithm.

It is known that the optimal subcarrier, bit, and power allocation without the relaxation of the integer variables is an NP-hard combinatorial problem [8]. There were several approaches to solve the constrained nonlinear problem. One promising approach was a scheme for solving an unconstrained nonlinear problem iteratively with the relaxation of the integer variables to real numbers [6] and there was another approach solving a sequence of unconstrained sub-problems with an interior point method [12]. However, the solutions of the above approaches are result from high computational complexity and its high computational cost makes it difficult to be applied in real-time applications although it can be used to provide a loose upper-bound for all possible allocation algorithms.

Since the computational complexity of the optimal subcarrier allocation algorithm is extremely high, various sub-optimal algorithms, such as the blockwise [1] and the decentralized allocation algorithms [2], have been developed for the realization of adaptive subcarrier allocation algorithm with the reduced complexity. Even though these algorithms allocate subcarriers in groups instead of considering each subcarrier for the reduction of complexity about a factor of group size, the system performances of the algorithms are close to that of the optimal solution. In the blockwise adaptive subcarrier allocation algorithm, all subcarriers are divided into blocks and a certain number of blocks with high average channel gains is assigned to each user based on the required data rate. However, there is a possibility that the group with relatively small average channel gain is assigned to a certain user because the group with the highest average channel gain has been assigned already to other user. As the result, the overall system performance may be degraded. Therefore, under consideration of the overall system capacity, the increase of system capacity can be achieved by reallocating blocks among users.

In the decentralized subcarrier allocation algorithm [2], all subcarriers are divided into a number of partitions and each user selects the partition with the highest average channel gain independently. During the allocation process, the conflict problem, which more than one user attempts to select the same partition simultaneously, occurs. Thus, the re-allocation of partitions among users is performed by comparing the usage value of each group for resolving the conflict problem among users. However, the usage value is updated by indirect measures for the system capacity such as a simple ranking factor, normalization process, the cost values, and a random factor, which provides a randomness in re-allocation of the groups over the users. Therefore, the overall system performance may be degraded by using the usage value instead of using the average channel gain of each group alone.

In this paper, an adaptive grouped-subcarrier allocation algorithm is proposed for the enhancement of system capacity in downlink environment of OFDM systems. The proposed algorithm is similar to the blockwise or the decentralized subcarrier allocation algorithm but all subcarriers are grouped according to the coherence bandwidth of channel. Moreover, instead of the usage value, the known average channel gain of each group is used to resolve the conflict problem among users in the proposed algorithm. Based on the proposed group allocation algorithm, an adaptive modulation is adopted for the groups of each user to increase the data rates by applying higher order modulation to carry more bits per OFDM symbol.

The rest of the paper is organized as follows. In Section II-A, the system model of multiuser OFDM systems is described. The characteristics of the blockwise subcarrier allocation and the decentralized subcarrier allocation algorithms are briefly examined in Section II-B and II-C respectively. In Section II-D, the adaptive grouped-subcarrier allocation algorithm is developed and proposed for the enhancement of system capacity in downlink environment of OFDM systems. The results of computer simulation are shown in Section III and the conclusions are given in Section IV.

II. Adaptive Subcarrier Allocation Algorithms

A. System Model

The configuration of the multiuser adaptive OFDM system is shown in Fig. 1. The system has N subcarriers and all subcarriers are shared with K users. It is assumed that the transmitter knows the downlink channel gains of all users. Based on the CSI from all users, a certain subset of subcarriers is assigned to each user and the subcarrier allocation information is sent to the receivers via a separate control channel. In the subcarrier allocation schemes, the subcarriers are exclusively assigned to users not to share a subcarrier with more than one user. The adaptive modulation is employed for the enhancement of system capacity and the number of bits per symbol for each subcarrier is determined with the channel gain

