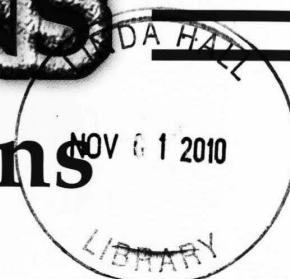


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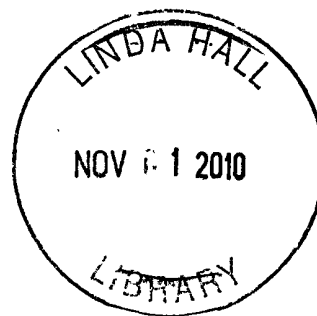
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PAPER

User Scheduling for Distributed-Antenna Zero-Forcing Beamforming Downlink Multiuser MIMO-OFDM Systems

Masaaki FUJII^{†a)}, *Member*

SUMMARY We describe a user scheduling scheme suitable for zero-forcing beamforming (ZFBF) downlink multiuser multiple-input multiple-output (MU-MIMO) orthogonal frequency-division multiplexing (OFDM) transmissions in time-division-duplex distributed antenna systems. This user scheduling scheme consists of inter-cell-interference mitigation scheduling by using fractional frequency reuse, proportional fair scheduling in the OFDM frequency domain, and high-capacity ZFBF-MU-MIMO scheduling by using zero-forcing with selection (ZFS). Simulation results demonstrate in a severe user-distribution condition that includes cell-edge users that the proposed user scheduling scheme achieves high average cell throughputs close to that provided by only ZFS and that it also achieves almost the same degree of user fairness as round-robin user scheduling.

key words: distributed antenna systems, fractional frequency reuse, multiuser MIMO, OFDM, user scheduling, zero-forcing beamforming

1. Introduction

Future wireless networks are expected to have high average cell throughputs so they can provide high-rate data services to a large number of users. To this end, distributed antenna systems (DAS) have recently attracted a considerable amount of attention for use as multiple-antenna deployment techniques that are based on macroscopic antenna diversity [1]. In DAS, the base station (BS) antennas of multiple-input multiple-output (MIMO) systems are geographically distributed within a cell to reduce the access distance between user equipment (UE) and a distributed antenna subset. This distributed antenna deployment secures a wireless link budget even for UE located at cell edges. In addition, transmit beamforming, e.g., maximum-ratio transmission used for DAS, enhances the desired signal strength, resulting in a high signal-to-interference ratio (SIR) in inter-cell interference (ICI) environments [2]. Therefore, DAS possesses a larger link budget and higher ICI tolerance than co-located (or centralized) antenna systems (CAS).

Zero-forcing beamforming (ZFBF) downlink multiuser (MU) MIMO orthogonal frequency-division multiplexing (OFDM) applied for DAS is thus expected to achieve higher average cell throughputs than that for CAS. However, ICI will severely degrade the average cell throughput, compared with that obtained in a non-ICI case. Using zero forcing with selection (ZFS) [3] as the user scheduling technique significantly can improve the average cell throughputs because of

the multiuser diversity. ZFS, however, sacrifices the fairness between users. In addition, the average cell throughputs for cell-edge users are expected to be much higher than that obtained with CAS. They, however, will be worse than that obtained in a non-ICI case. Therefore, more practical user scheduling schemes are needed for distributed-antenna ZFBF downlink MU-MIMO-OFDM systems.

Fractional frequency reuse (FFR) has been investigated as a type of geographical user scheduling to avoid adjacent-cell interference for users located within cell boundaries [4]. In FFR, the entire bandwidth is divided into a subchannel with a frequency reuse factor (FRF) equal to one and a subchannel with a higher FRF. Resource blocks (RBs) in a subchannel with FRF equal to one are allocated to users located in inner-cell zones, whereas RBs in a subchannel with a higher FRF are allocated to users located in cell-boundary zones. In a subchannel with a higher FRF, ICI is reduced at the expense of the available number of RBs in each cell. After the classification of all users into inner-cell and cell-boundary users, further user scheduling is needed for ZFBF downlink MU-MIMO-OFDM systems.

Frequency-domain user scheduling is required for MU-OFDM systems so that the channel conditions can be used as much as possible while satisfying some degree of fairness between the users. Maximum rate scheduling (MRS) can achieve a maximum sum rate by selecting only the UE with the best channel gain. UE with bad channel condition will, however, never be scheduled. Round-robin scheduling (RRS) gives equal opportunities to all UE. This, however, leads to a lower overall system performance. The well-known proportional fair scheduling (PFS) is an approach that compromises between MRS and RRS [5]. PFS schedules a user when its channel gain is higher than its average channel gain. By doing so, PFS operates somewhere in-between MRS and RRS.

Spatial-domain user scheduling has been proposed for ZFBF MU multiple input single output (MISO) or MIMO systems when the number of users exceeds that of the transmit antennas [3], [6]–[10]. Semi-orthogonal user selection (SUS) sequentially searches for a semi-orthogonal user set based on the channels' norm and orthogonality [6]. In addition, after a user set is determined by SUS, a selected user is replaced based on the orthogonality verification with another user who is more orthogonal to a scheduled user set [7]. ZFS and its simplified version [8] sequentially searches for a user set based on the ZFBF effective channel gain and provides higher throughputs than SUS. ZFS itself, however,

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does not possess a user-fairness element. A somewhat different approach is to use both user scheduling and receive antenna selection [9]. This scheme aims to increase sum rate while serving multiple streams to each UE. Unlike such antenna selection, however, beamforming at UE can create an equivalent single-stream channel for all receive antennas equipped with each user. Serving single stream to more scheduled users through such equivalent channels can provide higher user fairness and higher average throughputs. For more advanced techniques, a generic algorithm is used for the space and frequency domains to maximize the achievable throughputs [10].

In light of this background, we propose a user scheduling scheme that is suitable for distributed-antenna ZFBF downlink MU-MIMO-OFDM systems to balance the competing goals for high throughputs and user fairness. We integrated ICI-mitigation scheduling for low-SIR users by using FFR, PFS in the OFDM frequency domain, and high-capacity ZFBF-MU-MIMO scheduling for the remaining spatial streams by using ZFS into the overall user scheduling. The novelty of the scheme that we propose is as follows. We introduce FFR into DAS to further increase average user throughputs for users located in cell boundaries. In each of the higher-SIR user group and the lower-SIR user group, which are classified by FFR, PFS is applied for all users to secure user fairness. Unlike the original ZFS, the ZFS in our proposed user scheduling treats the user selected

by PFS as the first user and then selects other users to be allocated to the remaining streams. By applying the integrated user scheduling for DAS, we achieve high average cell throughputs while improving the average cell throughputs for potentially low-throughput users and also satisfying some degree of user fairness.

