PAPER

An Effective Downlink Resource Allocation Scheme Based on MIMO-OFDMA-CDM in Cellular System

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SUMMARY Orthogonal frequency division multiple access (OFDMA) is adopted as a multiuser access scheme in recent cellular systems such as long term evolution (LTE) and WiMAX. In those systems, the performance improvement on cell-edge users is crucial to provide high-speed services. We propose a new resource allocation scheme based on multiple input multiple output — orthogonal frequency division multiple access — code division multiplexing (MIMO-OFDMA-CDM) to achieve performance improvements in terms of cell-edge user throughput, bit error rate, and fairness among users. The proposed scheme adopts code division multiplexing for MIMO-OFDMA and a modified proportional fairness algorithm for CDM, which enables the fairness among users and a higher throughput. The performance improvements are clarified by theoretical analysis and simulations.
key words: *OFDMA-CDM, MIMO, cellular system, resource allocation, proportional fairness*

1. Introduction

There are growing demands for high-speed wireless communications. Especially in cellular systems, mobile users want not only to call but also to receive e-mail or to connect to the Internet, which is triggering an explosive increase in the packet traffic. However, the cellular channel suffers from multipath fading and the frequency selective fading degrades throughput performances. Orthogonal frequency division multiple access (OFDMA) [1]–[4], a multiple access method based on orthogonal frequency division multiplexing (OFDM), can linearly equalize the frequency selective fading and enables multiple access simultaneously. It is suitable for a high-speed access and is adopted as a standard access method in LTE and WiMAX. OFDMA has a tolerance for the frequency-selective channel because it has the same property as OFDM. Multipath fading is transformed into flat fading on each subcarrier because OFDMA consists of narrow-band subcarriers, and cyclic condition is satisfied by a guard interval insertion.

In addition, parallel signal processing can be done in OFDMA on every subcarriers. Because of this parallel processing suitability, OFDMA can be combined with multiple input multiple output (MIMO) straightforwardly, and higher speed transmission is expected. Here, the challenges of MIMO-OFDMA are to increase system capacity and to enhance a throughput of cell-edge users. The performance of OFDMA greatly depends on the resource allocation algorithm used. In the OFDMA downlink cellular system, the base station allocates subcarriers adaptively to mobile users. By allocating subcarriers to the users having good channel coefficients, OFDMA can obtain a multi-user diversity effect and the system capacity can be raised. However, most users far from the base station have poor channel conditions and less subcarriers are allocated when no additional care is supplied. Thus, fairness is not achieved. In general this allocation scheme can be categorized into two manners, maximum capacity (MAX) and proportional fairness (PF). In MAX scheme, each subcarrier is allocated to the user having the largest channel coefficient. This can maximize system capacity but the fairness among users is not guaranteed. On the other hand, PF scheme allocates subcarriers with considering users' fairness. PF scheme cannot keep the maximum capacity but can keep the fairness among users, and many schemes based on PF have been proposed [5]–[9]. PF scheme can improve the throughput of cell-edge users, which is important in recent cellular systems. In general, the system capacity and the fairness are in the trade-off relationship on subcarrier allocation schemes. Therefore, to keep fairness and to increase capacity are key goals of downlink transmission.

Meanwhile, to improve bit error rate (BER) performances, OFDMA with a spreading code in the frequency domain called OFDMA-code division multiplexing (OFDMA-CDM) was proposed in [10]–[12]. On the allocated subcarriers, data are spread in the frequency domain by spreading code and the frequency diversity effect is obtained. However, in the previous OFDMA-CDM systems [13], allocation is done at the subchannel unit which is a block of adjacent subcarriers to apply the spreading code directly. It results in the decrease of multi-user diversity. Furthermore, the PF-based allocation is little studied in OFDMA-CDM. Also, we proposed a MIMO-OFDMA-CDM with PF allocation in [14], [15] and evaluated the performance in single-cell. In [16], the proposed scheme was evaluated in multi-cell model but adaptive modulation and channel coding were not introduced and the improvement was limited. Therefore, in this paper, we propose a PF-based MIMO-OFDMA-CDM with adaptive modulation and achieve balanced performances of throughput, BER, and fairness in the multi-cell model, especially, the performance improvement of cell-edge users. The new contribution of this paper is to apply the PF-based resource allocation for MIMO-OFDMA-CDM in a subcarrier basis, which

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enhances the frequency diversity as well as the multi-user diversity.

This paper is organized as follows. In Sect. 2, the system model is introduced. Theoretical BER analysis is described in Sect. 3 and numerical results are shown in Sect. 4. Section 5 presents the conclusion.

2. System Model

2.1 Downlink Multi-Cell Model

Figure 1 shows the multi-cell model considered in this paper. We assume 19-cell model with the same frequency-band reuse over 3 cells, and thus, the co-channel interference is received from 6 secondary adjacent cells. Figure 2 shows the definition of user location. User k ($1 \leqq k \leqq K$) is identically-distributed at the distance of r_k from the center base station in the cell which is a regular hexagon with the radius of R. Here, the center area is defined as $r_k < 0.3R$, and similarly, the middle and edge areas are defined as $0.3R \leqq r_k < 0.8R$ and $0.8R \leqq r_k \leqq R$, respectively. The normalized distance $d_k = r_k/R$ is used in the following consideration. In this paper, the downlink multi-user transmission as shown in Fig. 3 is considered. The base station has N_{Tx} transmit antennas and a single frequency band is used for multi-user transmission. Each of K mobile station has N_{Rx} receive antennas.