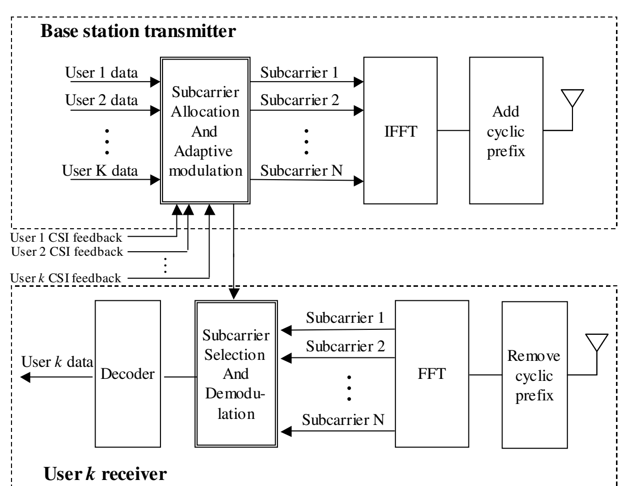

Fig. 1. A multiuser OFDM system

information. It is assumed that all users experience different frequency selective fading channels independently and the coherence bandwidth of the channel is larger than the bandwidth of a subchannel. Generally, the magnitude response of subchannels within the coherence bandwidth is assumed to be flat. However, the channel gains among subcarriers may have a variation even within the coherence bandwidth if a moderate correlation value is used for defining the coherence bandwidth [13]. In this paper, it is assumed that the channel gains among subcarriers have a variation even within the coherence bandwidth. Therefore, the average channel gain of each group is considered for the proposed subcarrier allocation algorithm.

B. Blockwise Subcarrier Allocation Algorithm [1]

The blockwise adaptive subcarrier allocation algorithm divides all subcarriers in blocks and assigns blocks to each user according to its required data rate and BER constraint. Each block consists of a number of adjacent subcarriers and the channel of a block of subcarriers is assumed to be flat because the channel gains of neighboring subcarriers in frequency domain are correlated when the bandwidth of neighboring subcarriers is smaller than the coherence bandwidth of channel.

The blockwise subcarrier allocation algorithm is a two-step method. Firstly, it adopts an adaptive block allocation to increase the system capacity by using CSI of all users compared to a static subcarrier allocation. By assigning a subset of blocks with highest average channel gains to the corresponding user, the system capacity can be increased more than a predetermined subcarrier allocation algorithm like OFDM-FDMA. Secondly, it employs an iterative improvement procedure to minimize the total required transmit power while satisfying multiusers' data rates and BER requirements. The total required transmit power, P, can be minimized by reallocating blocks among users under the total transmit power constraint, P_0. The algorithm is described briefly as follows.

Step 1:

1)Based on the channel information of the kth user, calculate and select the least number of blocks with the highest channel gains to satisfy its rate requirement.

2)Assign them to kth user if the selected blocks are not assigned to other users.

3)Otherwise, exclude those used blocks and find different blocks with next highest channel gains and repeat 2) of step 1.

4)Repeat all process of step 1 until all users are assigned with blocks to satisfy its data rate requirements.

Step 2:

1)Calculate P with the information of block allocation of step 1 and channel gains of all users.

2)If $P > P_0$, allocate one more block for each user according to step 1 and recalculate P.

3)Repeat step 2 until $P \leq P_0$.