2. Reference Signal (RS) Structures

The configurations of a BS equipped with N_D antennas and UE equipped with n_R antennas are shown in Figs. 1 and 2. We assume that there are K users in each cell. The signal-flow procedures of the RS and data transmissions are as follows.

- 1) BSs transmit cell-specific downlink RSs.
- 2) UEs receive the cell-specific downlink RSs, estimate channels, calculate average SIR and transmit beam-forming vectors, feedback the average SIR, and then transmit sounding RS.
- 3) BSs receive the sounding RSs, estimate multiuser channel vectors, schedule N_U users per resource block (RB), calculate ZFBF weight matrices, and then transmit UE-specific RSs.
- 4) Scheduled UEs receive the UE-specific RSs, calculate receive beamforming vectors and post-detection SINRs, select MCSs, and then feed back the MCS indexes.

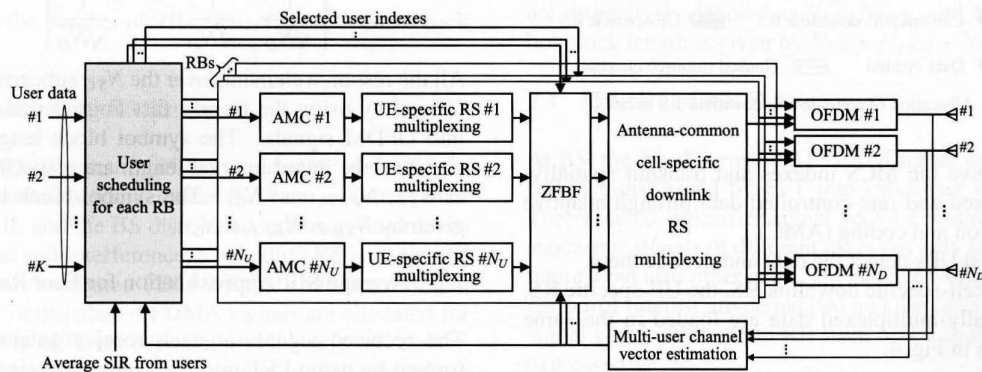


Fig. 1 BS configuration.

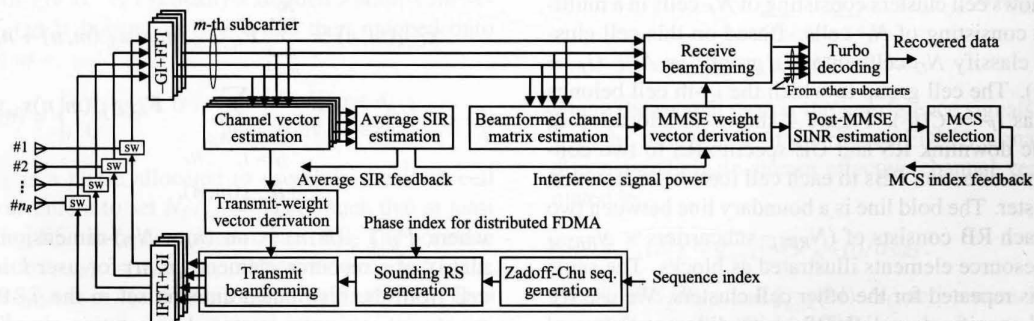


Fig. 2 UE configuration.

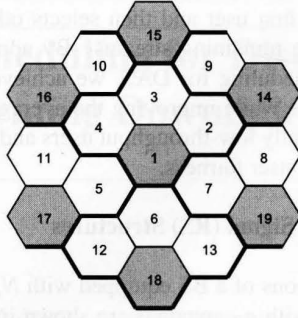


Fig. 3 Multi-cell layout with cell clusters consisting of $N_F (= 4)$ cells.

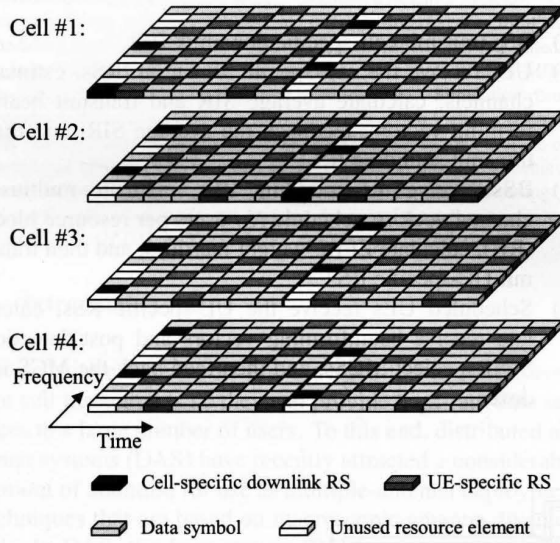


Fig. 4 Allocation of cell-specific downlink RS to cells.

- 5) BSs receive the MCS indexes and transmit spatially-multiplexed and rate-controlled data through adaptive modulation and coding (AMC).
 - 6) Scheduled UEs detect the data and decode them.
- Note that the cell-specific downlink RS, the UE-specific RS, and the spatially-multiplexed data are loaded in the same RBs as shown in Fig. 4.

2.1 Cell-Specific Downlink RS Structure

Figure 3 shows cell clusters consisting of N_F cells in a multi-cell layout consisting of N_C cells. Based on this cell clustering, we classify N_C cells into N_F groups as A_{i_F} , ($i_F = 1, \dots, N_F$). The cell group to which the i_C -th cell belongs is defined as $i_F = C(i_C)$. Figure 4 shows an allocation of cell-specific downlink RS and UE-specific RS to two consecutive time-direction RBs to each cell (cell #1–#4) within the cell cluster. The bold line is a boundary line between two RBs and each RB consists of (N_{RBSC} subcarriers $\times$ N_{RBMS} symbols) resource elements illustrated as blocks. The same allocation is repeated for the other cell clusters. We use N_F sets of cell specific downlink RSs with different time and frequency shifts for the N_F cells within each cell cluster.

