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Capacity-Fairness Controllable Scheduling Algorithms for Single-Carrier FDMA

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SUMMARY Scheduling imposes a trade-off between sum capacity and fairness among users. In some situations, fairness needs to be given the first priority. Therefore, a scheduling algorithm which can flexibly control sum capacity and fairness is desirable. In this paper, assuming the single-carrier frequency division multiple access (SC-FDMA), we propose three scheduling algorithms: modified max-map, proportional fairness (PF)-map, and max-min. The available subcarriers are grouped into a number of subcarrier-blocks each having the same number of subcarriers. The scheduling is done on a subcarrier-block by subcarrier-block basis to take advantage of the channel frequency-selectivity. The same number of non-contiguous subcarrier-blocks is assigned to selected users. The trade-off between sum capacity and fairness is controlled by changing the number of simultaneously scheduling users per time-slot. Capacity, fairness, and peak-to-average power ratio (PAPR) when using the proposed scheduling algorithms are examined by computer simulation.

key words: *SC-FDMA, multi-user scheduling, max-map, PF-map, max-min*

1. Introduction

The broadband wireless channel is characterized by the frequency-selective fading caused by multiple propagation paths with different time delays [1]. Orthogonal frequency division multi-access (OFDMA) [2] is a robust multi-access technique, which is immune against frequency-selective fading. However, OFDMA has the disadvantage of high peak-to-average ratio (PAPR) and hence, it requires expensive wide-range linear transmit power amplifiers [3]. Because of its lower PAPR, compared with OFDMA, single carrier-frequency division multiple access (SC-FDMA) [4] is suitable for uplink multi-access.

When the number of active users is more than the number of available channels, multi-user scheduling is necessary. Max-map scheduling [5], proportional fairness (PF)-map scheduling [6], [7], and max-min scheduling [8] are the well-known scheduling algorithms. By using multi-user scheduling, sum capacity improves due to increased multi-user diversity gain as the number of active users increases [9]. However, there is a trade-off relationship between sum capacity and fairness among users, which the above max-map, PF-map, and max-min scheduling algorithms cannot control. In certain situations (e.g., emergency, natural disasters) fairness should be given the first priority to provide equal throughput to all active users. Therefore, a scheduling algorithm which can flexibly control the sum capacity and fairness is desirable.

Several scheduling algorithms have been proposed which control the capacity and fairness: weighted PF (WPF) [10], adaptive PF (APF) [11], and adaptive fairness and throughput control (AFTC) [12]. The WPF [10] has difficulty to achieve the target fairness index in a dynamic scenario of varying users' locations [12]. The APF and the AFTC have the disadvantage of long convergence time.

In this paper, we propose three scheduling algorithms (modified max-map, PF-map, and max-min scheduling algorithms) for slotted packet transmission system using SC-FDMA. In each time-slot, some users among active users are selected as simultaneously scheduling users according to the scheduling algorithm. The sum capacity and fairness can be controlled by changing the number of simultaneously scheduling users per time-slot. The available subcarriers are grouped into a number of subcarrier-blocks each having the same number of subcarriers. The scheduling is done subcarrier-block by subcarrier-block basis to take advantage of the channel frequency-selectivity [13]. The same number of non-contiguous subcarrier-blocks is allocated to each selected user. The capacity, fairness and the PAPR when using the proposed algorithms are examined by computer simulation. Since multiple non-contiguous subcarrier-blocks are allocated to a selected user, the PAPR may increase; therefore, the impact of subcarrier-block size on the PAPR is also examined.

The rest of the paper is organized as follows. Section 2 presents the SC-FDMA transmission model and derives the channel capacity expression. Section 3 overviews the conventional scheduling algorithms. Section 4 describes the modified scheduling algorithms. Section 5 discusses the computer simulation results and Sect. 6 concludes this paper.

2. SC-FDMA Transmission Model

In this paper, we consider the single-cell and multi-user environment. Figure 1 shows the system model. The cell radius is denoted by R. The distance between the u-th (u=1,..., U) user and the base station (BS) is denoted by R_u. It is assumed that there are U active users in each cell and the scheduling algorithm selects U_t users from U active users for simultaneous access. The total number of available subcarriers is denoted by N_c. The number of subcarrier-blocks

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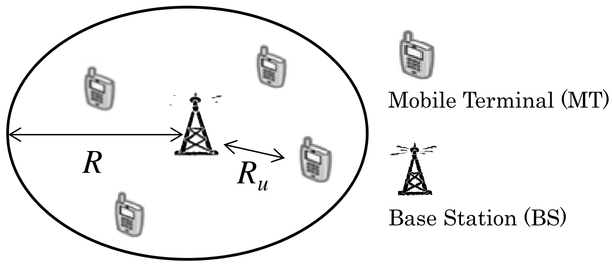


Fig. 1 System model.

is denoted by K, each subcarrier-block consisting of N_c/K contiguous subcarriers. D subcarrier-blocks are allocated to each simultaneously scheduling user (i.e., the number M of subcarriers allocated to each user is the same for all selected users and is $M = D \times N_c/K$).