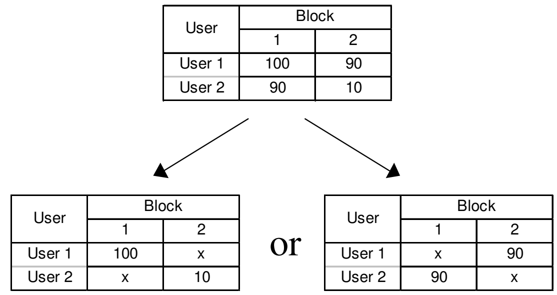

Fig. 2. A sample blockwise allocation plan

Although the system capacity can be increased by adopting a blockwise adaptive subcarrier allocation in step 1, there is a possibility that the system capacity is increased more by considering the comparative superiority in block allocation. When blocks are assigned to each user, the block with the highest channel gain is selected for the corresponding user in the algorithm. In the view of the enhancement of system capacity, however, it can increase the system capacity more to assign the block with the next highest channel gain to the corresponding user while assigning the block with the highest channel gain to other user. This case is shown in the sample allocation plan described in Fig. 2. When the average channel gain of each block is given as shown in the upper table of Fig. 2, the block 1 would be assigned to user 1 and block 2 is to user 2 by the blockwise allocation algorithm as shown in the left-bottom table of the figure. In this case, the system capacity is proportional to the summation of both users' channel gains, 110 units, which consists of 100 units from user 1 and 10 units from user 2. By swapping the assigned block between users as shown in the right-bottom table of the figure, however, the system capacity can be increased more with different channel gains such as 90 units from user 1 and 90 units from user 2. Therefore, even though the blockwise subcarrier allocation algorithm provides capacity increase than a static subcarrier allocation algorithm, it cannot resolve the comparative superiority problem.

C. Decentralized Subcarrier Allocation Algorithm [2]

The decentralized subcarrier allocation algorithm also is a dynamic allocation scheme for the enhancement of system capacity in multiuser OFDM systems. In the algorithm, all users divide all the subcarriers into a number of partitions in parallel and each user selects the partition with the highest average channel gain independently. However, since each user attempts to select the partition with the highest average channel gain, more than one user may conflict in the selection of the partition if a certain partition is the best one to them simultaneously. The important contribution of this algorithm is to resolve the conflict problem among users in the selection of partition and provides a solution using the comparative superiority in subcarrier allocation for the cases like a simple example allocation plan as shown in Fig. 2.

The algorithm has two steps to allocate the partitions to users. In the initialization step, all the necessary information are assembled and the conflict problem of partition allocation among users is resolved in the iteration step. The determination of allocation of partitions is based on the usage value of each partition for each user. The usage value of partition N is defined as follows

$$U_{N(t)} = U_{N(t-1)} \times w + \frac{U_{N(t-1)} \times (1-w)}{\frac{C_N}{K-1} + 1} \quad (1)$$

where $U_{N(t-1)}$ is the usage value of partition N during previous iteration $(t-1)$, the cost, C_N, is the number of other users that attempt to select the same partition N, K is the total number of users in the system, and w is the weightage factor to prevent drastic changes in usage values. The algorithm is described briefly as follows.

Initialization Step:

1)The channel magnitude response is divided into a number of partitions for each user.
2)Initialize the set of usage values for each user's partitions based on the average channel gain of each partition.
3)Assign the ranking factors to all partitions after arranging the usage values in ascending order.
4)Normalize the set of usage values of each user in parallel after multiplying a ranking factor with the initial usage value of each partition.
5)Based on the normalized usage values, assign the partition with the highest usage value to each user.
6)If there is any conflict that more than one user attempt to select the same partition, move to the iteration step.
7)Otherwise, exit the allocation process.

Iteration Step:

1)Recalculate the usage value of each partition based on the cost of allocation for all partitions for all users.
2)Modify the usage values using a noise factor.
3)Repeat the iteration step until either each partition is allocated to only one user or a maximum number of iterations is reached.
4)Allocate the partitions with either random or any forced patterns if the maximum number of iterations is reached.

As shown in (1), the usage value of a partition would be reduced if the partition is selected by more than one user due to the increase of the cost, C_N, while the usage value of unselected partition stays in the same value because of $C_N = 0$. However, the usage value of unselected partition would be relatively increased by the normalization process while those of the selected partitions decrease. The iteration step is repeated until each partition is only assigned to one user. Furthermore, the noise factor providing a randomness in the usage values is introduced for the case where the conflict problem is not resolved even after the maximum number of iterations.