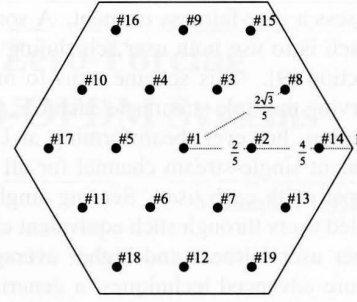


Fig. 5 Distributed antenna geometry.

In the resource elements carrying RS for a given cell, no symbols, which are denoted as unused resource elements in Fig. 4, are transmitted from other cells within the same cell cluster to avoid adjacent cell interference. Identical cell-specific downlink RSs are allocated for all the distributed antennas shown in Fig. 5 as antenna-common cell-specific downlink RS.

An N_D -dimensional antenna-common cell-specific downlink RS vector is given for the resource element at the m -th subcarrier and the n -th symbol by

$$s_{ic}(m, n) = w_{CSRS} \alpha_{CSRS} s_{CSRS}, \quad (1)$$

where s_{CSRS} is an arbitrary complex-valued signal with a unit power and it is boosted by $\alpha_{CSRS} = \sqrt{N_F}$. The fixed transmit weight vector w_{CSRS} is simply set as

$$w_{CSRS} = \left[\frac{1}{\sqrt{N_D}}, \frac{1}{\sqrt{N_D}}, \dots, \frac{1}{\sqrt{N_D}} \right]^T. \quad (2)$$

All the resource elements over the N_{SC} subcarriers are transformed by using the inverse fast Fourier transform (IFFT) into OFDM signals. The symbol block length, the IFFT size, and the guard interval length are respectively denoted as N_{SB} , N_{FFT} , and N_{GI} . The symbol block length is thus given by $N_{SB} = N_{FFT} + N_{GI}$.

2.2 Average SIR Approximation for User Ranking

The received signals at each receive antenna are transformed by using FFT into N_{SC} subcarrier signals. The n_R -dimensional frequency-domain received cell-specific downlink RS vector is given at user k in the i_C -th cell by

$$\begin{aligned} x_{ic,k}(m, n) &= \sum_{j_C=1}^{N_C} \mathbf{F}_{ic,k,j_C}(m, n) s_{j_C}(m, n) + \mathbf{n}_{ic,k}(m, n) \\ &= \sum_{\substack{j_C \in A_{i_F} \\ j_F = 1, \dots, N_F}} \mathbf{F}_{ic,k,j_C}(m, n) s_{j_C}(m, n) \\ &\quad + \mathbf{n}_{ic,k}(m, n), \end{aligned} \quad (3)$$

where $\mathbf{F}_{ic,k,j_C}(m, n)$ is an ($n_R \times N_D$)-dimensional channel matrix at a resource element (m, n) for user k in the i_C -th cell from the distributed antenna set in the j_C -th cell, and $\mathbf{n}_{ic,k}(m, n)$ is a noise vector. For notation simplicity, interference signals caused by large propagation delays are not

included in (3). An n_R -dimensional composite channel vector is estimated for each cell group j_F as

$$\begin{aligned}\hat{f}_{i_c, k, j_F}(m, n) &= \mathbf{x}_{i_c, k}(m, n) s_{CSRS}^* / \alpha_{CSRS} \\ &= \sum_{j_c \in A_{j_F}} \mathbf{F}_{i_c, k, j_c}(m, n) \mathbf{w}_{CSRS} \\ &\quad + \tilde{\mathbf{n}}_{i_c, k}(m, n),\end{aligned}\quad (4)$$

where the superscript $*$ denotes the complex conjugate and $\tilde{\mathbf{n}}_{i_c, k}(m, n) = \mathbf{n}_{i_c, k}(m, n) s_{CSRS}^* / \alpha_{CSRS}$. Note that the resource element positions (m, n) for cell-specific downlink RSs are different for each cell group j_F as shown in Fig. 4. The estimated composite channel vector is then averaged over the two consecutive time-direction RBs as

$$\bar{f}_{i_c, k, j_F}(M) = \frac{1}{N_{CSRS}} \sum_{(m, n)} \hat{f}_{i_c, k, j_F}(m, n), \quad (5)$$

where M is a frequency-direction index for the RBs and $N_{CSRS} (= 4)$ is the number of cell-specific downlink RSs allotted in the two consecutive time-direction RBs. The average signal-to-interference power ratio (SIR) is approximated as

$$SIR_{i_c, k} = \frac{\sum_{M=1}^{N_{RB}} \frac{1}{n_R} \|\bar{f}_{i_c, k, i_F}(M)\|^2}{\sum_{\substack{j_F=1, \\ j_F \neq i_F}}^{N_F} \sum_{M=1}^{N_{RB}} \frac{1}{n_R} \|\bar{f}_{i_c, k, j_F}(M)\|^2}, \quad (6)$$

where N_{RB} is the number of RBs. This SIR value is fed back to BS.

2.3 Uplink Sounding RS Structure

A sounding RS is transmitted from each UE to the BS so that the BS can know what channel has been established between each UE and the BS distributed antennas. In order to avoid adjacent cell interference, a sounding RS is generated in the form of distributed FDMA signals and the different comb phases in distributed FDMA signals are allocated for users located in different cells within the same cell cluster. To enable multiple users ($= N_A$) located in the same cell to simultaneously access the BS, the comb phase allocated to a cell is further divided into multiple different comb phases as shown in Fig. 6. A cyclically-extended Zadoff-Chu sequence $c_{ZC}(p)$ is boosted by α_{SRS} and then mapped onto subcarriers as

$$c_{i_c, k}(m) = \begin{cases} \alpha_{SRS} c_{ZC}(p) & m = N_F N_A p + \delta_{i_c, k} \\ 0 & m \neq N_F N_A p + \delta_{i_c, k} \end{cases}, \quad (7)$$

where $\delta_{i_c, k}$ is a phase allocated to user k in the i_c -th cell and it is convenient to set $N_F N_A \leq N_{RBSC}$ such that at least one sounding RS can be contained in each RB. The boosting factor is set to $\alpha_{SRS} = \sqrt{N_F N_A}$. When K exceeds N_A , the sounding RS for user $k(> N_A)$ is transmitted to the next time slot.