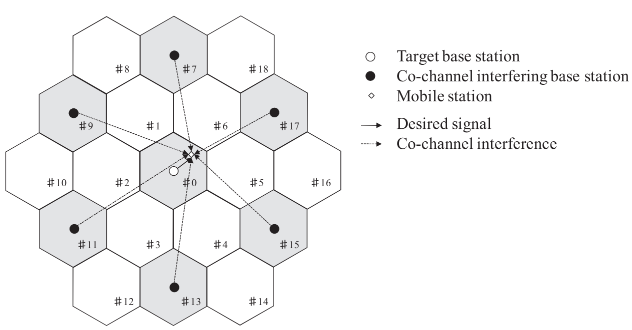


Fig. 1 19-cell model.

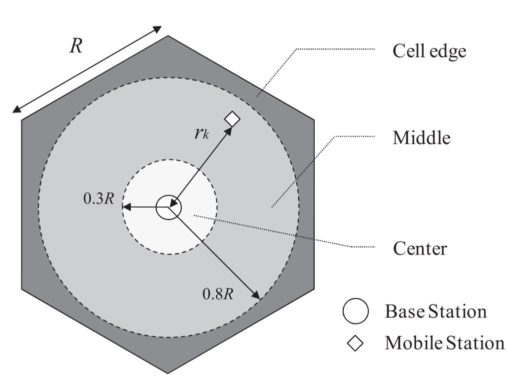


Fig. 2 Definition of user location.

2.2 Block Diagram of Transmitter and Receiver

Figures 4 and 5 show the block diagrams of transmitter and receiver, respectively. In the base station, input data are serial-to-parallel converted into each antenna, a cyclic redundancy check (CRC) coded, channel coded by recursive systematic convolutional (RSC) code, and modulated by QPSK or 16QAM by adaptive modulation. Then, data are allocated to subcarriers according to the channel state information (CSI) which is preliminarily received from the mobile stations and to the calculated signal to interference plus noise power ratio (SINR). After that, a frequency spreading is done, transformed by inverse fast Fourier transform (IFFT), a guard interval (GI) is inserted, and data are transmitted. In the receiver, after removing GI, the measured

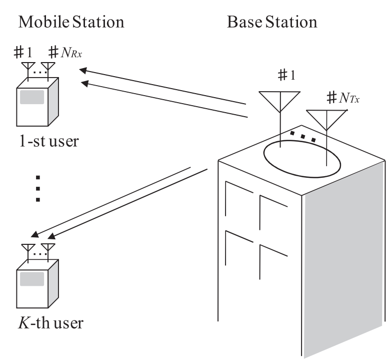


Fig. 3 Downlink transmission model.

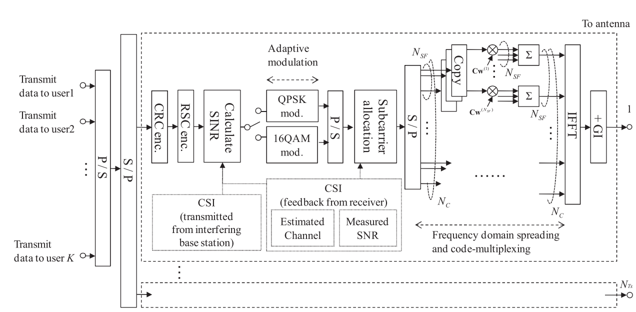


Fig. 4 Block diagram of transmitter in base station.

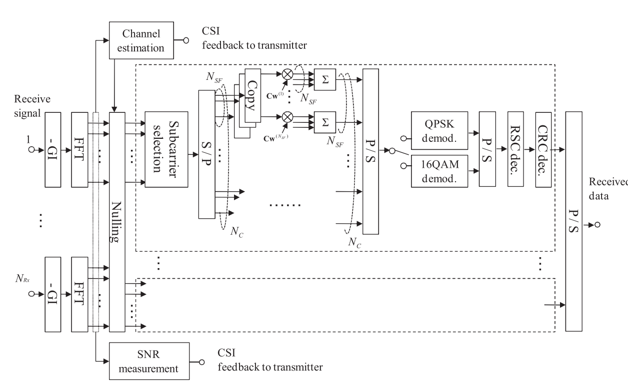


Fig. 5 Block diagram of receiver.

SNR and estimated channel state information are reported to base station via feedback link. Then, the allocated subcarriers are extracted and the signal processing is done in the reverse direction of transmitter. Finally, the data are decoded.

2.3 MIMO-OFDMA Channel

It is assumed that the transmission channel is frequency-selective consisting of discrete L delay paths and its impulse response between tx-th transmit antenna and rx-th receive antenna of k-th user from j-th base station is given by $h_{j-k,rx,tx}(\tau)$ as follows:

$$h_{j-k,rx,tx}(\tau) = \sum_{l=0}^{L-1} h'_{j-k,l,rx,tx}\delta(\tau - \tau_l) \tag{1}$$

where $h'_{j-k,l,rx,tx}$ and τ_l are the complex channel coefficient and the delay time of l-th path, respectively. This channel coefficient is normalized as $E\left[\sum_{l=0}^{L-1}\left|h'_{j-k,l,rx,tx}\right|^2\right] = 1$ and if the propagation loss and shadowing is taken into account, $h_{j-k,l,rx,tx}$ is given by

$$h_{j-k,l,rx,tx} = \sqrt{d_{j-k}^{-\alpha}10^{-\beta_{j-k}/10}}h'_{j-k,l,rx,tx} \tag{2}$$

where d_{j-k} is the k-th user distance from the j-th base station, α is the propagation loss exponent, and β_{j-k} is the shadowing deviation. The shadowing component obeys the lognormal distribution as follows:

$$f_L(x) = \begin{cases} \dfrac{1}{\sqrt{2\pi}\beta x}\exp\left\{-\dfrac{(\log x - \mu)^2}{2\beta^2}\right\}, & x > 0 \\ 0, & x \le 0 \end{cases} \tag{3}$$