The decentralized subcarrier allocation algorithm provides a solution increasing the system capacity compared to the blockwise subcarrier allocation algorithm by considering comparative superiority in subcarrier allocation. However, the method for updating the usage value of each partition is based on the simple quantitative factors such as the ranking factor, the cost value, and the weightage factor not the substantial values of each partition's channel gain only. Moreover, the normalization of the usage value makes it difficult to compare the channel gains of a partition from all users, which is an important comparison for the enhancement of system performance. Instead of using the simple factors, the substantial values of each partition like channel gains would provide a more realistic solution if the system capacity is compared based on the comparative superiority after swapping the partitions of all concerning partitions. The following proposed algorithm provides a solution that resolves the conflict problem among users with more substantial values and increases system capacity more.

D. The Proposed Subcarrier Allocation Algorithm Using Comparative Superiority

When an equal amount of power is allocated to each subcarrier, the channel capacity of each subcarrier can be regarded as proportional to its channel gain. Thus, overall system capacity can be increased by assigning the subcarriers with high channel gains first [4]. While complying with the above approach, subcarriers can be allocated in group for the reduced complexity of an adaptive subcarrier allocation algorithm likewise the blockwise subcarrier allocation or the decentralized subcarrier allocation algorithms, which were discussed in the previous sections. In the proposed algorithm, each group with the highest average channel gain is selected for the corresponding user and the comparative superiority, which is performed by swapping groups, is adopted for the enhancement of system capacity. It is assumed that each group has the same number of subcarriers and the number of subcarriers for each group is determined by the coherence bandwidth.

The proposed algorithm is similar to the blockwise or the decentralized subcarrier allocation algorithm. However, instead of the usage value that is employed in the decentralized allocation algorithm, the known average channel gain of each group is used to resolve the conflict problem among users in the proposed algorithm. Since the proposed algorithm adopts the comparative superiority concept, which is based on only the comparison of the average channel gains of all groups, for the conflict problem, the system performance can be substantially enhanced more than those of the blockwise algorithm and decentralized algorithm. The proposed algorithm is a two-step group allocation algorithm. Each user attempts to select the best group independently at step 1 and the selected groups are reallocated by comparing the opportunity cost of using groups among users to increase the overall system capacity at step 2. When the number of groups assigned to each user is predetermined, the algorithm is described briefly as follows.

Step 1:

1)All the channel gains of each user are divided into a number of groups based on the coherence bandwidth.

2)Select the groups with the highest average channel gain of each user and assign them to the corresponding user.

3)If there are any groups that more than one user attempt to select simultaneously, then move to the step 2 for reallocation.

4)Otherwise, exit the allocation process.

Step 2:

1)Build an union set, S, by combining the set of unassigned groups, $\{U\}$, and the set of groups conflicting with more than one user, $\{C\}$

2)After reordering the groups within the union set according to the average channel gain of each group, initialize the allocation by assigning the group with the highest average channel gain within the union set to the corresponding user and then do iteration for capacity enhancement.

3)Iteration:

a)Within the union set, S, build all the cases for swapping groups between any paired users.

b)Compute the increase of system capacity, $\triangle C$, with the following equation for all the swapping cases from a).

$$\triangle C = C_{i,j} - C \tag{2}$$

where C is the system capacity before swapping and $C_{i,j}$ is system capacity after swapping group i and group j, and $i, j \in S$.

c)If $\triangle C$ is positive, swap the groups between users and update C with $C_{i,j}$ and move to next case.

d)Otherwise, skip the case and move to next case.

e)Repeat the iteration until $\forall \triangle C \leq 0$.

The major operations in step 1 and step 2 are sorting and swapping respectively. Therefore, the computational complexity of the proposed algorithm can be approximated by estimating the two major operations. If K groups are available for K users, the computational complexity of sorting process in step 1 is approximated as $O(K \cdot KlogK)$. When the number of groups in the set S is $L(\leq K)$, the all possible swapping cases is $O(C_2^L) \approx O(L^2)$. Thus, the total computation complexity can be approximated as $O(K^2 logK + L^2)$.