We use a transmit beamforming that is based

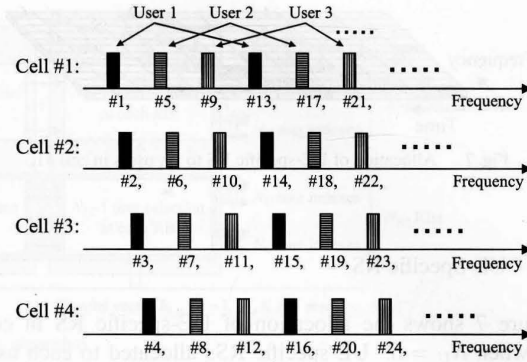


Fig. 6 Allocation of sounding RS to multiple users in multi-cells ($N_F = 4$ and $N_A = 3$).

on the maximum ratio combining (MRC) for uplink sounding RS. Using the weight vector $\mathbf{v}_{i_c, k}^*(M) = \bar{f}_{i_c, k, i_F}(M) / \|\bar{f}_{i_c, k, i_F}(M)\|$, the Zadoff-Chu sequence mapped onto subcarriers is beamformed as

$$\mathbf{c}_{i_c, k}(m) = \mathbf{v}_{i_c, k}^*(M) c_{i_c, k}(m). \quad (8)$$

The sounding RS vector is transformed by IFFT into distributed FDMA signals. Note that the constant amplitude property of the Zadoff-Chu sequence is lost by multiplying RB by a transmit beamforming weight vector although such a property is maintained when $n_R = 1$. The symbol block length, the IFFT size, and the guard interval length are respectively denoted as N_{SB} , N_{FFT} , and N_{GI} . The symbol block length is given by $N_{SB} = N_{FFT} + N_{GI}$.

2.4 Uplink Channel Estimation

At BS, the N_D -dimensional received signal vector at the i_c -cell is transformed by FFT into subcarrier signal vectors. The received subcarrier signal vector contains the received subcarrier signals of different users not only from the cell of interest but also other cells. The received signals at the subcarrier of interest are demapped and the received subcarrier signal vector at the M -th RB from user k in the i_c -th cell is expressed as

$$\begin{aligned}\mathbf{y}_{i_c, k}(M) &= \mathbf{F}_{i_c, k, i_c}^T(m) \mathbf{v}_{i_c, k}^*(M) c_{i_c, k}(m) \\ &\quad + \sum_{j_c \in A_{i_F}} \sum_{\delta_{j_c, k} = \delta_{i_c, k}} \mathbf{F}_{i_c, k, j_c}^T(m) \mathbf{v}_{j_c, k}^*(M) \\ &\quad c_{j_c, k}(m) + \mathbf{n}_{i_c}(m),\end{aligned}\quad (9)$$

where the second term is the interference signals from users with the same phase of distributed FDMA signals. An N_D -dimensional single-stream effective channel vector is estimated by

$$\hat{\mathbf{g}}_{i_c, k}(M) = \mathbf{y}_{i_c, k}(M) c_{ZC}^*(p) / \alpha_{SRS}. \quad (10)$$

Based on $SIR_{i_c, k}$ and $\hat{\mathbf{g}}_{i_c, k}(M)$, N_U active users are selected out of K users for the M -th RB.

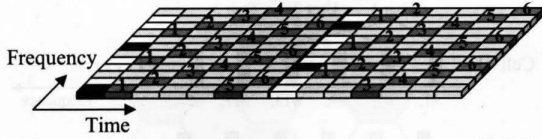


Fig. 7 Allocation of UE-specific RS to six users in cell #1.

2.5 UE-Specific RS

Figure 7 shows the allocation of UE-specific RS in cell #1 when $N_U = 6$. UE-specific RSs allocated to each user are deployed in equally-spaced subcarrier intervals so that the channel can be interpolated for the subcarriers where UE-specific RS is not deployed. Data symbols or UE-specific RS to be transmitted to N_U users are arranged as $\mathbf{a}_{ic}(m, n) = [a_{ic,1}(m, n), a_{ic,2}(m, n), \dots, a_{ic,N_U}(m, n)]^T$, where $a_{ic,1}(m, n)$ has an average power of $E[|a_{ic,1}(m, n)|^2] = 1/N_U$ for data symbols. For UE-specific RS to be transmitted, $\mathbf{a}_{ic}(m, n)$ is set as $\mathbf{a}_{ic}(m, n) = [0, \dots, 0, s_{ic,i_U}(m, n), 0, \dots, 0]^T$, where $s_{ic,i_U}(m, n)$ is given by

$$s_{ic,i_U}(m, n) = \alpha_{UERS} s_{UERS}, \quad (11)$$

where s_{UERS} is an arbitrary complex-valued signal with a transmit power of $1/N_U$ and α_{UERS} is a boosting factor. It is convenient to allot $\alpha_{UERS} = \sqrt{N_U}$ because there are $(N_U - 1)$ unused resource elements for a single user. In the end, we set the transmit power as $|s_{ic,i_U}(m, n)|^2 = 1$. The beamformed transmit signal is obtained by

$$s_{ic}(m, n) = \mathbf{W}_{ic}(M) \mathbf{a}_{ic}(m, n). \quad (12)$$

All of the beamformed resource elements are then transformed by IFFT into an N_D -dimensional OFDM signals as $s_{ic}(t)$.

3. User Scheduling

Figure 8 shows the user scheduling algorithm that we propose, which consists of ICI-mitigation scheduling using FFR, PFS in the frequency domain, and high-capacity scheduling by ZFS. Figure 9 shows a multi-cell structure where FRF is equal to one and three, respectively, in the inner-cell and cell-boundary zones. The number of RBs allocated for the inner-cell and cell-boundary users is respectively N_{UF} and N_{RF} as illustrated in Fig. 10. The user scheduling procedures that select N_U users out of K users at each RB are as follows.

- 1) Using the average SIR values fed back from K UEs, K users are ranked and then classified into K_H inner-cell users and K_L cell-boundary users.
- 2) K_H inner-cell users and K_L cell-boundary users are respectively allocated to N_{UF} RBs and N_{RF} RBs.
- 3) In each user group, in descending order of rank, all users select an RB with its own highest channel gain without duplication of RBs. This is repeated until the

whole RB is allocated to an arbitrary single user.

