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Efficient Channel Allocation Algorithm with Partial CSI for the PB/MC-CDMA System

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Abstract An efficient channel allocation algorithm is proposed for the Partial Block MC-CDMA system. Partial channel state information is used for determining the signal-to-noise ratio of all frequency-block-bands. The prior is done to maximize the frequency-block-band allocated to each block user. The proposed system improves the fairness among users and allocates frequency-block-bands with better channel conditions to each block user; hence, maximizes the system's total throughput. The fairness of the proposed channel allocation algorithm is analyzed by using Jain's fairness index, and compared to that of the conventional scheme. Moreover, the processing time needed to execute the proposed algorithm is calculated and compared with the conventional and optimal algorithms.

Keywords Channel allocation algorithms · Channel state information (CSI) · Fairness index · Partial block MC-CDMA system

1 Introduction

Demands for wideband communication schemes, with higher data rates and higher frequency utilization, have brought much attention to the development of new technologies. Multi-Carrier Code Division Multiple Access (MC-CDMA) is a communication system that can achieve larger capacities, and higher data rates in multi-path fading channels [1,2]. However,

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multiple user access in the MC-CDMA system is limited by the length of the spreading code. Moreover, as the number of users increases, severe multiple access interference (MAI) is produced [3,4]. In order to solve the previous problems, the Partial Block MC-CDMA scheme was initially proposed in [3], and developed with more details in [4]. The MC-CDMA system uses the entire bandwidth for all users, while the users of the PB/MC-MCDA system only use the frequency-block-band assigned to them, thus decreasing the amount of interference. Furthermore, the user capability of the PB/MC-CDMA system is greater compared to that of the MC-CDMA system because it reuses the orthogonal code in every frequency block [4].

In the PB/MC-CDMA system, the total bandwidth is divided into frequency-block-bands, each consisting of a certain number of adjacent sub-carriers. Each user is assigned to the bth frequency-block-band without taking into consideration the channel state of the bth frequency-block-band [3,4]. To the best knowledge of the authors, no channel allocation algorithm has been proposed for the PB/MC-CDMA system.

Several channel allocation algorithms have been proposed for conventional multi-carrier systems. In [5–8], maximum throughput can be achieved by allocating each subcarrier to the user with the maximum SNR, however, these techniques do not consider the fairness among users. The algorithms proposed in [9–12] employ iterative water filling allocation to obtain fairness among users, but do not consider maximizing the throughput of the system.

To achieve an efficient channel allocation, we need accurate channel state information (CSI) to improve the performance, and efficiency of the system. However, it is impossible to obtain perfect CSI, and even if an accurate CSI is obtained, the system will increase its time delay due to large feedback data; hence, the performance of the system will decrease [13]. To solve these problems, we proposed a channel allocation algorithm for the PB/MC-CDMA system by using partial CSI. As a result, the proposed system is capable of using less feedback data; hence, diminishing the time delays of the system. Moreover, the proposed algorithm takes into consideration the fairness among users, and increases the average SNR of the system; consequently, maximizes the total throughput of the system.

2 Overview of the PB/MC-CDMA System and the Proposed System Structure

2.1 Principles of the PB/MC-CDMA System

In the conventional MC-CDMA system users have access to the entire transmission bandwidth. However, in the PB/MC-CDMA system, users employ frequency-block-bands rather than the whole bandwidth. The spreading code is reused in every block. By reusing the spreading code, the proposed scheme accommodates more users than the conventional MC-CDMA system. Furthermore, the desired signal is interfered only by users within the same frequency-block-band.

The users of the PB/MC-CDMA system employ frequency-block-bandwidth rather than the whole bandwidth. The total bandwidth is divided into B sub-blocks, and every frequency-block-band is indexed by b, where $b = (0, 1, \ldots, B-1)$. The previous is represented as $B = N/K$, where N is the total number of sub-carriers available, and K is the length of the orthogonal spreading code. The number of simultaneous users the PB/MC-CDMA system can accommodate is $K \cdot B/M$, where M represents the number of blocks used by each user, whereas the MC-CDMA scheme only supports K simultaneous users. Each user has an orthogonal spreading code with length K and $M \cdot K$ adjacent sub-carriers. In this paper, we assigned M to be equal to one for simplicity.