The channel capacity $C_u(t)$ of the u-th user at the t-th time-slot is given by [13]

$$C_u(t) = \frac{1}{N_c}\sum_{n=0}^{N_c-1} C_u(n,t) = \frac{1}{N_c}\sum_{n=0}^{N_c-1} \varepsilon_u(n,t)\log_2\left(1 + \frac{P_{r,u}}{N}|H_u(n,t)|^2\right), \quad (1)$$

where $C_u(n,t)$ denotes the u-th user capacity of the n-th subcarrier allocated at the t-th time-slot. $\varepsilon_u(n,t)$ in Eq. (1) takes 0 or 1; $\varepsilon_u(n,t) = 1(0)$ if the n-th subcarrier is allocated to the u-th user (otherwise). $H_u(n,t)$ denotes the n-th frequency complex-valued channel gain between the u-th user and the BS. $N = N_0/T_s$ is the noise power with N_0 and T_s being respectively the single-sided noise power spectrum density of additive white Gaussian noise (AWGN) and the symbol duration. $P_{r,u}$ is the local averaged received signal power (averaging is done over fading) associated with the u-th user at BS and is given as

$$P_{r,u} = \overline{P}_t \cdot r_u^{-\alpha} \cdot 10^{-\eta_u/10}, \quad (2)$$

where $\overline{P}_t = P_t \cdot R^{-\alpha}$ is the normalized MT transmit power with P_t being the MT transmit power. $r_u = R_u/R$ is the normalized distance. α and η_u are the path loss exponent and the shadowing loss in dB between the u-th user and the BS, respectively.

3. Conventional Scheduling Algorithms

In Sect. 3, we describe the conventional scheduling algorithms which are executed on a subcarrier-block by subcarrier-block basis. In this paper, the block averaged channel gain $H_u(k,t)$ and the capacity $C_u(k,t)$ on the k-th subcarrier-block associated with the u-th user are introduced for examining the impact of the subcarrier-block size on the PAPR. They are defined as

$$H_u(k,t) = \frac{1}{N_c/K}\sum_{n=kN_c/K}^{(k+1)N_c/K} |H_u(n,t)|^2, \quad (3)$$

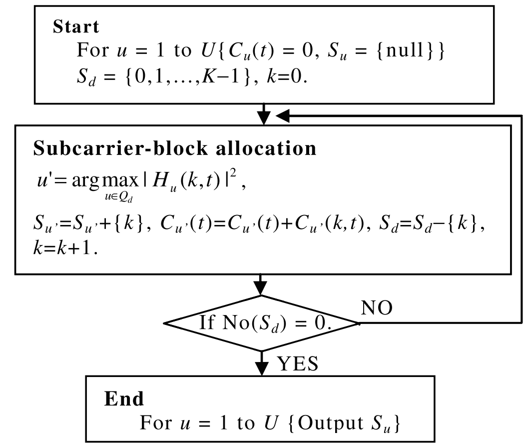


Fig. 2 Conventional max-map.

$$C_u(k,t) = \frac{1}{N_c/K}\sum_{n=kN_c/K}^{(k+1)N_c/K} C_u(n,t). \quad (4)$$

3.1 Max-Map

Max-map scheduling algorithm is carried out based on the following sum capacity maximization problem:

$$\max \sum_{u=1}^{U} C_u(t). \quad (5)$$

To maximize sum capacity, max-map scheduling algorithm allocates each subcarrier-block to the users who have the highest channel gain. Figure 2 shows a flowchart of max-map scheduling algorithm. S_u is a set of subcarrier-blocks which have already been allocated to the u-th user. S_d is a set of subcarrier-blocks which have not been allocated yet. $\{x\}$ denotes a set of x. No(x) is the number of elements of set $\{x\}$. User-selection for the k-th subcarrier-block is performed as

$$u' = \arg\max_{u \in Q_d} |H_u(k,t)|^2. \quad (6)$$

Max-map scheduling can achieve the highest sum capacity while fairness among users is poor.

3.2 PF-Map

In the PF-map scheduling algorithm, the subcarrier-block allocation is carried out based on the following maximization problem:

$$\max \sum_{u=1}^{U}\sum_{k=0}^{K-1} C'_u(k,t). \quad (7)$$

where $C'_u(n,t)$ denotes the normalized capacity given by [6. 7]

$$C'_u(k,t) = \frac{C_u(k,t)}{\overline{C}_u(t)}. \quad (8)$$

In Eq. (8), $\overline{C}_u(t)$ is the channel capacity averaged over past slots according to

$$\overline{C}_u(t) = \begin{cases} \left(1-\frac{1}{T_c}\right)\overline{C}_u(t-1) & u \neq selected\ user \\ \left(1-\frac{1}{T_c}\right)\overline{C}_u(t-1) + \frac{1}{T_c}C_u(t) & u = selected\ user \end{cases} \quad (9)$$

where T_c is the equivalent averaging interval in slots. PF-map scheduling achieves a good balance between the sum capacity and fairness among active users.

3.3 Max-Min

Max-min scheduling allocates subcarrier-blocks so as to maximize fairness based on following maximization problem

$$\max \min_{u \in U} C_u(t). \quad (10)$$

In this paper, we use the suboptimal algorithm [8] which nearly achieves the above optimization problem with low complexity. The flowchart of the conventional max-min algorithm is shown in Fig. 3.

Step 1 Allocate one subcarrier-block which has the highest channel gain to each user, i.e., the k'-th subcarrier-block is allocated to the u-th user according to

$$k' = \arg\max_{k \in S_d} |H_u(k,t)|^2. \quad (11)$$

The subcarrier-block which has been allocated to a user previously is not allocated to the other users to avoid duplication.

Step 2 Allocate another one subcarrier-block which satisfies Eq. (11) to the u'-th user according to

$$u' = \arg\min_{u \in Q_d} C_u(t). \quad (12)$$

Step 2 is repeated until all subcarrier-blocks are allocated to the users.

This algorithm can be used only when the number of active users is smaller than the total number of available subcarrier-blocks. Max-min scheduling algorithm provides the highest fairness while sum capacity degrades compared to max-map and PF-map scheduling algorithms.