- 4) In each RB, the remaining $(N_U - 1)$ users are selected based on ZFS so that the sum rate can be maximized. The following Sects. 3.1–3.3 present the detail of the user scheduling procedures.

3.1 ICI-Mitigation Scheduling by FFR

At each cell, K user indexes are sorted in descending $SIR_{ic,k}$ order as $\Gamma = \{\gamma_1, \dots, \gamma_K\}$. The sorted user-index set Γ is partitioned into a high-SIR group Γ_H and a low-SIR group Γ_L . Each user set is respectively denoted as

$$\Gamma_H = \{\gamma_1^H, \dots, \gamma_{K_H}^H\} \text{ and } \Gamma_L = \{\gamma_1^L, \dots, \gamma_{K_L}^L\},$$

where K_H and K_L are the number of users in each user set and $K = K_H + K_L$. Note that the users are not classified here based on their distance from the center of a cell because the received signal power is not always attenuated proportional to the distance due to shadowing and instantaneous fading. The SIR measured with cell-specific downlink RS does not correspond to the SIR in a ZFBF data transmission. The users in the low-SIR group are, however, more likely to suffer from ICI in a ZFBF downlink MU-MIMO data transmission. The users in the high- and low-SIR groups are thus respectively regarded as inner-cell and cell-boundary users. The inner-cell users are allocated to RBs with FRF equal to one, whereas the cell-boundary users are allocated to cell-specific RBs with FRF equal to three.

3.2 PFS in OFDM Frequency Domain

Based on the determined order in each user group, each user selects one RB with the largest channel gain from among the available RBs to pursue a higher capacity. When another user has already selected an RB, the RB with the second largest channel gain is selected. When the number of available RBs is larger than that of users, the above procedure is repeated until each of all available RBs is occupied by a single arbitrary user. We do not use any user exclusion criterion, for instance, based on channel gain so that all users can be allocated to at least one RB. The search for users to be allocated as the first user in RB is carried out in the following way.

- 1) Initialization:

Set $n = 0$.

Set $\Pi_1^H = \{\text{null}\}$.

- 2) While $n < N_{UF}$:

$n = n + 1$.

$k = \text{mod}(n - 1, K_H) + 1$.

Find an RB, M , such that

$$\pi_{\gamma_k^H} = \arg \max_{M=1, \dots, N_{UF} \text{ and } M \notin \Pi_{k-1}^H} \left\| \hat{\mathbf{g}}_{ic, \gamma_k^H}(M) \right\|^2.$$

$$\Pi_k^H = \Pi_{k-1}^H \cup \{\pi_{\gamma_k^H}\}.$$

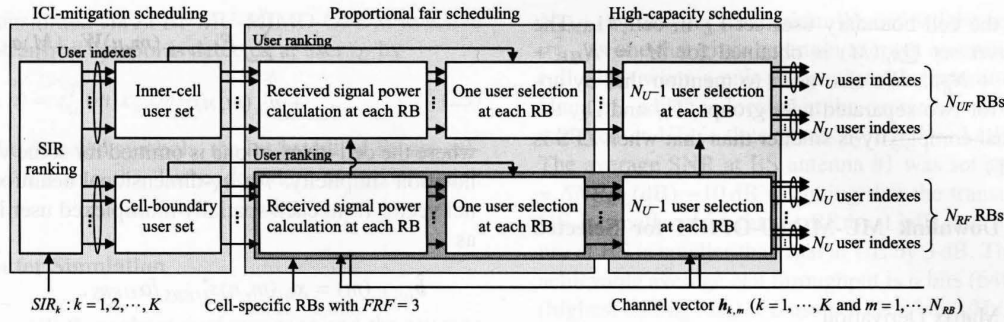


Fig. 8 User scheduling algorithm.

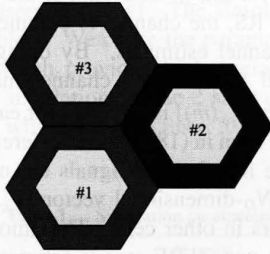


Fig. 9 Cell partitioning into inner-cell and cell-boundary zones for FFR (FRF = 3).

At the end of the procedure, the selected RB set is obtained as $\Pi_{N_{UF}}^H = \{\pi_{\gamma_1^H}, \pi_{\gamma_2^H}, \dots, \pi_{\gamma_{\text{mod}(N_{UF}-1, K_H)+1}^H}\}$. Likewise, the same procedure is applied for the cell-boundary user set Γ_L to obtain $\Pi_{N_{RF}}^L$. The selected RB sets $\Pi_{N_{UF}}^H$ and $\Pi_{N_{RF}}^L$ contain RB indexes in ascending order of Γ_H and Γ_L , respectively. Finally, each selected RB set is permuted in ascending order of RB index. The resultant user sets are respectively denoted as $\Lambda_{UF} = \{\lambda_1, \dots, \lambda_{N_{UF}}\}$ and $\Lambda_{RF} = \{\lambda_{N_{UF}+\beta_{ic}N_{RF}+1}, \dots, \lambda_{N_{UF}+\beta_{ic}N_{RF}+N_{RF}}\}$, where λ_M is a user index for the M -th RB and β_{ic} ($= 0, 1$, or 2) is a cell-specific RB allocation shift in subchannels with FRF equal to three. Note that users' channel gains vary less in DAS than in CAS. This thus leads to higher user fairness through PFS.

3.3 High-Capacity ZFBF-MU-MIMO Scheduling by ZFS

When ZFBF is supposed to be used for transmit beamforming, the throughput of the ZFBF transmission is given for an N_U -tuple user set Q_{N_U} by [11]

$$R_{zf}(Q_{N_U}) = \sum_{i=1}^{N_U} [\log_2(\mu c_i(Q_{N_U}))]_+, \quad (13)$$

where $[x]_+ = \max\{0, x\}$ and $c_i(Q_{N_U})$ is an effective channel gain and it is obtained as

$$c_i(Q_{N_U}) = \left\{ \left[(G(Q_{N_U})G^H(Q_{N_U}))^{-1} \right]_{i,i} \right\}^{-1}, \quad (14)$$

where $G(Q_{N_U})$ is a channel matrix for Q_{N_U} and the subscript

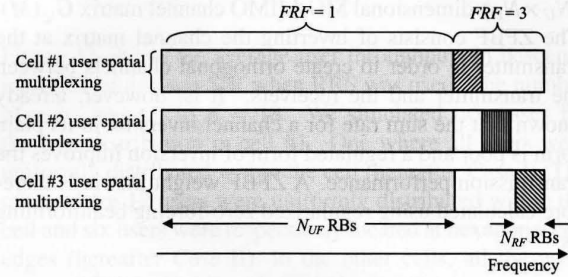


Fig. 10 Allocation of users to RBs with FRF = 1 and cell-specific RBs with FRF = 3.