where μ is the mean value of lognormal distribution and x is the instantaneous shadowing amplitude. Then, the channel gain in the frequency domain is obtained by

$$H_{j-k,n,rx,tx} = \sum_{l=0}^{L-1} h_{j-k,l,rx,tx}\exp\left(-j2\pi n\frac{\tau_l}{N_c}\right) \tag{4}$$

where n is the subcarrier index. The channel matrix of user k and subcarrier n in MIMO transmission is given by

$$\mathbf{H}_{j-k,n} = \begin{bmatrix} H_{j-k,n,1,1} & H_{j-k,n,1,2} & \cdots & H_{j-k,n,1,N_{Tx}} \\ H_{j-k,n,2,1} & H_{j-k,n,2,2} & \cdots & H_{j-k,n,2,N_{Tx}} \\ \vdots & \vdots & \ddots & \vdots \\ H_{j-k,n,N_{Rx},1} & H_{j-k,n,N_{Rx},2} & \cdots & H_{j-k,n,N_{Rx},N_{Tx}} \end{bmatrix} \tag{5}$$

Using this matrix, the receive vector $\mathbf{R}_{k,n} = (R_{k,n,1}, \cdots, R_{k,n,N_{Rx}})^T$ of user k is given by

$$\mathbf{R}_{k,n} = \sqrt{P_{t,0-k,n}}\mathbf{H}_{0-k,n}\mathbf{s}_{0-k,n} + \mathbf{N}_{0-k,n} + \sum_{j,j\neq 0}^{N_{iBS}} \sqrt{P_{t,j-k,n}}\mathbf{H}_{j-k,n}\mathbf{s}_{j-k,n} \tag{6}$$

where $P_{t,k,n}$ is the transmit power, N_{iBS} $(= 6)$ is the number of co-channel interfering base stations, $\mathbf{s}_{j-k,n} = (s_{j-k,n,1}, \cdots, s_{j-k,n,N_{Tx}})^T$ is the transmit vector and, $\mathbf{N}_{k,n} = (N_{k,n,1}, \cdots, N_{k,n,N_{Rx}})^T$ is the frequency-domain noise components obtained by

$$N_{k,n,rx} = \frac{1}{\sqrt{N_c}}\sum_{t=0}^{N_c-1} n_{k,t,rx}\exp\left(-j2\pi n\frac{t}{N_c}\right) \tag{7}$$

The third term of right hand side in (6) is the interference component from second adjacent cells.

2.4 Calculation of Channel Capacity

It is assumed that the base station knows all users CSI via feedback links. When the singular value decomposition (SVD) is applied for the channel matrix $\mathbf{H}_{j-k,n}$ of (5), it is described by

$$\mathbf{H}_{j-k,n} = \mathbf{U}_{j-k,n}\mathbf{\Lambda}_{j-k,n}\mathbf{V}_{j-k,n}^H \tag{8}$$

where each matrices are given by

$$\mathbf{V}_{j-k,n}^H = \left[e_{j-k,n,N_{Rx},\lambda_1}, e_{j-k,n,N_{Rx},\lambda_2}, \cdots, e_{j-k,n,N_{Rx},\lambda_{\min(N_{Rx},N_{Tx})}}\right] \tag{9}$$

$$\mathbf{\Lambda}_{j-k,n} = diag\left[\sqrt{\lambda}_{j-k,n,1}, \sqrt{\lambda}_{j-k,n,2}, \cdots, \sqrt{\lambda}_{j-k,n,\min(N_{Rx},N_{Tx})}\right] \tag{10}$$

$$\mathbf{U}_{j-k,n} = \left[e_{j-k,n,N_{Tx},\lambda_1}, e_{j-k,n,N_{Tx},\lambda_2}, \cdots, e_{j-k,n,N_{Tx},\lambda_{\min(N_{Rx},N_{Tx})}}\right] \tag{11}$$

Here $j = 0$ is a channel from the target base station, $e_{j-k,n,N_{Rx/Tx},\lambda_i}$ is the unitary submatrix for eigenvalue λ_i of the channel matrix $\mathbf{H}_{j-k,n}$, $\mathbf{\Lambda}_{j-k,n}$ is the diagonal matrix with positive eigenvalue, and $\mathbf{U}_{j-k,n}$ and $\mathbf{V}_{j-k,n}^H$ are unitary matrices. Since the channel gain is highly correlated with eigenvalue, the channel condition of all users can be obtained at the base station. The SINR $\gamma_{k,n,i}$ of user k at subcarrier n of i-th eigenvalue is calculated by

$$\gamma_{k,n,i} = \frac{P_{t,0-k,n}\lambda_{0-k,n,i}}{N_{Tx}N_0 + \sum_{j,j\neq 0}^{N_{iBS}} P_{t,j-k,n}\lambda_{j-k,n,i}} \tag{12}$$

Then, channel capacity is obtained by

$$C_{k,n} = \sum_{i=1}^{RANK(\mathbf{H}_{k,n})} \log(1 + \gamma_{k,n,i}) \tag{13}$$

where $\lambda_{j-k,n,i}$ is i-th eigenvalue of the MIMO channel matrix at k-th user's n-th subcarrier from j-th base station, and RANK($\mathbf{H}_{k,n}$) is the rank of channel matrix.

2.5 Conventional Allocation Scheme

In conventional MIMO-OFDMA-CDM schemes, a group of subcarriers is bundled and treated as a *subchannel* to apply the code spreading. The resource allocation is conducted for the subchannels by the maximum capacity criterion [13].