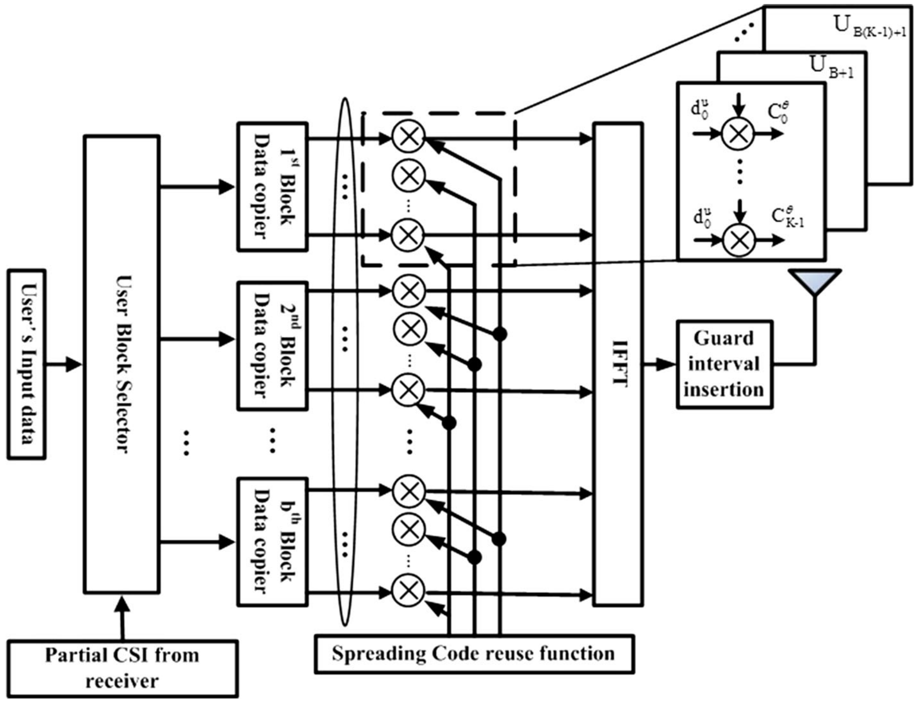

Fig. 1 Schematic diagram of the proposed PB/MC-CDMA transmitter

2.2 Proposed System Structure

A graphical description of the proposed PB/MC-CDMA transmitter is given in Fig. 1. First, a baseband modulator transforms the user's input data into a multilevel sequence of complex numbers using one of several digital modulation techniques. For illustration purposes, QPSK modulation is used in this letter. The modulated data symbol is assigned to the bth frequency-block-band by the block selector unit, which uses partial CSI from the receiver. The proposed scheme increases the average SNR of the system compared to that of the conventional scheme, and takes into consideration the fairness among users. The block selector unit applied in the proposed system will be explained with more details in the next section.

Each user's QPSK data symbols are assigned to a specific frequency-block-band, and are spread over the frequency block by using the user's orthogonal spreading code. The spreading code is defined as $C = (c_0, c_1, c_2, \ldots, c_{K-1})$, where c_K has a value of ± 1, and is selected from a Walsh–Hadamard code matrix. An orthogonal multi-carrier signal is generated by using the IFFT. A guard interval is inserted between the PB/MC-CDMA symbols to avoid intersymbol interference (ISI), and inter-carrier interference (ICI) caused by multi-path fading channels [4]. The complex equivalent low-pass transmitted signal is written as

$$s(t) = \sum_{\mu=0}^{U-1} \sum_{i=0}^{I-1} \sum_{k=0}^{K-1} d_{\mu,k}^{b}(i) C_k^{\theta} e^{j2\pi(Kb+k)(t-iT_s)/T_s} \tag{1}$$

$$T_s = t_s + T_g \tag{2}$$

where $d^{b}_{\mu,k}$ is the μth user's and kth subcarrier's ith complex data symbol for the bth frequency-block-band. Whereas I is the total number of symbols, K is the number of sub-carriers of each block, and θ is the code reuse function [4]. In the next section we will go into detail as of how b is determined for the μth user. The duration and guard time are denoted as t_s and T_g, respectively.