i , i refers to the (i, i) entry of the matrix. And μ in (9) is obtained by solving the water-filling equation

$$\sum_{i \in Q_n} \left[\mu - \frac{1}{c_i(Q_n)} \right]_+ = P, \quad (15)$$

where the total transmit power is constrained to P . Searching for an N_U -tuple user set from among K users that yields maximum $R_{zf}(Q_{N_U})$ has prohibitive complexity. The reduced-complexity suboptimal algorithm, ZFS, is outlined as follows.

The original ZFS starts by searching for a user with the largest channel gain. We, however, have already selected one user for each RB. The first user for each RB thus should be the one selected by using PFS. The search for users to be allocated to the remaining $(N_U - 1)$ streams is carried out by ZFS for the M -th RB as follows.

1) Initialization:

Set $n = 1$.

Set $Q_1(M) = \{\lambda_M\}$.

2) While $n < N_U$:

$n = n + 1$.

Find a user, k , such that

$$q_n = \arg \max_{k \in \Gamma_H \setminus Q_{n-1}(M)} R_{zf}(Q_{n-1}(M) \cup \{k\}).$$

Set $Q_n(M) = Q_{n-1}(M) \cup \{q_n\}$.

At the end of the procedure, the scheduled user set $Q_{N_U}(M)$ is obtained for $M = 1, \dots, N_{UF}$. The same procedure is

applied for the cell-boundary user set Γ_L in cell #1. The scheduled user set $Q_{N_U}(M)$ is obtained for $M = N_{UF} + 1, \dots, N_{UF} + N_{RF}$. We also need to mention that by applying ZFS for two separated user groups, Γ_H and Γ_L , the computational complexity is smaller than that when ZFS is applied for Γ .

4. ZFBF Downlink MU-MIMO-OFDM for Selected Users

4.1 ZFBF Matrix Derivation

Based on the scheduled user set $Q_{N_U}(M)$, we set up an $(N_U \times N_D)$ -dimensional MU-MIMO channel matrix $G_{ic}(M)$. The ZFBF consists of inverting the channel matrix at the transmitter in order to create orthogonal channels between the transmitter and the receivers. It is, however, already known that the sum rate for a channel inversion in its plain form is poor and a regulated form of inversion improves the transmission performance. A ZFBF weight matrix is therefore calculated using regularized zero-forcing beamforming as

$$W_{ic}(M) = G_{ic}^H(M) (G_{ic}(M)G_{ic}^H(M) + \varepsilon I_{N_U})^{-1}, \quad (16)$$

where ε is a small value used to regulate an inverse and I_{N_U} is an $(N_U \times N_U)$ -dimensional identity matrix. The regulating value is set to $\varepsilon = N_U \sigma_{UE}^2$ [12], where σ_{UE}^2 is a noise variance at UE. The diagonal loading parameter ε (> 0) causes inter-user interference, but the optimum value of ε maximizes the SINR at the receivers. The weight vector $w_{ic,i_U}(M)$ in the transmit beamforming matrix $W_{ic}(M)$ is used in the normalized form of $w_{ic,i_U}^H(M)w_{ic,i_U}(M) = 1$.

4.2 Transmit ZFBF for UE-Specific RS and Data Symbols

Data symbols or UE-specific RS to be transmitted to N_U users are arranged as $\mathbf{a}_{ic}(m, n) = [a_{ic,1}(m, n), a_{ic,2}(m, n), \dots, a_{ic,N_U}(m, n)]^T$, where $a_{ic,1}(m, n)$ has an average signal power of $E[|a_{ic,1}(m, n)|^2] = 1/N_U$ for data symbols in the subchannel where $FRF = 1$ and it is adjusted to FRF/N_U in the subchannel where $FRF = 3$ to maintain the same average total transmit signal power. The beamformed transmit signal is obtained by

$$s_{ic}(m, n) = W_{ic}(M)\mathbf{a}_{ic}(m, n). \quad (17)$$

All the beamformed resource elements are then transformed by IFFT into an N_D -dimensional OFDM signals.

4.3 Receive MMSE Beamforming

The n_R -dimensional received signal vector at user i_U at the first cell ($i_C = 1$) is transformed by FFT into subcarrier signals. The received subcarrier signal vector is given by

$$\mathbf{x}_{i_U}(m, n) = \mathbf{F}_{1,i_U,1}(m, n)W_1(M)\mathbf{a}_1(m, n)$$

$$+ \sum_{j_C=2}^{N_C} \mathbf{F}_{1,i_U,j_C}(m, n)W_{j_C}(M)\mathbf{a}_{j_C}(m, n) + \mathbf{n}_{i_U}(m, n), \quad (18)$$

where the cell index of one is omitted for some variables for notation simplicity. An n_R -dimensional beamformed channel vector from each spatially multiplexed user is estimated as

$$\hat{\mathbf{b}}_{i_U,j_U}(m) = \mathbf{x}_{i_U}(m, n)s_{UE}^*/\alpha_{UE}, \quad (19)$$

where $j_U (1 \leq j_U \leq N_U)$ is a multiplexed user index and the resource element position (m, n) is the one assigned to UE-specific RS for the j_U -th user. For the subcarrier without UE-specific RS, the channel is obtained by interpolating adjacent channel estimates. By doing this, an $(n_R \times N_U)$ -dimensional beamformed channel matrix $\hat{\mathbf{B}}_{i_U}(m) = [\hat{\mathbf{b}}_{i_U,1}(m), \dots, \hat{\mathbf{b}}_{i_U,N_U}(m)]$ is obtained for each subcarrier.