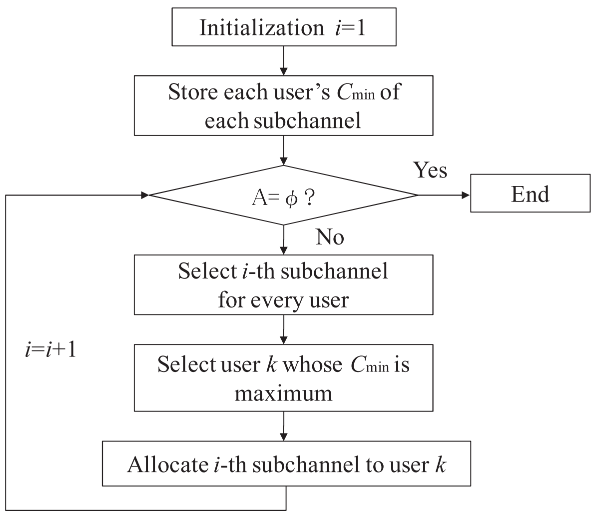


Fig. 6 Flowchart of conventional resource allocation algorithm.

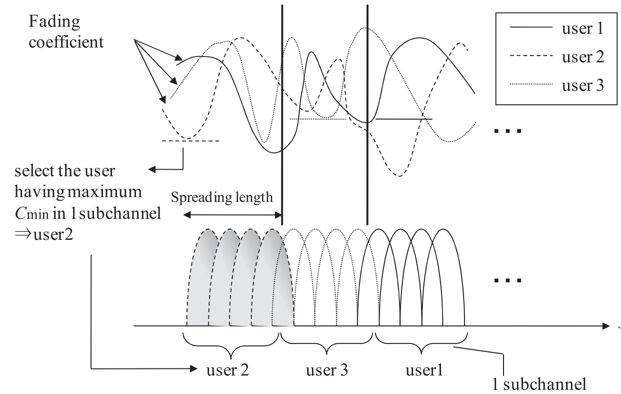


Fig. 7 Example of frequency-domain allocation and spreading of conventional scheme.

First, the base station calculates channel capacities of all user k and all subcarrier n by the feedback CSI using (13). If i is subchannel number, $n = (i-1)N_{sub} + l$, where N_{sub} is the subchannel length which is equivalent to the spreading factor N_{SF}, and l is the l-th subcarrier on i-th subchannel. Then, the base station allocates the subchannel i to the user k having the largest minimum channel capacity as follows.

$$k_{allocate}(i) = \arg\max_{k}\left(\min_{l} C_{k,(i-1)N_{sub}+l}\right) \tag{14}$$

Figure 6 shows the MAX-based resource allocation algorithm of the conventional scheme where A is a set of unallocated subcarriers and ϕ is an empty set. After the subchannels are allocated, a frequency-domain spreading is conducted in each subchannel as shown in Fig. 7. A Walsh code is used for spreading which is given by

$$\mathbf{Cw}_L = \mathbf{Cw}_{L/2} \otimes \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}, {}^{\forall}L = 2^{\gamma}, \gamma \geq 1, Cw_1 = 1 \tag{15}$$

This algorithm improves the multiuser diversity effect and raises the system throughput. However, subcarriers are rarely allocated to cell-edge users and the fairness cannot be kept. Moreover, the subchannel-unit allocation decreases the multiuser diversity effect compared with the subcarrier-unit allocation.

2.6 Proposed Allocation Scheme

We utilize a resource allocation scheme suitable for code division multiplexing (CDM) with taking into account the proportional fairness (PF) among users [14], [15]. Figure 8 shows the proposed allocation algorithm where n ($\leqq N_c$) is the index of subcarriers and Ω_k is a number of subcarriers allocated to user k. C_k is k-th user's temporal total capacity given by

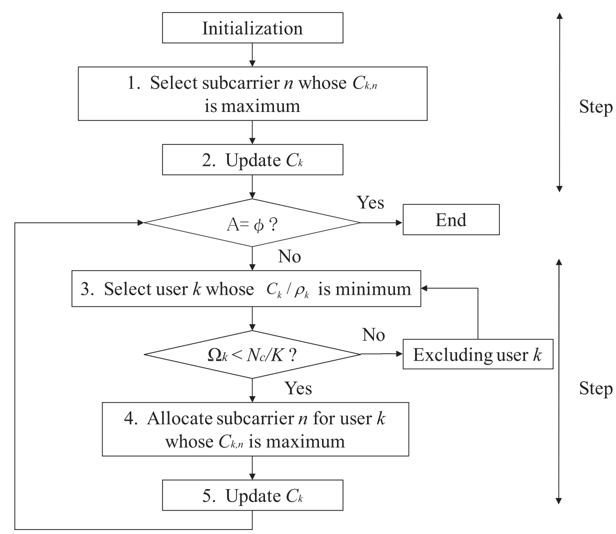


Fig. 8 Flowchart of proposed resource allocation algorithm.

$$C_k = \sum_{n \in \Omega_k} \sum_{i=1}^{RANK(\mathbf{H}_{k,n})} \log_2(1 + \gamma_{k,n,i}) \tag{16}$$

In Step 1, each user temporarily chooses the subcarrier n whose $C_{k,n}$ is maximum for user k as follows

$$n_{allocate}(k) = \arg\max_{n}(C_{k,n}) \tag{17}$$

and the channel capacity is calculated using (13). Step 1 is a round-robin allocation because all users can select the best subcarrier.