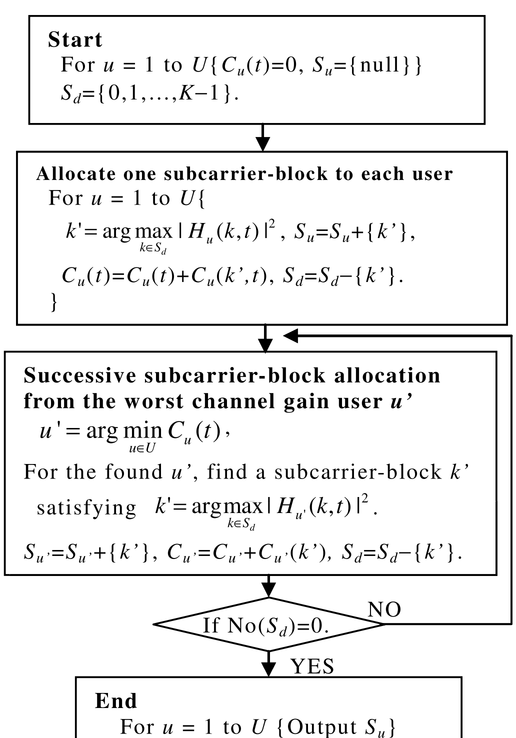


Fig. 3 Conventional max-min.

4. Modified Scheduling Algorithms

By using the conventional scheduling, the sum capacity and fairness among users vary according to the channel variation and hence, the trade-off relationship between the sum capacity and fairness among users cannot be controlled. The trade-off can be controlled by changing the number of simultaneously scheduling users per time-slot. In this paper, we propose the modified scheduling algorithms so as to control the trade-off between the sum capacity and fairness among users by selecting the constant number of simultaneously scheduling users. Each of three modified scheduling algorithms is composed of three steps and is described in the following subsections.

4.1 Modified Max-Map

Figure 4 shows the flowchart of the modified max-map scheduling algorithm. D is the number of subcarrier-blocks per simultaneously scheduling user and is given by $D = K/U_t$, where U_t is the number of simultaneously scheduling users per time-slot. Q_d is a set of users to whom the subcarrier-block allocation has not yet been computed. The modified max-map scheduling algorithm is carried out as follows. In Step 1, the tentative subcarrier-block allocation is done on active users by using the conventional max-map scheduling algorithm. In Step 2, one user is selected as a new simultaneously scheduling user from remaining active users who have not yet been selected as a simultaneously scheduling user. In Step 3, the subcarrier-block adjustment is done on the selected user to make the number of subcarrier blocks equal to $D(= K/U_t)$. Step 2 and Step 3 are repeated until all U_t users have been allocated D subcarrier-blocks. The modified max-map scheduling algorithm is summarized as follows.

Step 1 Tentative subcarrier-block allocation by conventional max-map scheduling algorithm

Step 2 User-selection

Select the u_{MAX}–th user according to

$$u_{MAX} = \arg\max_{u \in Q_d} C_u(t). \quad (13)$$

Then, the u_{MAX}-th user is removed from Q_d (i.e., Q_d =

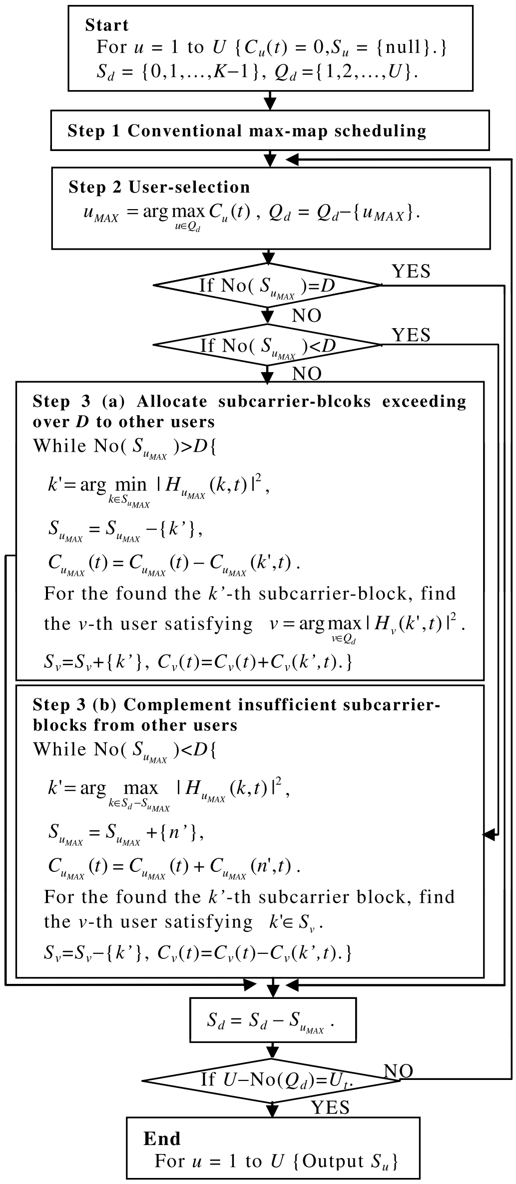


Fig. 4 Modified max-map.

$Q_d - \{u_{MAX}\}$).