The second term in (18) is the interference signals from other cells. The interference signals are unknown to user i_U because the N_D -dimensional vector $W_{j_C}(M)\mathbf{a}_{j_C}(m, n)$ is unknown to users in other cells. The amount of inter-cell interference in a non-ZFBF case is estimated in the course of calculating (6) as

$$\sigma_{\xi,i_U}^2(M) = \frac{1}{n_R} \sum_{j_F=2}^{N_F} \|\tilde{\mathbf{f}}_{i_U,j_F}(M)\|^2. \quad (20)$$

The interference signal power $\sigma_{\xi,i_U}^2(M)$ is used by scaling $\hat{\sigma}_{\xi,i_U}^2(M) = \eta\sigma_{\xi,i_U}^2(M)$ to roughly approximate the variance of the interference signals in the M -th RB, where η is a scaling factor.

The MMSE receive beamforming vector is derived by using a Moore-Penrose pseudo-inverse for $N_U > n_R$ in case more than $(n_R - 1)$ inter-user interference streams remain due to imperfect transmit beamforming. It is given by

$$\mathbf{z}_{i_U}(m) = \hat{\mathbf{b}}_{i_U,i_U}^H(m) \left(\hat{\mathbf{B}}_{i_U}(m)\hat{\mathbf{B}}_{i_U}^H(m) + \sigma^2(M)\mathbf{I}_{n_R} \right)^{-1}, \quad (21)$$

where $\sigma^2(M) = N_U\sigma_{UE}^2 + \hat{\sigma}_{\xi,i_U}^2(M)$ and σ_{UE}^2 is a noise variance at the receiver. The resulting post-MMSE SINR is estimated for each subcarrier as

$$\text{SINR}_{i_U}(m) = \frac{|\mathbf{z}_{i_U}^T(m)\hat{\mathbf{b}}_{i_U,i_U}(m)|^2}{\sigma^2(M) + \sum_{j_U=1, j_U \neq i_U}^{N_U} |\mathbf{z}_{i_U}^T(m)\hat{\mathbf{b}}_{i_U,j_U}(m)|^2}. \quad (22)$$

The SINR for the M -th RB is determined as the minimum value among $\text{SINR}_{i_U}(m)$ for the corresponding subcarriers, that is, $\text{SINR}_{i_U}(M) = \min \text{SINR}_{i_U}(m)$. A modulation and coding set (MCS) is selected based on $\text{SINR}_{i_U}(M)$ so that the transmission rate can be maximized while satisfying the target average packet error rate (PER). The selected MCS index is fed back to BS. Based on the selected MCS, $N_U(N_{UF} + N_{RF})$ rate-controlled data streams are generated

and then transmitted via ZFBF MU-MIMO-OFDM to active users. The transmit symbol is detected at user i_U by

$$\hat{s}_{i_U}(m, n) = \mathbf{z}_{i_U}^T(m) \mathbf{x}_{i_U}(m, n). \quad (23)$$

Based on the detected symbols, the bit-by-bit LLRs are calculated and fed into the Turbo decoders to recover each packet data.

5. Computer Simulation

The average cell throughput performances and the average user throughput performances of distributed-antenna ZFBF downlink MU-MIMO-OFDM systems were evaluated for the scheduled users in cell #1. The simulation parameters are listed in Table 1. We chose the parameters of $N_D = 19$ and $n_R = 4$, which provided high average cell throughputs in another simulation. Table 2 shows the MCS selection thresholds, which were obtained for a symbol length of

Table 1 Simulation parameters.

Number of cells	$N_C = 19$
Cell cluster size for cell-specific RS and sounding RS	$N_F = 4$
Inter-site distance	500 m
Number of BS antennas	$N_D = 19$
Number of UE antennas	$n_R = 4$
Number of users	$K = 12$ or $18/\text{cell}$
Number of simultaneously accessing users to BS through sounding RS	$N_A = 3/\text{cell}$
Number of downlink spatially multiplexed users	$N_U = 6$
Number of subcarriers	$N_{SC} = 1200$
IFFT/FFT size	$N_{FFT} = 2048$
Guard interval length	$N_{GI} = 144$
OFDM symbol duration	$T_S = 71.4 \mu\text{s}$ (GI is included.)
Resource block size in frequency domain	$N_{RBSC} = 12$ subcarriers
Resource block size in time domain	$N_{RBSM} = 7$ OFDM symbols
Number of RBs in frequency domain	$N_{RB} = N_{SC}/N_{RBSC} = 100$
Number of RBs with $FRF = 1$	$N_{UF} = 76$
Number of RBs with $FRF = 3$	$N_{RF} = 8/\text{cell}$
Cell-specific downlink RS boosting	$\alpha_{CSRS} = 2.0$
Sounding RS boosting	$\alpha_{SRS} = 3.46$
UE-specific RS boosting	$\alpha_{UERS} = 2.45$
1 packet size	2 time-direction RBs
Data symbol length accommodated in 1 packet	$N_{SMBL} = 116$
Target average PER	1.0×10^{-2}
Scaling factor for estimating variance of ICI in ZFBF	$\eta = 9.0$ for RBs with $FRF = 1$ $\eta = 0.3$ for RBs with $FRF = 3$
Path loss exponent	$\beta = 3.5$
Standard deviation of shadowing	$\sigma_s = 7.0$ (dB)
Path model	Six exponentially-decayed paths
Path attenuation/path interval	1.5 dB/5 samples
RMS delay spread	0.25 μs /Tx antenna
Maximum Doppler frequency	0 Hz (quasi-static condition)

N_{SMBL} by another simulation. We defined the noise variance σ_{UE}^2 as one that gives a certain average received SNR at the cell edges when a unit-power signal is transmitted from antenna #1, which is located at the center of a cell. The noise variance at UE is thus given by $\sigma_{UE}^2 = 1/10^{SNR_{UE}(\text{dB})/10}$. The average SNR at BS antenna #1 was set as $SNR_{BS}(\text{dB}) = SNR_{UE}(\text{dB}) - 10$ dB assuming that the transmit power at UE is smaller than that at BS by 13 dB and the noise figure at BS is smaller than that at UE by 3 dB. The maximum achievable average cell throughput is 6 bits (64QAM) $\times$ 4/5 (highest coding rate) $\times$ 6 users = 28.8 bits/s/Hz.

5.1 Average User Throughputs in Descending Order of Average SIR.

Figure 11 shows the average user throughputs in descending order of average SIR when RRS was used. The number of users was set to $K = 18$. We simulated two cases for the user distribution in cell #1. One where all users were uniformly distributed within the cell (hereafter Case I). The other where 12 users were uniformly distributed within the cell and six users were respectively located at hexagonal cell edges (hereafter Case II). In the other cells, all the users were uniformly distributed within each cell.