In Step 2, the subcarrier n is allocated to the user k whose C_k/ρ_k is minimum where ρ_k is the desired priority parameter for user k. Here, the number of subcarriers for each user is restricted not to exceed N_c/K by the following constraint condition

$$k_{selected} = \arg\min_{k \backslash \Omega_k \geq N_c K}(C_k/\rho_k) \tag{18}$$

where $\rho_k = 1$ if an identical fairness for all users is desired. By (18), the subcarriers are equally divided to all users and the maximum length of spreading code can be applied for all

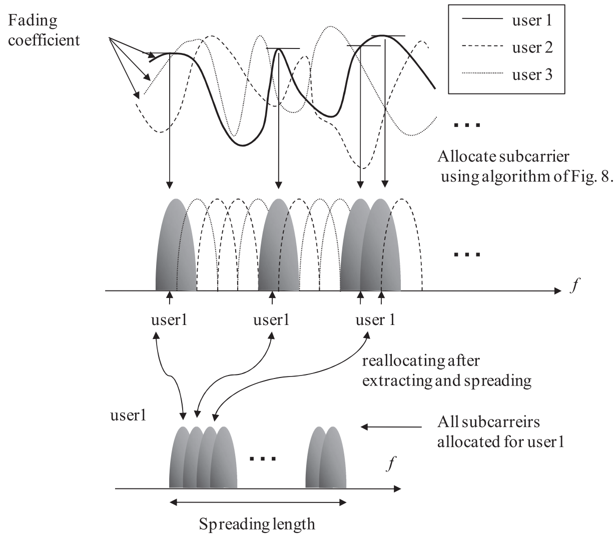


Fig. 9 Example of frequency-domain allocation and spreading of proposed scheme.

users. Controlling the fairness of each user is available by changing ρ_k. However, only the case of $\rho_k = 1$ is considered in the following. The selected user k by (18) obtains the subcarrier n and C_k is re-calculated by (16). This allocation step is iterated until A becomes empty set. Thus, subcarriers with good channel condition are sequentially allocated to the user with small C_k, and the proportional fairness and the system capacity enhancement is balanced.

2.7 Code Division Multiplexing in Proposed Scheme

Figure 9 illustrates an example of subcarrier allocation and code spreading of user 1. After Ω_k is obtained by the algorithm in Fig. 8, all subcarriers for user k are once extracted, code-spread in the frequency direction, and re-allocated to original subcarriers [14], [15]. The code-spreading is done with Walsh sequence. In the proposed scheme, all subcarriers of Ω_k is used for spreading and multiplexing so that the frequency diversity effect can be maximized. In addition, the multi-user diversity is also maximized by the subcarrier-unit allocation. The novel point of the proposed scheme is to enable the longer-length code spreading by the equivalent subcarrier allocation as shown in Fig. 8, which is a PF-based algorithm, and to reallocate users' subcarriers after spreading to the selected subcarriers. The transmission signal for user k at n-th subcarrier are given by

$$s_{j-k,n,tx} = \left(\frac{1}{\sqrt{\Omega_k}} \sum_{p=0}^{\Omega_k - 1} \mathbf{Cw}_L^{(p+1)} \hat{s}_{j-k,p,tx} \right) \exp(j2\pi f_{k,n} t)$$
$$k = 1 \sim K, \quad \Omega_k = N_{SF} = N_c/K \tag{19}$$

where N_{SF} is the spreading factor, $\hat{s}_{j-k,p,tx}$ is the information symbol of user k at p-th subcarrier, $f_{k,n}$ is the subcarrier frequency, and $\mathrm{Cw}_L^{(p+1)}$ is $(p+1)$-th element of spreading code. $\hat{s}_{j-k,p,tx}$ is given by the adaptive modulation. The throughput of the system can be raised by using adaptive modulation in which QPSK and 16QAM are adaptively changed according to channel coefficient on each subcarrier. In the proposed scheme, the modulation is determined by $C_{k,n}$ of (13) i.e. the channel gain and noise are considered for adaptive modulation. The threshold of both modulations is determined by throughput criterion.

2.8 SINR Based MMSE Criteria Detection

In the receiver, a MIMO detection and a channel equalization is processed by multiplication of channel inverse matrix to the receive vector. The channel inverse matrix $\mathbf{G}_{k,n}$ is obtained by

$$\begin{cases} \mathbf{G}_{ZF,k,n} = \mathbf{H}_{0-k,n}^H \left(\mathbf{H}_{0-k,n} \mathbf{H}_{0-k,n}^H + \delta \mathbf{I}_{N_{Rx}} \right)^{-1} \\ \mathbf{G}_{SNR\_MMSE,k,n} = \mathbf{H}_{0-k,n}^H \left(\mathbf{H}_{0-k,n} \mathbf{H}_{0-k,n}^H + N_{Rx} \sigma_N^2 \mathbf{I}_{N_{Rx}} \right)^{-1} \\ \mathbf{G}_{SINR\_MMSE,k,n} = \mathbf{H}_{0-k,n}^H \left\{ \mathbf{H}_{0-k,n} \mathbf{H}_{0-k,n}^H + N_{Rx} \left(\sigma_N^2 + \sigma_{I,k}^2 \right) \mathbf{I}_{N_{Rx}} \right\}^{-1} \end{cases} \tag{20}$$

where $\mathbf{H}_{0-k,n}$ is the channel matrix, ^{H} means the Hermite transpose, σ_N^2 is the noise variance, $\sigma_{I,k}^2$ is the power of co-channel interference at user k, and $\mathbf{I}_{NRx}$ is the N_{Rx}-th unit matrix. δ is an arbitrary real number and the small value increases the accuracy of inverse matrix. By multiplication of $\mathbf{G}_{k,n}$ to (6) from left hand, the receive symbols are obtained. It is well-known that a SINR-based MMSE criterion is the best weight for multi-cell environment, because it considers the fading and co-channel interference.