The transmitted signal goes through a frequency-selective fading channel. Lastly, the received signal is represented as follows

$$\begin{aligned} r(t) &= \int_{-\infty}^{+\infty} s(t-\tau)h(\tau;t) + n(t) \\ &= \sum_{\mu=0}^{U-1}\sum_{i=0}^{I-1}\sum_{k=0}^{K-1} Z^{b}_{\mu,k}(t)\, d^{b}_{\mu,k}(i) C^{\theta}_{k} e^{2\pi(K\beta+k)\frac{t-iT_s}{T_s}} + n(t) \end{aligned} \tag{3}$$

where $Z^{b}_{u,k}(t)$ is the received complex envelope of the $(Kb+k)$th sub-carrier's signal and the μth user, allocated to the bth frequency-block-band. Whereas $n(t)$ is the additive white Gaussian noise (AWGN) introduced into the system. Finally, the guard time is removed, and the signal is converted to sub-carrier components using the FFT. The μth user's signal is assigned to the bth frequency-block-band, and it is despread by using its corresponding orthogonal spreading code. At last, the signals are combined and demodulated.

3 Proposed Channel Allocation Scheme

The proposed channel allocation algorithm for the PB/MC-CDMA system is described in Fig. 2. We divide the total bandwidth into frequency-block-bands, each comprising of several adjacent subcarriers. Next, partial CSI from the receiver is used for calculating the SNR from all users. To estimate the partial CSI, pilot based channel estimation is used [14]. The pilot sequence matrix is generated as follows

$$X = \left[x_{1,}, x_2, x_3, \ldots, x_{KB}\right], \tag{4}$$

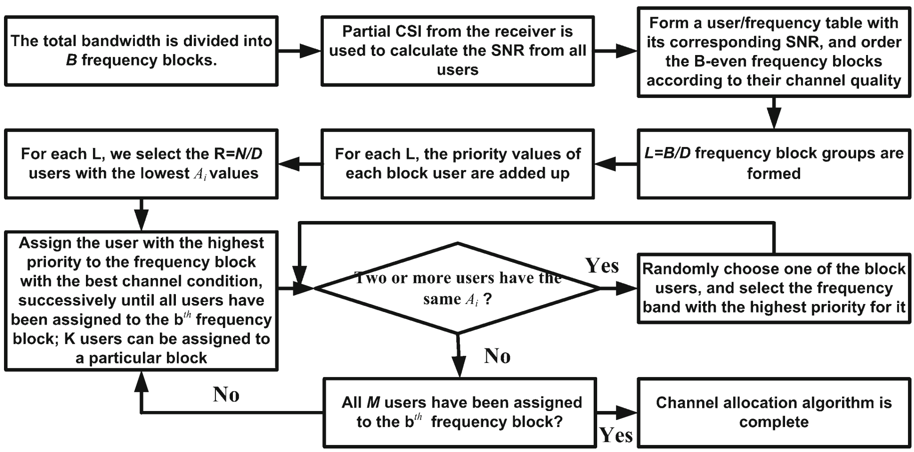

Fig. 2 Proposed channel allocation algorithm

User \ Frequency Block	1	2	3	4
1	20dB	10dB	15dB	5dB
2	10dB	5dB	15dB	20dB
3	15dB	20dB	5dB	10dB
4	5dB	20dB	10dB	15dB
5	15dB	5dB	20dB	10dB
6	20dB	5dB	15dB	10dB
7	5dB	15dB	10dB	20dB
8	15dB	10dB	20dB	5dB

Partial CSI from 8 users and 4 frequency blocks.

User \ Frequency Block	1	2	3	4
1	1	3	2	4
2	3	4	2	1
3	2	1	4	3
4	4	1	3	2
5	2	4	1	3
6	1	4	2	3
7	4	2	3	1
8	2	3	1	4

Frequency block prioritization.

Fig. 3 Block users are ordered according to their channel quality

where *KB* is the number of users. The received signals of the pilot sequence is represented as follows

$$Y = HX + N, \tag{5}$$

where H is the estimated channel and N refers to AWGN. Further, Y and N are $KB \times L$ matrices, where L is the length of the pilot symbol. Then, the maximum-likelihood (ML) estimation of the channel matrix is given by

$$\hat{H} = YH^{+}, \tag{6}$$

where $(\bullet)^{+}$ represents the pseudo-inverse matrix. Next, the channel gain, $\hat{G}$, is given by $\hat{G} = \left(\hat{H}\right)^{+}$. Finally, the SNR of the μth user is given as

$$\rho_{\mu} = \frac{E\left[xx^{*}\right]}{\sigma^{2}\left\|\hat{G}_{\mu}\right\|^{2}}, \tag{7}$$

where $\hat{G}_{\mu}$ is the gain of the μth user, $\|\cdot\|$ is the norm, and * is the Hermitian conjugate. After calculating the SNR of all block users, the PB/MC-CDMA channel allocation algorithm is given as follows:

1. We form a user/frequency table with its corresponding SNR; the rows correspond to the user, while the columns are for the frequency-block-bands.
2. The B-even frequency-block-bands are ordered according to their channel quality. The frequency block with the highest SNR has the highest priority order, while the one with the lowest SNR has the lowest priority. A value of one is given to the best frequency-block-band (highest priority) successively until the frequency-block-band with the lowest SNR is found, and it is given the value of B. Steps one and two are described in Fig. 3 for eight users and $K = 2$.

3. The B-even frequency-block-bands are divided by the factor $D = 2^c$, where c is a positive integer number different from zero, to form L frequency-block-band groups, given as $L = B/D$. Each frequency block group is composed of adjacent frequency blocks. In this paper, we used $c = 1$ for illustration purposes.
4. For each of the L frequency block groups, the priority values of each block user are added up. The final summation defines the sub-group state information A_i, $for\ i = 1, 2, \ldots, L$. The user with the lowest state information value, A_i, has the highest priority within the group.
5. For each of the frequency block groups, we select the R users with the lowest state information values, for $R = KB/D$.
6. Assign the user with the highest priority to the frequency-block-band with the best channel condition, successively until all users have been assigned to the bth frequency-block-band; K users can be assigned to a particular block. In case two or more block users have the same A_i, we randomly choose one of the block users, and select the frequency-block-band with the highest priority for it, and successively for the rest of the block users with same priority.

Step 6 is repeated for each sub-group until all block users have optimally been allocated to their frequency-block-band. Figure 4 illustrates the proposed scheme, steps 2–7.

In Fig. 4 the users have been assigned to a frequency block with better channel conditions. In the conventional PB/MC-CDMA system, for eight users and $K = 2$, users 1 and 2 would be assigned to the first frequency-block-band, users 3 and 4 to the second frequency-block-band, successively until all users have been allocated [3,4]. But for the proposed system, K users are allocated to the frequency-block-band that offers the best channel conditions. In the next section we will analyze the performance of the proposed system in terms of Jain's fairness index and throughput.

4 Experimental Results and Discussion

Computer simulations were done to evaluate the performance of the proposed channel allocation algorithm. The system was analyzed for 8 frequency-block-bands, while the SNR of each user was randomly generated to be in the range of 0–20 dB. The rest of the parameters applied in our simulations are shown in Table 1. For comparison reasons, the parameters described in Table 1 comply with the simulation parameters applied in [3] and [4]. The number of sub-carriers is 128, the spreading factor is 16, and the number of users varies from 8 to 128. The simulation employs an 18-path exponential Rayleigh fading channel model with a 1-sample delay interval between paths, in which the attenuation of the path is 1 dB. The length of the guard interval (GI) is 25 % of the symbol duration. The equal gain combining (EGC) scheme was implemented as the combining method. This method combines the subcarriers after compensation of the phase shift caused by fading. Moreover, EGC can reduce the loss of orthogonality between subcarriers, caused by frequency selective fading, without complexity.

The proposed system was analyzed in terms of the system's total throughput, the processing time needed to execute the algorithm, and Jain's fairness index. The results obtained for the proposed system were compared to those of the optimal and conventional systems. In this manuscript we refer to the "conventional" or "fixed" system as the one proposed in [3,4]. In [3,4], each user is assigned successively to the bth frequency-block-band without taking into consideration the channel state of the bth frequency-block-band. In the case of the "optimal"