Step 3 Subcarrier-block adjustment

(a) If No($S_{u_{MAX}}$) is larger than D,
the k'-th ($k' \in S_{u_{MAX}}$) subcarrier-block which satisfies

$$k' = \arg\min_{k \in S_{u_{MAX}}} |H_{u_{MAX}}(k,t)|^2 \tag{14}$$

is removed from the u_{MAX}-th user (i.e., $S_{u_{MAX}} = S_{u_{MAX}} - \{k\}$). The removed subcarrier-blocks is allocated to the v-th user (i.e., $S_v = S_v + \{k'\}, v \in Q_d$) who satisfies

$$v = \arg\max_{v \in Q_d} |H_v(k',t)|^2. \tag{15}$$

The above process is repeated until No($S_{u_{MAX}}$) $=D$.

(b) If No($S_{u_{MAX}}$) is smaller than D,
the k'-th subcarrier-block ($k' \in (S_d - S_{d_{MAX}})$) which satisfies

$$k' = \arg\max_{k \in S_d - S_{u_{MAX}}} |H_{u_{MAX}}(k,t)|^2 \tag{16}$$

is allocated to the u_{MAX}-th user (i.e., $S_{u_{MAX}} = S_{u_{MAX}} + \{k'\}$) from the v-th user ($v \in Q_d$). Then, the k'-th subcarrier-block is removed from S_v ($S_v = S_v - \{k'\}$). The above process is repeated until No($S_{u_{MAX}}$)=D.

Step 2 and Step 3 are repeated until all subcarrier-blocks are allocated to U_t users (i.e., U–No(Q_d)=U_d).

4.2 Modified PF-Map

The modified PF-map scheduling algorithm can be carried out in the same manner as the modified max-map scheduling algorithm. However, instead of the conventional max-map scheduling algorithm, the conventional PF-map algorithm is used for tentative subcarrier-block allocation in Step 1. Furthermore, $C_u(t)$ in Eq. (13) is replaced by $C'_u(t)$ defined as

$$C'_u(t) = \frac{1}{K} \sum_{k=0}^{K-1} C'_u(k,t). \tag{17}$$

4.3 Modified Max-Min

Figure 5 shows the flowchart for the modified max-min scheduling algorithm. The modified max-min scheduling algorithm is carried out as follows. In Step 1, the tentative subcarrier-block allocation is done by using the conventional max-min scheduling algorithm on remaining active users who have not yet been selected as a simultaneously scheduling user. In Step 2, one user who has minimum capacity is selected from remaining active users as a new simultaneously scheduling user so as to maximize the fairness. In Step 3, the number of subcarrier-blocks of the selected user is adjusted to $D = K/U_t$. In the modified max-min scheduling algorithm, the subcarrier-block adjustment affects the user-selection on the next iteration unlike the modified max-map and PF-map scheduling algorithms. Therefore, the removal of the subcarrier-blocks allocated to the active user is done after the subcarrier-block adjustment. As a consequence, the modified max-min scheduling algorithm repeats Step 1 to Step 3 until all U_t users have been allocated $D(=K/U_t)$ subcarrier-blocks. The modified max-min scheduling algorithm is summarized as follows.

Step 1 Tentative subcarrier-block allocation by conventional max-min scheduling algorithm

Step 2 User-selection
Select the u_{MIN}-th user according to

$$u_{MIN} = \arg\min_{u \in U} \overline{C}_u(t). \tag{18}$$

Then, the u_{MIN}-th user is removed from Q_d (i.e., $Q_d = Q_d - \{u_{MIN}\}$).

Step 3 Subcarrier-block adjustment

(a) If No($S_{u_{MIN}}$) is larger than D,
the k'-th subcarrier-block satisfying Eq. (14) is removed from $S_{u_{MIN}}$ (i.e.,$S_{u_{MIN}} = S_{u_{MIN}} - \{k'\}$). The above

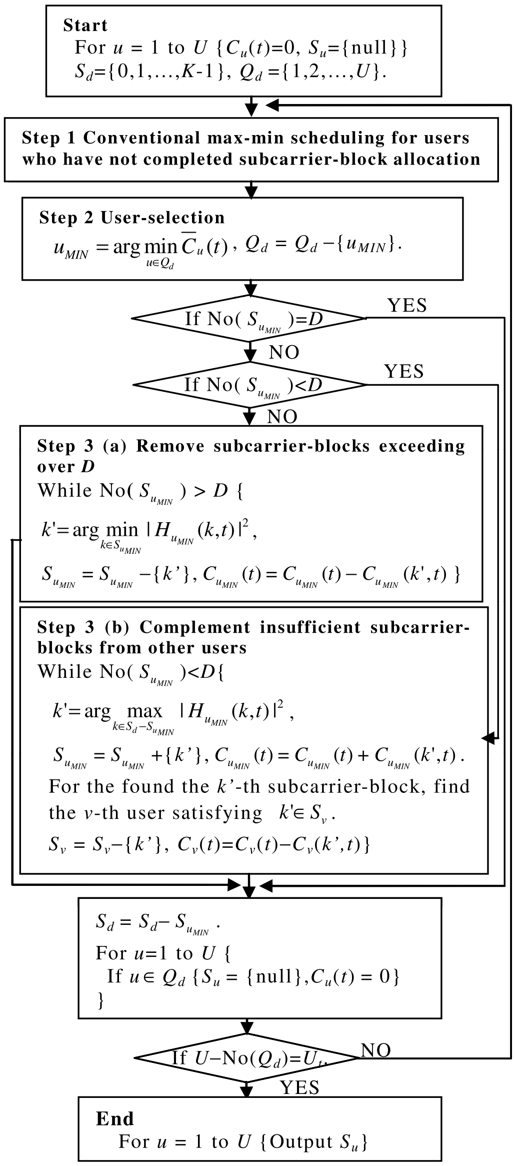


Fig. 5 Modified max-min.

process is repeated until No($S_{u_{MIN}}$)=D.