3. Bit Error Rate Analysis

We consider the performance analysis of MIMO-OFDMA-CDM. Assuming QPSK modulation and perfect CSI in the receiver, the theoretical BER is given in [17], [18] by

$$p_b \left(\frac{E_s}{N_0}, \{H_{k,n}\} \right) = Q \left(\sqrt{\gamma \left(\frac{E_s}{N_0}, \{H_{k,n}\} \right)} \right) \tag{21}$$

where Q(•) is the Q-function [4], [17] of

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-t^2/2} dt \tag{22}$$

and γ is an instantaneous SINR. This SINR of MIMO-OFDMA-CDM can be obtained by

$$\gamma \left(\frac{E_s}{N_0}, \{\lambda_{k,n,rx}\} \right) = \frac{P_{t,0-k,n} \dfrac{1}{N_{SF}} \sum_{n \in \Omega_k} \lambda_{0-k,n,rx}}{N_{Tx} N_0 + \sum_{j,j \neq 0} P_{t,j-k,n} \lambda_{j-k,n,rx}} \tag{23}$$

In MIMO transmission, the antenna multiplexing channel can be treated as $\min(N_{Tx}, N_{Rx})$-parallel independent SISO channel by decomposing the channel matrix $\mathbf{H}$ into eigenvalue λ. Therefore, by substituting H into λ, SINR is obtained by (23) and p_b is obtained by the average of Q-function for all λ as follows

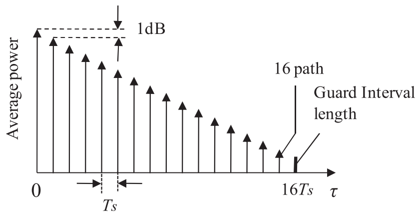


Fig. 10 Delay profile.

Table 1 Common parameters.

Transmitter	Transmission scheme	MIMO-OFDMA-CDM downlink
	Number of antennas	(N_{Tx}, N_{Rx})=(2, 2)
	Resource allocation scheme	Proportional fairness
	Desired rate ratio	ρ_k =1 for all users
	Spreading code	Walsh
	Number of subcarriers	N_c=1024
	1OFDMsymbol length	1024*Ts*
	Guard interval length	16*Ts*
Channel	Fading	16path 1dB-decayed Quasi static Rayleigh
	Cell model	Hexagonal grid
	Cell layout	19 cell sites without sectrization
	Path loss exponent	α=3.5
	Standard deviation of shadowing loss	β=7 (dB)
Receiver	Channel estimation	Ideal
	MIMO detection and equalization	Nulling (SINR based MMSE criteria)

Table 2 Simulation parameters for theoretical analysis.

Transmission scheme	OFMDA-CDM downlink	MIMO-OFDMA-CDM downlink
Number of antennas	(N_{Tx}, N_{Rx})=(1, 1)	(N_{Tx}, N_{Rx})=(2, 2)
Modulation	QPSK	
Number of users	K=4, 8, 16	
Spreading length	N_{SF}=256, 128, 64	

$$p_b\left(\frac{E_s}{N_0}\right) = \operatorname*{ave}_{\lambda}\left[Q\left(\sqrt{\gamma\left(\frac{E_s}{N_0}, \{\lambda_{k,n,i}\}\right)}\right)\right] \quad (24)$$

The performance of SISO and MIMO-OFDMA-CDM are evaluated. The delay profile of channel is assumed as in Fig. 10. The theoretical and simulation results on simulation condition of Tables 1 and 2 are shown in Fig. 11. In the figure, the horizontal axis is the SNR of cell-edge users at the cell boundary. The equivalent average SNRs of cell-middle and cell-center users when the path loss exponent is $\alpha = 3.5$ is given by

$$\mathrm{SNR}_{(\mathrm{middle})} = \mathrm{SNR}_{(\mathrm{edge})} + 3.39\,\mathrm{dB}$$
$$\mathrm{SNR}_{(\mathrm{center})} = \mathrm{SNR}_{(\mathrm{edge})} + 18.30\,\mathrm{dB}$$

All three SNRs are those at the region boundaries in Fig. 2. Hereafter, the common simulation parameters are used as listed in Table 1. From the figure, it is confirmed that (24) coincides the probability of MIMO-OFDMA-CDM. It is found that the performances are improved with the increase of users by the effect of user diversity in both SISO and MIMO cases. However, there are error floors after SNR = 20 dB in all cases due to the co-channel interference from adjacent cells.

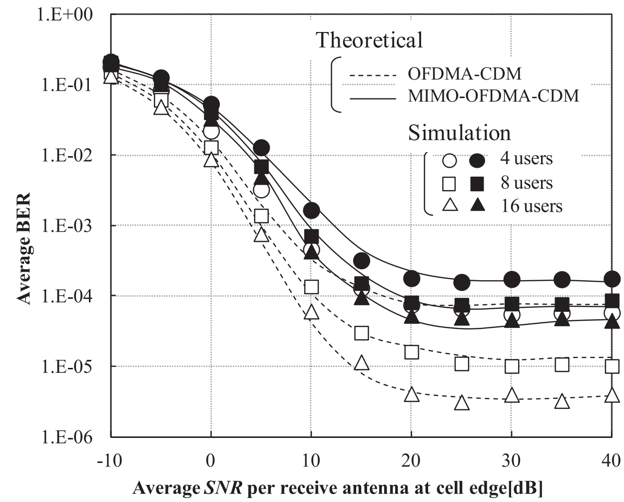


Fig. 11 Comparison of BER in simulation and theory.

4. Numerical Results

In this section, the performances of MIMO-OFDMA-CDM in multi-cell environments are evaluated through computer simulations.