There is a possibility that a group with subcarriers in deep fade is modulated with lower order modulation to carry less bits per OFDM symbol because the average channel gain of group is low. Therefore, the system capacity can be increased more by swapping subcarriers in deep fade among groups at the cost of increase of computational complexity if there is the benefit of system capacity via the swapping subcarriers. The following step may be considered as an optional process to enhance the system performance under consideration for the balance between the enhancement of system performance and the reduction of complexity for practical implementation. The algorithm for swapping subcarriers is described as follows.

Step 3: (Optional)

1)Find a subcarrier, of which channel gain is the lowest within its group, and build a subset, T, that consist of the found subcarriers from all groups.

2)Build all the cases for swapping subcarriers between any paired subcarriers within the set, T.

3)Compute the increase of system capacity, $\triangle C$, with

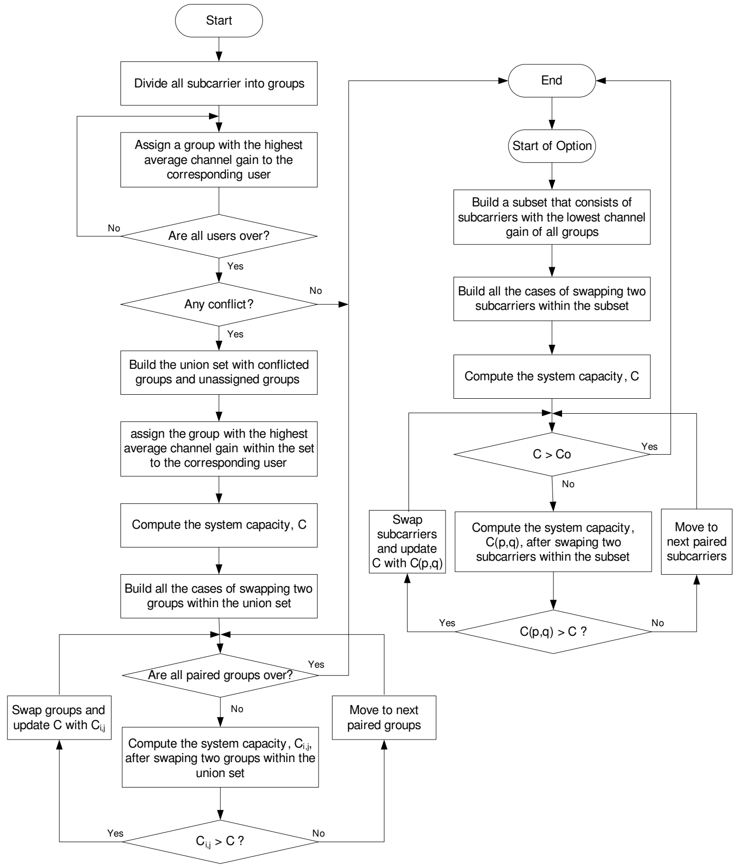

Fig. 3. Flow chart for the proposed grouped-subcarrier allocation algorithm with optional process

the following equation for all the swapping cases from 2).

$$\triangle C = C(p,q) - C \tag{3}$$

where C is the system capacity before swapping and $C(p,q)$ is system capacity after swapping pth subcarrier and qth subcarrier within the set, T.

4)If $\triangle C$ is positive, swap the subcarriers between groups and update C with $C(p,q)$ and move to next case.

5)Otherwise, skip the case and move to next case.

6)Repeat the iteration until $C \geq C_0$ where C_0 is the predetermined upper limit of system capacity to avoid the excessive number of iterations.

The above optional process may require a high computational complexity due to lots of swapping cases among subcarriers just for the marginal benefits in the system capacity. Therefore, as described in the algorithm, a certain predetermined upper limit of system capacity can be established for the computationally efficient realization of the proposed optional algorithm. Fig. 3 shows the flow chart for the proposed algorithm with optional process.