(b) If No($S_{u_{MIN}}$) is larger than D, the k'-th subcarrier-block ($k' \in (S_d - S_{u_{MIN}})$) satisfying Eq. (16) is allocated to the u_{MIN}-th user (i.e., $S_{u_{MIN}} = S_{u_{MIN}} + \{k'\}$) from the v-th user ($v \in Q_d$). Then, the k'-th subcarrier-block is removed from S_v (i.e., $S_v = S_v - \{k'\}$). Above process is repeated until No($S_{u_{MIN}}$)=D.
After (a) or (b), all subcarrier-blocks which are allocated to active users removed from the users.

Step 1, Step 2, and Step 3 are repeated until all subcarrier-blocks are allocated to U_t users (i.e., $U - \text{No}(Q_d) = U_t$).

It should be noted that the modified max-min scheduling algorithm can be used only when the number of active users is equal to or smaller than the total number of available subcarrier-blocks.

5. Computer Simulation

We evaluate, by Monte-Carlo numerical computation methods, the cumulative distribution function of channel capacity (CDF) and fairness index [14]. Fairness index F is given by

$$F = \frac{\left(\sum_{u=0}^{U-1} \overline{C}_u(t)\right)^2}{U \cdot \sum_{u=0}^{U-1} \overline{C}_u(t)^2}. \tag{19}$$

As fairness becomes higher, F approaches 1. On the other hand, as fairness becomes lower, F approaches $1/U$. PAPR is defined as [15]

$$\text{PAPR} = \frac{\max\{|s(\tau)|^2\}_{\tau=0\sim N_c-1}}{\text{E}\{|s(\tau)|^2\}}, \tag{20}$$

where $\max\{x(\tau)\}_{\tau=0\sim N_c-1}$ and $\text{E}\{x(\tau)\}$ denote the largest value among $\{x(0), ..., x(\tau), ..., x(N_c-1)\}$ and the ensemble average of $x(\tau)$, respectively. $\{s(0), ..., s(\tau), ..., s(N_c-1)\}$ is transmit time-domain signal.

The numerical evaluation conditions are summarized in Table 1. The channel is assumed to be an L=16 path frequency-selective block Rayleigh fading channel. The total number U of users and the total number N_c of subcarriers are set to U=N_c=128. The number U_t of simultaneously scheduling users per time-slot is changed from U_t = 1 to 128.

5.1 Outage Capacity and Fairness

Figures 6 and 7 plot the trade-off between the capacity and fairness with the number U_t of simultaneously scheduling users per time-slot as a parameter. The x% outage user capacity (fairness index) is the one below which the user capacity (fairness index) falls with a probability of x%. It is seen from Figs. 6 and 7 that by increasing U_t, the fairness consistently improves for the modified max-map scheduling algorithm. On the other hand, in the case of modified PF-map and max-min scheduling algorithms, by increasing U_t, the fairness first improves and then starts to deteriorate beyond $U_t = N_c/8$. The reason for this is given below. The modified max-map scheduling algorithm preferentially selects users in good channel condition. When U_t is small, only users in a good channel condition are selected, resulting in a very low fairness. However, by increasing U_t, the number of selected users in a bad channel condition gradually increases and therefore, fairness consistently improves. On the other hand, the modified PF-map and max-min scheduling algorithms preferentially select users in a bad channel condition. Therefore, by increasing U_t, the number of selected users in a good channel increases and fairness among users improves. However, when U_t is too large (i.e., U_t>N_c/8), the number of users in a good channel condition who have higher capacity becomes larger than that of users in a bad channel condition and as a consequence,

Table 1 Numerical evaluation conditions.

Fading type	Block Rayleigh fading
Power delay profile	Uniform
No. of paths	L=16
Time delay	$\tau' = l, l = 0 \sim L-1$
Total No. of users	$U = 128$
Total No. of subcarriers	$N_c = 128$
No. of simultaneously scheduling users	$U_t = 1, 2, 4, 8, 16, 32, 64, 128$
Path loss exponent	$\alpha = 3.5$
Shadowing loss standard deviation	$\eta = 8.0$ (dB)
Normalized transmit SNR	$\overline{P}_t$=10 (dB)

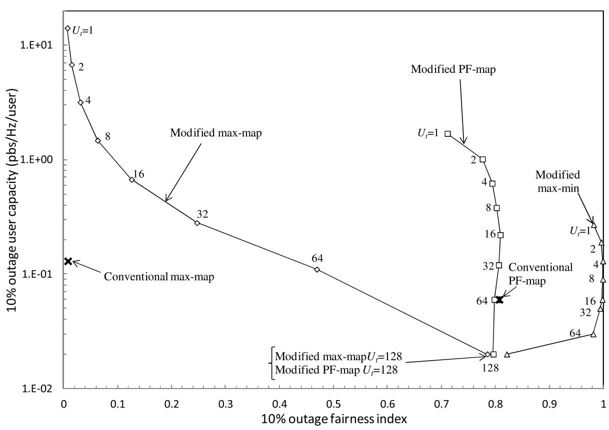


Fig. 6 User capacity-fairness trade-off. $K = 128$ ($N_c/K = 1$).