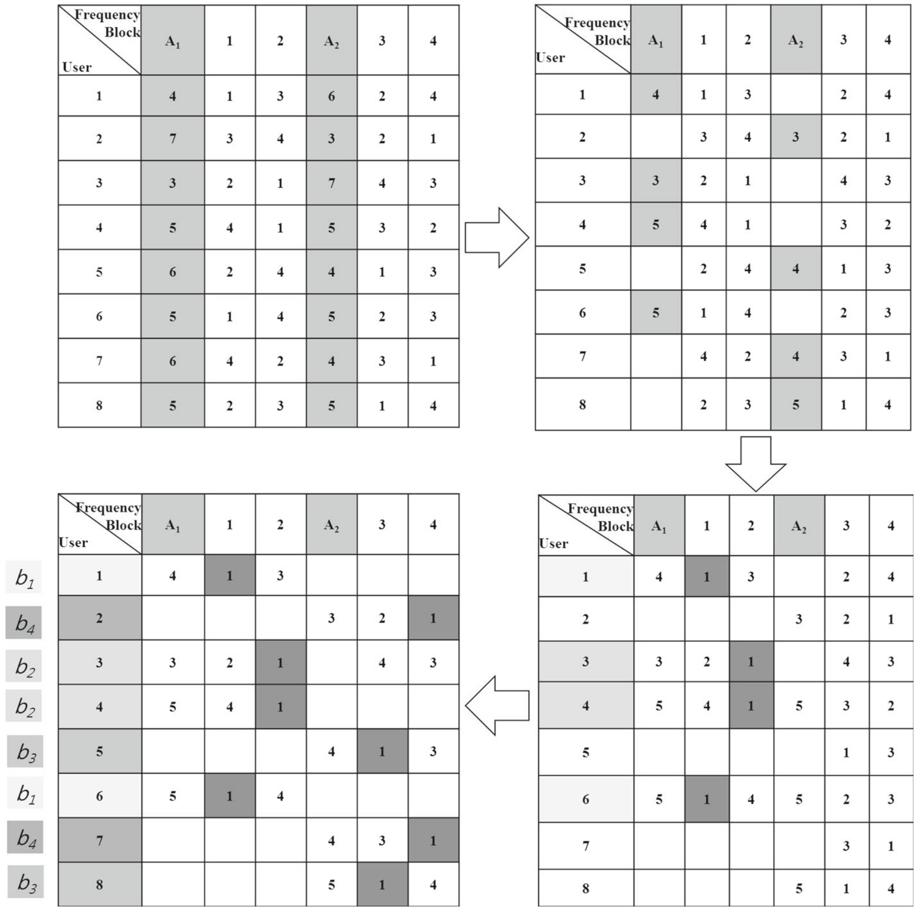

Fig. 4 Channel block allocation for $c = 1$

method, we refer to it as the technique in which each user is assigned to the best frequency-block-band available according to a set of possible combinations. A set of users can each be assigned to a specific frequency-block-band in different ways forming permutations [15]. The "optimal" method consists on performing all of the possible combinations, and then determine the one in which all users are assigned to the best frequency-block-band. The main drawback of the "optimal" method is related to the complexity needed to perform all of the possible combinations.

In Fig. 5 we illustrate the throughput of the proposed system for different number of users. Overall, the proposed channel allocation algorithm outperforms the conventional method. The optimal scheme slightly outperforms the proposed method, but the difference is so small that we can assume that they have the same throughput. Overall, as the number of uses increases, the system's throughput decreases.

Figure 6 describes the processing time needed to execute the proposed, optimal, and conventional systems. It refers to the CPU time, given in seconds, needed to execute each of the algorithms. As expected, the conventional system does not use much time to allocate a channel to each user. The proposed channel allocation algorithm requires less processing time

Table 1 Simulation parameters

Parameter	Value
Bandwidth	20 MHz
Modulation	QPSK
Number of subcarriers	128
FFT size	128
Spreading factor (K)	16
Symbol rate	156.25 KHz
Number of data symbols	64
Number of pilot symbols	4
Number of users	8, 16, 32, 64, 128
Length of guard interval	25 % of a symbol length
Combining method	EGC
Short spreading code	Walsh–Hadamard code
Channel model	18-path exponential Rayleigh