4.1 Effect of CDM

Figure 12 shows the BER comparison of CDM and non-CDM under the simulation condition of Table 3. The error floor caused by the co-channel interference of adjacent cells at the conventional OFDMA is cleared in OFDMA-CDM. This improvement is obtained by the frequency diversity effect of frequency domain CDM and the large effect can be obtained with the smaller number of users. When a number of users is less, the more allocated subcarriers per user become, and the long spreading code which generates a large diversity effect can be applied. Thus, when a multiuser diversity cannot be expected with fewer users, this CDM especially becomes effective. Here, as the similar conventional schemes, an adaptation of modulation and coding scheme (MCS) can also be applied to improve the BER performance other than CDM. However, even if the MCS is applied, the proposed CDM can still be applied and the more improvement is expected. Since the code spreading is applied just after coding, modulation, subcarrier allocation, the additional mechanism is not much needed.

4.2 Effect of Channel Coding in MIMO-OFDMA-CDM

The performance improvement of MIMO-OFDMA-CDM by channel coding is confirmed as shown in Fig. 13 with the simulation parameters of Table 4. The co-channel interference from adjacent cells is removed by the convolutional code in tradeoff with the rate decrease. From the result we

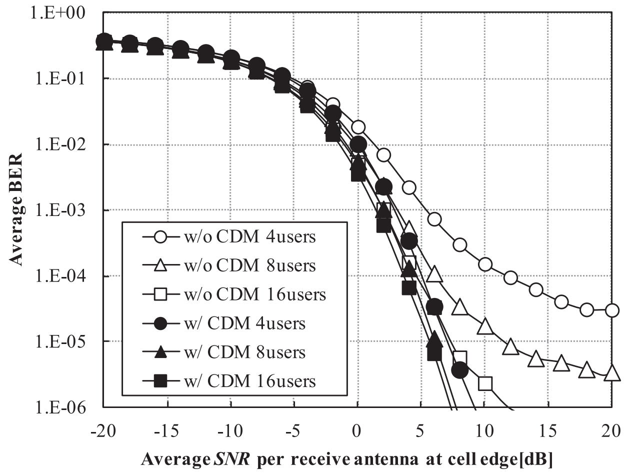


Fig. 12 Effect of CDM for RSC coded MIMO-OFDMA.

Table 3 Simulation parameters for effect of CDM.

Transmission scheme	MIMO-OFMDA-CDM downlink	MIMO-OFDMA downlink
Modulation	QPSK	
Channel coding	RSC[7,5] code	
Encoding ratio	1/2	
Decoding	Soft Viterbi	
Spreading code	Walsh	-
Number of users	K=4, 8, 16	
Spreading length	N_{SF}=256, 128, 64	-

Table 4 Simulation parameters for effect of encoding.

Transmission scheme	MIMO-OFMDA-CDM downlink	
Modulation	QPSK	
Channel coding	-	RSC[7,5] code
Encoding ratio	-	1/2
Decoding	-	Soft Viterbi
Number of users	K=4, 8, 16	
Spreading length	N_{SF}=256, 128, 64	

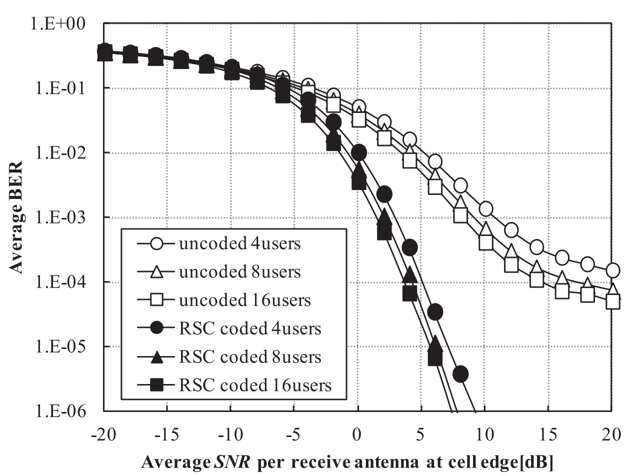


Fig. 13 Effect of channel coding in MIMO-OFDMA-CDM.

can see that the channel coding is necessary in this system.

Table 5 Simulation parameters for comparison of conventional scheme and proposed scheme.

	Conventional scheme		Proposed scheme
Transmission scheme	MIMO-OFMDA-CDM downlink		
Modulation	QPSK, 16QAM, 64QAM		
Channel coding	RSC[7,5] code		
Encoding ratio	1/2		
Decoding	Hard Viterbi		
Resource allocation scheme	Maximum capacity (subchannel unit)	Proportional fairness (subchannel unit)	Proportional fairness (subcarrier unit)
Number of users	K=8		
Spreading length	N_{SF}=8		N_{SF}=128
Subchannel length	N_{sub}=8		—
1 packet length	1024symbol		
Error detection	CRC-16		

4.3 Throughput Performance Comparison

In this subsection, the throughput performances are evaluated. Here, the throughput η_k at user k as the evaluation function is defined from the system model (Fig. 2) by

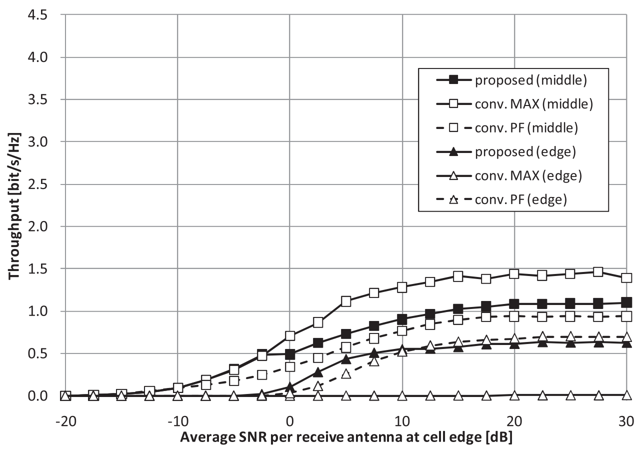
$$\eta_k = \frac{\Omega_k}{N_c} \frac{N_{bit}}{N_{bit}+N_{CRC}} \frac{N_c}{N_c+N_g} N_{CR} N_{Tx} M_k (1-PER_k) \quad (25)$$

where Ω_k is the number of allocated subcarriers, N_c is the number of subcarriers, N_{bit} is the number of information bit, N_{CRC} is a CRC code length, N_g is a guard interval length, N_{CR} is an encoding rate, N_{Tx} is the number of transmit antennas, M_k, PER_k are average bits of adaptive modulation and packet error rate, respectively. Then, a total throughput is calculated by the sum of all users' throughput as follows