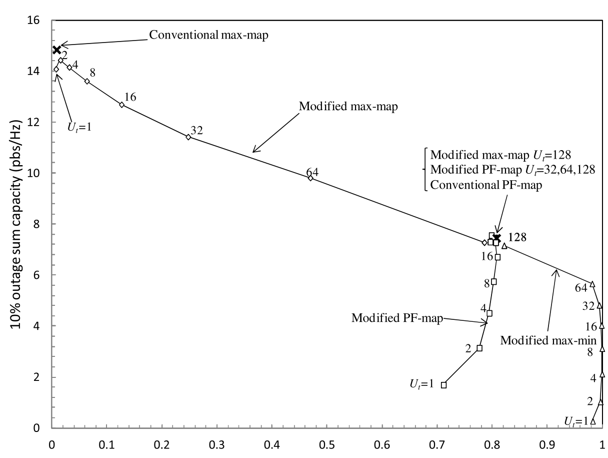
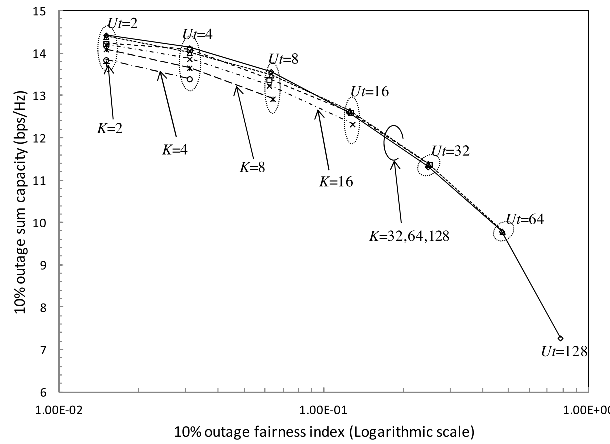


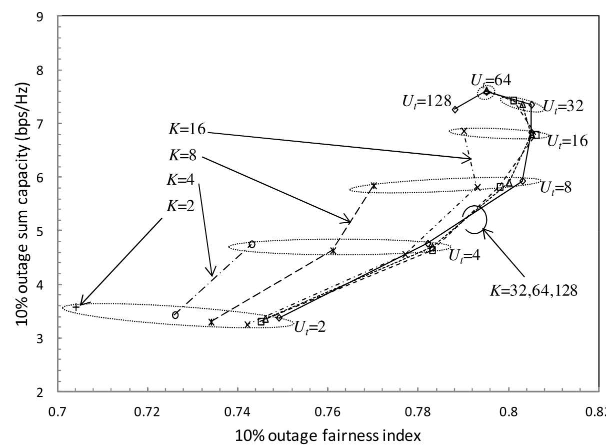
Fig. 7 Sum capacity-fairness trade-off. $K = 128$ ($N_c/K = 1$).

fairness among users gets worse.

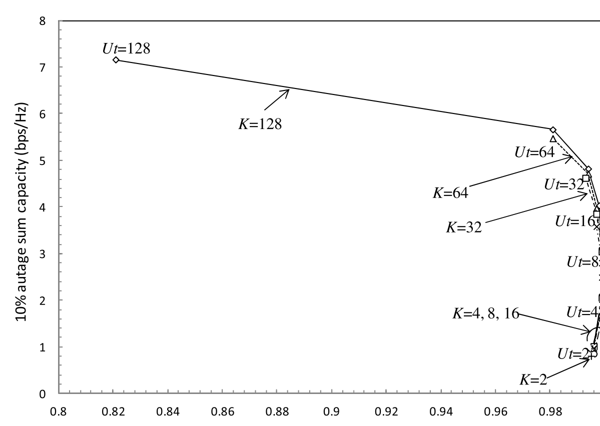
We conclude from Figs. 6 and 7 that the trade-off relationship between capacity and fairness can be controlled by changing the number of simultaneously scheduling users per time-slot. The controllable range of fairness index depends on the scheduling algorithm; it is between 0.01 and 0.78 with the modified max-map scheduling algorithm while it is between 0.82 and 1 with modified max-min scheduling algorithm. By appropriately switching between the modified max-map and modified max-min scheduling algorithms according to the target fairness index, the fairness can be controlled over an entire range. In the case of modified PF-map scheduling algorithm, increasing the value of U_t increases the sum capacity while decreasing the user capacity.



(a) Modified max-map



(b) Modified PF-map



(b) Modified max-min

Fig. 8 Sum capacity-fairness trade-off.

Figure 8 plots the trade-off between the sum capacity and fairness for the modified max-map, the modified PF-map, and the modified max-min scheduling algorithms with the number U_t of simultaneously scheduling users per

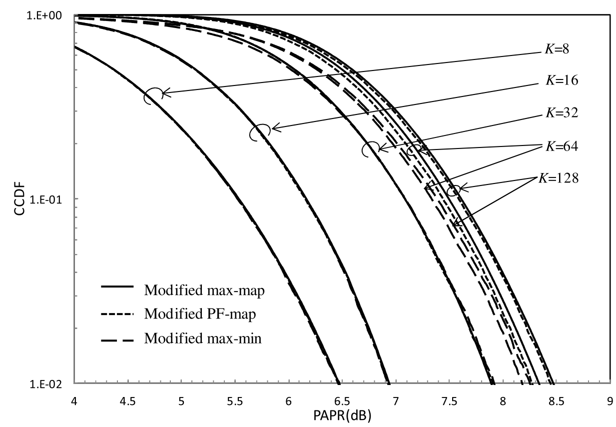


Fig. 9 CCDF of PAPR.