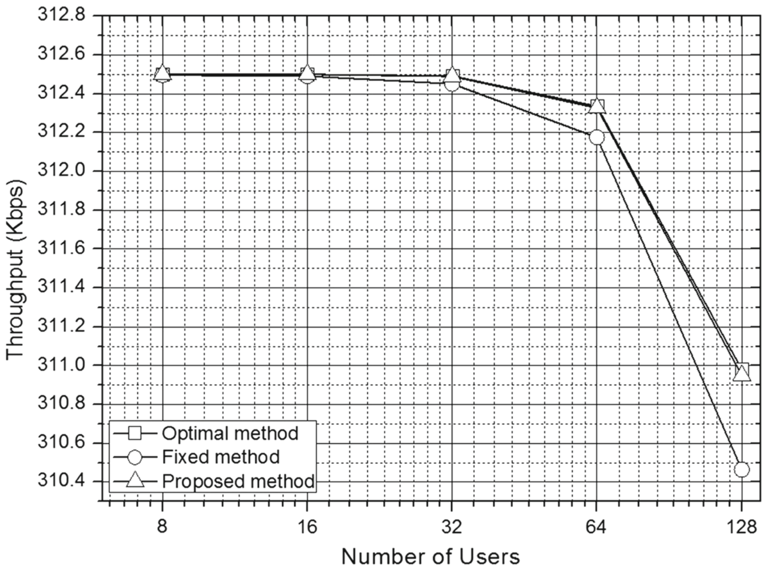

Fig. 5 Throughput of the optimal, conventional, and proposed systems

compared to that of the optimal system. As a result, the complexity of the proposed algorithm is reduced when compared to that of the optimal system. Therefore, less complex digital systems will be needed by implementing the proposed system; consequently, a reduction in the costs will be achieved.

The fairness of the proposed system is obtained by using Jain's index. The fairness of the system is given as follows [16]

$$J\left(E\left[R_1\right], E\left[R2\right], E\left[R_3\right], \ldots, E\left[R_U\right]\right) = \frac{\left[\sum_{i=1}^{U} E\left[R_i\right]\right]^2}{\sum_{i=1}^{U} E\left[R_i\right]^2}, \tag{8}$$

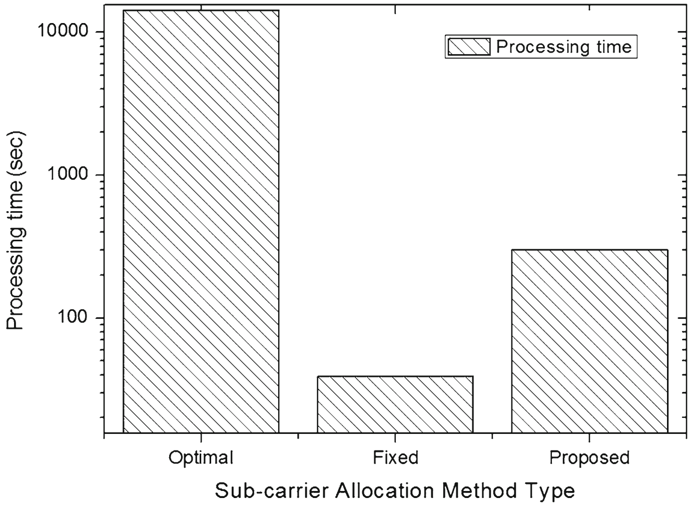

Fig. 6 Processing time needed to execute the optimal, conventional, and proposed systems

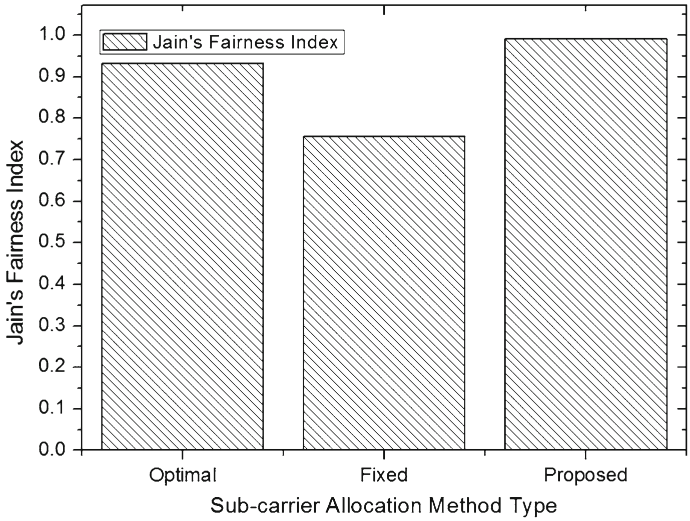

Fig. 7 Fairness index of the optimal, conventional, and proposed systems

where R_i is the historical average throughput of user i, while $E[\cdot]$ denotes the average operator. Figure 7 shows Jain's fairness index of the proposed, optimal, and conventional systems. Overall, the proposed system offers the best fairness among users compared to the other systems. The prior is because the proposed system allocates channels with better conditions to each user.