III. Simulation Results

The comparison of the overall system capacity has been performed through the simulations for a static, an adaptive blockwise, a decentralized, and the proposed subcarrier allocation algorithms. It is assumed that an equal amount of power is allocated to each subcarrier and each user is allocated with an equal number of subcarriers. In addition. the same number of groups is used in all allocation schemes for a fair comparison. The system capacity, $\sum_{i=1}^{L} R(h_i)$, is defined as

$$\sum_{i=1}^{L} R(h_i) = \sum_{i=1}^{L} \frac{B}{L} \log_2(1 + SNR \cdot \overline{h_i}^2) \tag{4}$$

where B is a bandwidth, L is the number of groups, SNR is a signal-to-noise ratio and $\overline{h_i}$ is the average channel gain of ith group, which is selected for a certain user in terms of higher system capacity.

For the performance comparison, all algorithms are simulated under the same condition. It is assumed that $K(=8)$ users share $N(=1024)$ subcarriers over a $B(=10MHz)$ band in the system. The allocation plan of all subcarrier allocation algorithms except for a static

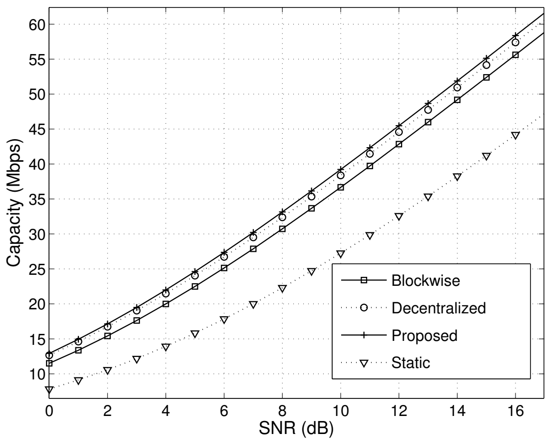

Fig. 4. Performance comparison for the blockwise, the decentralized, the proposed, and static subcarrier allocation algorithms

scheme is updated after every 1000 OFDM symbols in a frequency selective Rayleigh fading channel with an exponential power delay profile.

Fig. 4 shows the comparison of the overall system capacity for a static, an adaptive blockwise, an adaptive decentralized, and the proposed subcarrier allocation algorithm without using the optional process. As shown in the figure, the overall system capacity of the proposed algorithm is much larger than that of a static subcarrier allocation algorithms for the same SNR. For example, it is shown that the proposed algorithm achieves approximately 4.5dB gain of SNR for 40Mbps than the static subcarrier allocation algorithm. Furthermore, the proposed algorithm outperforms the alternative schemes in terms of system capacity even though the increase of system capacity is relatively small. In addition, the more performance enhancement of the proposed algorithm can be achieved by using the optional process at the cost of the increased complexity of the system.

IV. Conclusion

An adaptive grouped-subcarrier allocation algorithm using comparative superiority is proposed for the enhancement of system capacity in a multiuser OFDM system. In the proposed algorithm, assuming that the CSI of all users are known, all subcarriers are divided into groups over its coherence bandwidth and the groups with high average channel gain are assigned to the corresponding user for the enhancement of system capacity.

In addition, the proposed algorithm provides a simple solution for the conflict problem among users by reallocating only the conflicted groups and unassigned groups instead of performing the re-allocation of entire groups. Furthermore, the comparative superiority concept, which swaps the groups between users if the system capacity is increased, is adopted in the re-allocation process for the enhancement of system performance. Based on the proposed group allocation algorithm, an adaptive modulation is adopted for the groups of each user to increase the data rates by applying higher order modulation to carry more bits per OFDM symbol. Simulation results demonstrate that the proposed algorithm increases the system capacity effectively over a static, an adaptive blockwise, and a decentralized subcarrier allocation algorithms even without using its optional process.

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