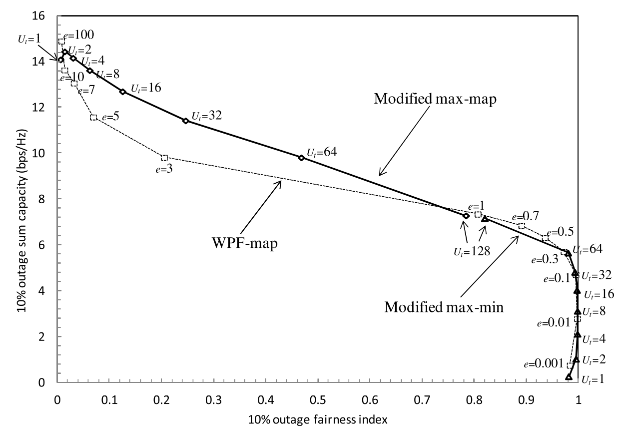


Fig. 10 Capacity-fairness trade-off comparison.

time-slot and the number K of subcarrier-blocks as parameters. For the modified max-map scheduling algorithm (see Fig. 8(a)), by increasing K while keeping U_t the same, the frequency diversity gain increases and hence, the sum capacity increases, however, the fairness is almost the same. It should be noticed that, the increase of sum capacity is very small beyond $K = 32$, because contiguous subcarriers tend to be allocated to each user. For the modified PF-map scheduling algorithm (see Fig. 8(b)), by increasing K while keeping U_t the same, the sum capacity is almost the same, however, the fairness improves because the transmission probability for the users who have a low average capacity gets higher. On the other hand, in the case of modified max-min scheduling algorithm (see Fig. 8(c)), the impact of K on the sum capacity and fairness is negligibly small.

5.2 PAPR Performance

Figure 9 shows the CCDF of PAPR when using modified max-map, PF-map, and max-min scheduling algorithms assuming $U_t = 8$ and QPSK data modulation. The total number of subcarriers is fixed to $N_c = 128$ and we vary the number of subcarrier-blocks K. It is seen from Fig. 9 that by increasing K from 8 (the subcarrier-block size is 16) to 128 (the subcarrier-block size is 1), the PAPR increases for all three modified scheduling algorithms. The possible reason is as follows. The number D of subcarrier-blocks per simultaneously scheduling user is given by $D = K/U_t$, where U_t denotes the number of simultaneously scheduling users per time-slot. By increasing K while keeping U_t the same, subcarriers allocated to each user tend to be more widely distributed and hence, PAPR increases. When $K = 8$, the 1% PAPR (above which the measured PAPR rises with a probability of 1%) is reduced by about 2 dB compared to $K = 128$. When K is small, since the subcarrier-blocks size is large and contiguous subcarriers tend to be allocated to each of simultaneously scheduling users irrespective of scheduling algorithm, three modified scheduling algorithms provide similar PAPR. However, when K is large, the modified max-min scheduling algorithm provides lower PAPR than the modified max-map and PF-map scheduling algorithms. The reason for this is given below. In the case of modified max-map and PF-map scheduling algorithms, subcarrier-blocks are allocated to users whose channel gain is high so as to improve the sum capacity and therefore, subcarriers allocated to each user tend to be more widely distributed due to frequency-selective fading. On the other hand, in the case of modified max-min scheduling algorithm, the subcarrier-block allocation is done so as to maximize the channel capacity of a user having the smallest average capacity. Therefore, unlike from the modified max-map and PF-map scheduling algorithms, more contiguous subcarriers tend to be allocated to each simultaneously scheduling user even if K is large and hence, the modified max-min scheduling algorithm provides lower PAPR.

5.3 Comparison with WPF, APF, and AFTC

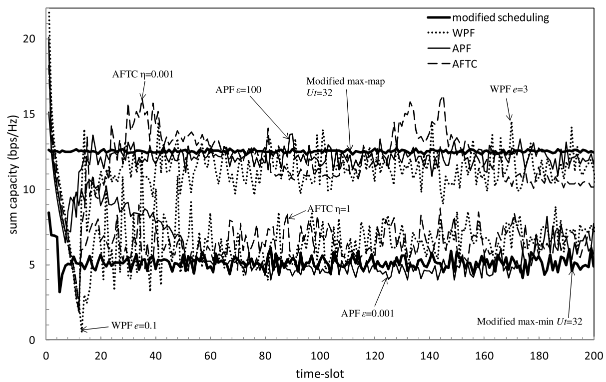
Figure 10 compares sum capacity-fairness trade-off among the modified max-map, PF-map, and max-min scheduling algorithms (K=128) and the Weighted Proportional Fairness (WPF). For the k-th subcarrier-block, the WPF scheduling carries out the user-selection as follows [10]:

$$u' = \arg\min_{u \in Q_d} \frac{\{C_u(k,t)\}^e}{\overline{C}_u(t)}, \tag{21}$$

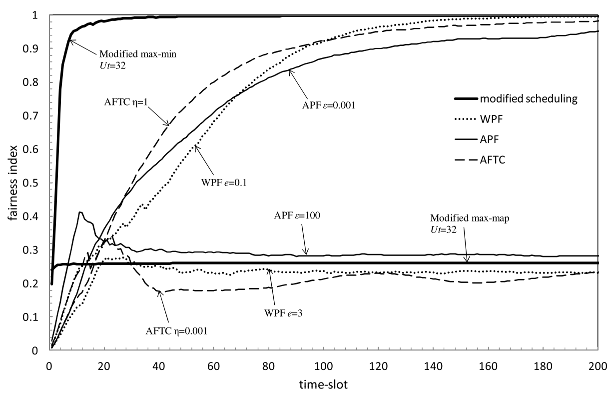
where e denotes the control parameter for controlling capacity-fairness trade-off.

It is seen from Fig. 10 that the modified max-map scheduling algorithm can achieve higher sum capacity than the WPF when $U_t = 2 \sim 64$, since the modified max-map scheduling algorithm selects users in a good channel condition only and hence, can obtain higher multi-user diversity gain. The modified max-min scheduling algorithm achieves sum capacity-fairness trade-off similar to WPF over a range of the fairness index from 0.82 to 1.