5 Conclusions

In this letter a dynamic channel allocation scheme was introduced for the PB/MC-CDMA scheme using partial CSI. The proposed system uses less feedback data; hence, diminishes the delay time of the system. Moreover, the proposed algorithm takes into consideration the fairness among users. According to Jain's fairness index, the proposed scheme improves the fairness among users compared with those of the conventional and optimal PB/MC-CDMA systems. Furthermore, the proposed scheme increases the average SNR of the system compared with that of the conventional scheme; consequently, maximizes the total throughput of the system. Moreover, the proposed channel allocation algorithm requires less processing time compared to that of the optimal system; therefore, the complexity of the proposed algorithm is reduced when compared to the optimal system. Therefore, the proposed algorithm is a viable option for multicarrier wireless systems, specifically for the PB/MC-CDMA scheme.

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References

1. Hara, S., & Prasad, R. (1999). Design and performance of multicarrier CDMA system in frequency-selective Rayleigh fading channels. *IEEE Vehicular Technology Magazine*, *48*(4), 1584–1595.
2. Hara, S., & Prasad, R. (1997). Overview of multicarrier CDMA. *IEEE Communications Magazine*, *35*(12), 126–133.
3. Lee, K. J., & Lee, K. S. (2006). Clustered OFDMA in the multi-path fading channel. *Proceedings Computational Science and its Applications 3984*(1), 708–716.
4. Lee, K. J., & Lee, K. S. (2008). Adaptive resource allocation for the PB/MC-CDMA system in frequency selective fading channels. *IEICE Transactions on Communications*, *E91*(B(12)), 4042–4045.
5. Wong, C., Cheng, R., Lataif, K., & Murch, R. (1999). Multiuser OFDM with adaptive subcarrier bit, and power allocation. *IEEE Journal on Selected Areas in Communications*, *17*(10), 1747–1758.
6. Kivanc, G., Li, G., & Liu, H. (2003). Computationally efficient bandwidth allocation and power control for OFDMA. *IEEE Transactions on Wireless Communications*, *2*(6), 1150–1158.
7. Jang, J., & Lee, K. B. (2003). Transmit power adaptation for multiuser OFDM systems. *IEEE Journal on Selected Areas in Communications*, *21*(2), 171–178.
8. Shen, Z., Andrews, J., & Evans, B. (2003). Optimal power allocation in multiuser OFDM systems. In *Proceedings IEEE Global Telecommunications Conference* (Vol. 1, pp. 337–341).
9. Kim, K., Han, Y., & Kim, S. L. (2005). Joint subcarrier and power allocation in uplink OFDMA systems. *IEEE Communications Letters*, *9*(6), 526–528.
10. Munz, G., Pfletschinger, S., & Speidel, J. (2002). An efficient waterfilling algorithm for multiple access OFDM. In *Proceedings IEEE Global Telecommunications Conference* (Vol. 1, pp. 681–685).
11. Yu, W., Rhee, W., Boyd, S., & Cioffi, J. (2001). Iterative water-filling for Gaussian vector multiple-access channels. In *Proceedings IEEE International Symposium on Information Theory*
12. Gao, L., & Cui, S. (2008). Efficient subcarrier, power, and rate allocation with fairness consideration for OFDMA uplink. *IEEE Transactions on Wireless Communications*, *7*(5), 1507–1511.
13. Song, D., & Chen, C. W. (2007). Scalable H.264/AVC video transmission over MIMO wireless systems with adaptive channel selection based on partial channel information. *IEEE Transactions on Circuits and Systems for Video Technology*, *17*(9), 1218–1226.
14. Coleri, S., Ergen, M., Puri, A., & Bahai, A. (2002). Channel estimation techniques based on pilot arrangement in OFDM systems. *IEEE Transactions on Broadcasting*, *48*(3), 223–229.
15. Papoulis, A., & Unnikrishna Pillai, S. (2002). *Probability random variables and stochastic processes*. Singapore: McGraw-Hill Higher Education.
16. Almatarneh, R. K., Ahmed, M. H., & Dobre, O. A. (2010). Performance analysis of proportional fair scheduling in OFDMA wireless systems. In *Proceedings Fall IEEE Vehicular Technology Conference* (pp. 1–5).

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