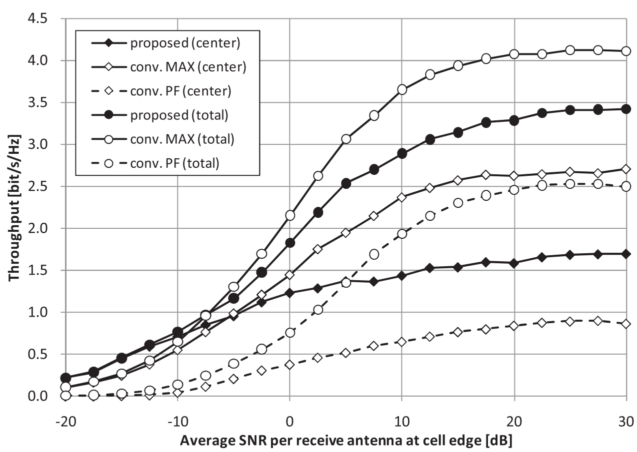
$$\eta_{total} = \sum_{k=1}^{K} \eta_k \quad (26)$$

In addition, each throughput of cell-center, middle, and edge user is calculated. The simulation condition is listed in Table 5 and the performances are compared with the conventional scheme of Sect. 2.5. Similarly, the performances of the conventional subchannel scheme with PF-based allocation are compared. The PF-based subchannel allocation is conducted by the similar manner of Fig. 8 except the limitation of number of subchannels because spreading can be done with any number of subchannels.

From the results of Fig. 14, we can see that the total throughput of conventional MAX scheme is the best of three schemes and that of the proposed scheme is about 0.7 bit/sec/Hz lower at high SNR region. However, the throughput of cell-edge user is almost zero even if SNR is increased in the conventional MAX scheme, while that is greatly improved in the proposed scheme from SNR of 0 dB. This is because the conventional MAX algorithm only aims at the capacity enhancement so that the cell-edge user which has worse channel coefficients is rarely allocated. On the other hand, the proposed scheme balances the allocation for all users based on PF algorithm and achieves a wider-area



(a)



(b)

Fig. 14 Throughput evaluation of conventional and proposed scheme: (a) edge and middle, (b) center and total.

cell coverage including cell-edge user. Compared with the PF-based conventional scheme, the proposed scheme has a similar throughput performance of cell-edge users. However, the total throughput is much higher than the conventional scheme because of the effective utilization of user and frequency diversities.

4.4 Evaluation of Proportional Fairness

Finally, the fairness is evaluated. A fairness among users is calculated at the same condition by Jain's fairness index (JFI) [19] defined by

$$JFI = \left(\sum_{k=1}^{K} C_k \right)^2 \Bigg/ K \sum_{k=1}^{K} C_k^2 \qquad (27)$$

where C_k is total channel capacity of user k described in (16). JFI is closer to one when the difference of each user's channel capacity is small and the fairness is achieved. The result in Fig. 15 shows that the proposed scheme highly keeps the fairness compared with the conventional MAX scheme of 2.5. This is because the proposed scheme adopts

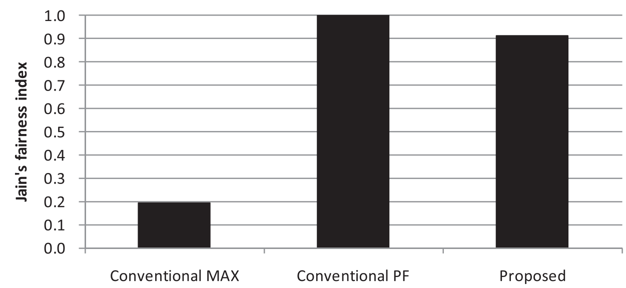


Fig. 15 Jain's fairness index.

PF scheme while the conventional scheme adopts MAX scheme. Furthermore, compared with the conventional PF scheme, both indexes are over 0.9 but the proposed scheme has slightly smaller fairness. However, it can be seen from Fig. 14(b) that the total throughput of the proposed scheme is much higher because of the powerful effect of frequency and user diversities. In addition, at SNR around 0 to 10 dB, which is the realistic SNR at cell edge, the proposed scheme has the largest cell-edge throughput. Therefore, it can be concluded that the proposed scheme perform the higher balance of throughput and fairness.

5. Conclusions

In this paper, we proposed a new PF-based MIMO-OFDMA-CDM scheme for downlink cellular systems and showed the performance improvements by numerical and theoretical analysis. We clarified the effect of code division multiplexing in MIMO-OFDMA, channel coding, and adaptive modulation in multi cell environments. By utilizing the PF algorithm and CDM, enhanced OFDMA performance in terms of BER, throughput, and JFI is achieved. Although the total throughput was less than the conventional scheme at the lower SNR of 20 dB, the cell-edge throughput was greatly improved in the proposed scheme. Thus, a balanced OFDMA resource allocation scheme has been constructed.

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