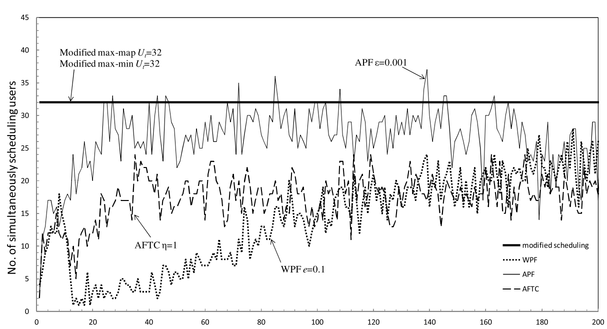
Figure 11 shows the temporal behavior of eight scheduling algorithms: the modified max-map scheduling algorithm (U_t = 32), the modified max-min scheduling algorithm (U_t = 32), the WPF (e = 1 and e = 3), the APF with $\varepsilon = 0.001$ and $\varepsilon = 100$ (note that ε is the control parameter for



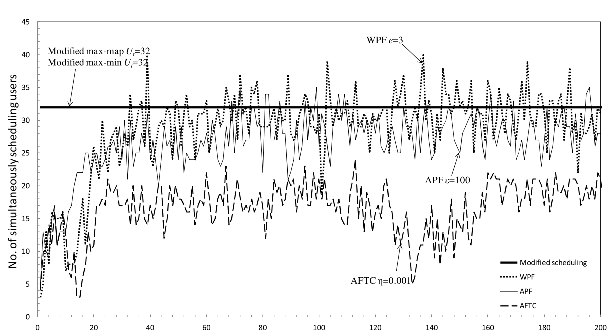
(a) Sum capacity.



(b) Fairness index.



(c1) No. of simultaneously scheduling users per time-slot: modified max-map ($U_t = 32$), modified max-min ($U_t = 32$), WPF ($e = 0.1$), APF ($\varepsilon = 0.001$), and AFTC ($\eta = 1$).



(c2) No. of simultaneously scheduling users per time-slot: modified max-map ($U_t = 32$), modified max-min ($U_t = 32$), WPF ($e = 3$), APF ($\varepsilon = 100$), and AFTC ($\eta = 0.001$).

Fig. 11 Temporal behavior of scheduling algorithms.

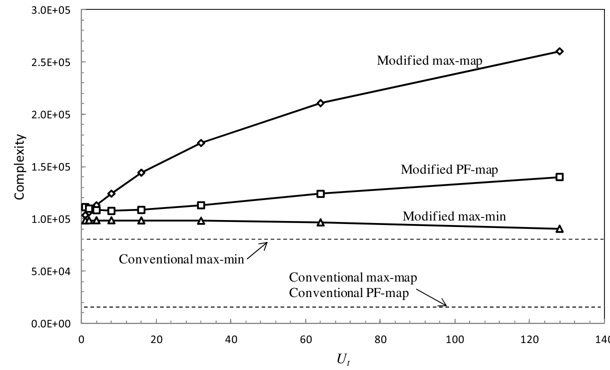


Fig. 12 Complexity comparison of modified and conventional scheduling algorithms.

controlling capacity-fairness trade-off [11]), and the AFTC with $\eta = 1$ (note that η is the control parameter for controlling capacity-fairness trade-off [12]). Sum capacity, fairness index, and the number of simultaneously scheduling users per time-slot are compared. It can be seen from Fig. 11 that smaller sum capacity variations and faster fairness convergence are achieved for the modified scheduling algorithms than the other scheduling algorithms. When using the WPF with $e = 0.1$, the number of simultaneously scheduling users per time-slot significantly changes, resulting in wider variations in sum capacity. Also seen from the figure is that when the targeted fairness is high (i.e., the WPF with $e = 0.1$, the APF with $\varepsilon = 0.001$, and the AFTC with $\eta = 1$), the WPF, APF, and AFTC require longer convergence time.

5.4 Complexity Comparison

Figure 12 shows a complexity comparison between modified and conventional scheduling algorithms. The complexity is defined as the total number of comparisons per time-slot. The proposed scheduling algorithms require higher complexity than the conventional max-min scheduling algorithm. As the number U_t of simultaneously scheduling users per time-slot increases, the complexity increases for modified max-map and PF-map scheduling algorithms. On the other hand, the computational complexity of the modified max-min scheduling algorithm is almost constant regardless of U_t and is almost the same as that of the conventional max-min scheduling algorithm. Therefore, the modified max-min scheduling algorithm requires lower complexity for subcarrier-block adjustment than the modified max-map and PF-map scheduling algorithms.

6. Conclusion

In this paper, we presented the modified max-map, PF-map, and max-min scheduling algorithms for SC-FDMA. The modified algorithms always select the predetermined number of simultaneously scheduling users irrespective of users' channel conditions. It was confirmed by computer simulation that the modified scheduling algorithms can control the sum capacity and fairness by changing the number of simultaneously scheduling users per time-slot. The controllable range of fairness index depends on the scheduling algorithm. By appropriately switching between the modified max-map and modified max-min scheduling algorithms according to the target fairness index, the fairness can be controlled over an entire range. The modified scheduling algorithms can narrow the time variations in the sum capacity and fasten the convergence rate of fairness index compared to WPF, APF, and AFTC. Our modified scheduling algorithms are also applicable to OFDMA downlink. Performance comparison between OFDMA and SC-FDMA using our proposed modified scheduling algorithms is left as an interesting future study.

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