In both cases, the average user throughputs decreased as the average SIR decreased. The average SIR approximation used in (6) can thus indicate that the lower it is the lower the average user throughput will be. The average SIR approximation is therefore helpful for classifying users into inner-cell and cell-boundary users. Specifically, in Case II, the average user throughputs for low-SIR users were more prone to decrease due to a smaller channel gain and a larger ICI. As a result, the average user throughput disparity between the highest-throughput user and the lowest-throughput user enlarged. The user ranking based on the average SIR approximation can therefore predict the user ranking of the expected average user throughputs.

Table 2 MCS selection thresholds.

Index	Modulation	Coding rates	SNR thresholds (dB)
1	QPSK	1/3	0.4
2		1/2	2.6
3		2/3	4.6
4		3/4	5.6
5		4/5	6.2
6	16QAM	1/3	4.8
7		1/2	7.6
8		2/3	10.2
9		3/4	11.4
10		4/5	12.2
11	64QAM	1/3	8.8
12		1/2	11.8
13		2/3	14.8
14		3/4	16.6
15		4/5	17.4

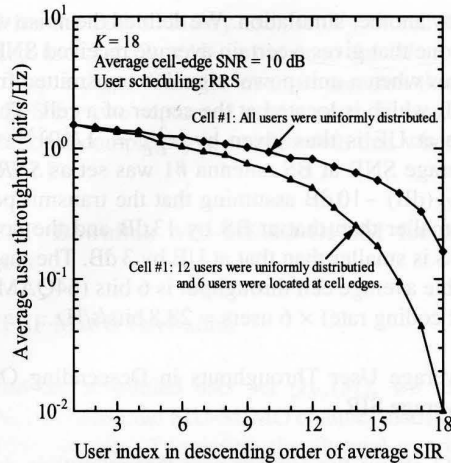


Fig. 11 Average user throughputs in descending order of average SIR when RRS was used.

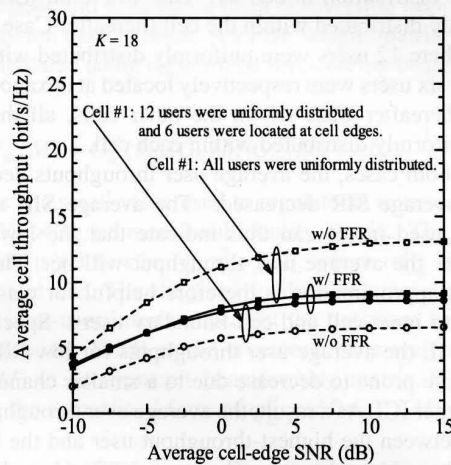


Fig. 12 Average cell throughputs of low-SIR users when proposed user scheduling with and without FFR is applied for $K = 18$.

5.2 Effect of FFR for Low-SIR Users

Figure 12 shows the average cell throughputs in the subchannel allocated to low-SIR users in the proposed user scheduling for both Case I and Case II. To evaluate the FFR effect on the average cell throughput performance, we set $FRF = 1$ and 3 in such a subchannel. Here $FRF = 1$ means there was no ICI-mitigation scheduling, that is, no FFR. For $K = 18$, K_H was set to ten and K_L was set to eight. Note that K_L low-SIR users were the cell-edge users in most cases, but not always so due to shadowing and instantaneous fading.

In Case I, the average cell throughputs when $FRF = 1$ were higher than those when $FRF = 3$ because the disparity between high-SIR users' average throughputs and low-SIR users' average throughputs was small, as shown in Fig. 10. On the other hand, in Case II, low-SIR users suffered from severe ICI, as shown in Fig. 10, and thus those users' average throughputs degraded when $FRF = 1$. Us-

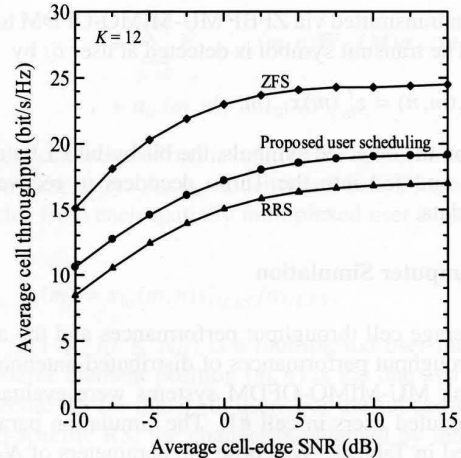


Fig. 13 Average cell throughputs for various user scheduling schemes when $K = 12$.

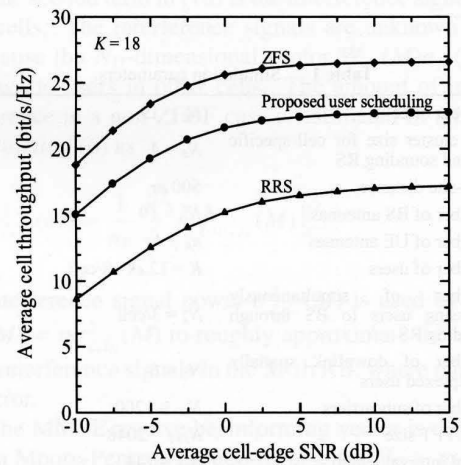


Fig. 14 Average cell throughputs for various user scheduling schemes when $K = 18$.

ing FFR improved the average cell throughput by approximately 2.0 bps/Hz at an average cell-edge SNR of 15.0 dB. The proposed user scheduling with $FRF = 3$ can cope with these severe conditions imposed on the user distribution.

5.3 Average Cell Throughput Comparison

Figures 13 and 14 show the average cell throughput comparisons of RRS, ZFS, and the proposed user scheduling when all the users ($K = 12$ and 18) were uniformly distributed within each cell. In the proposed user scheduling, when $K = 12$, the number of users in the high-SIR user set was set to $K_H = 6$ and that in the low-SIR user set was also set to $K_L = 6$. Because of $K_H = K_L = N_U$, ZFS used in the proposed user scheduling outputs the K_H users and the K_L users, respectively. When $K = 18$, K_H was set to 10 and K_L was set to 8.

For both $K = 12$ and 18, ZFS exhibited the highest average cell throughputs because it selected a user set that

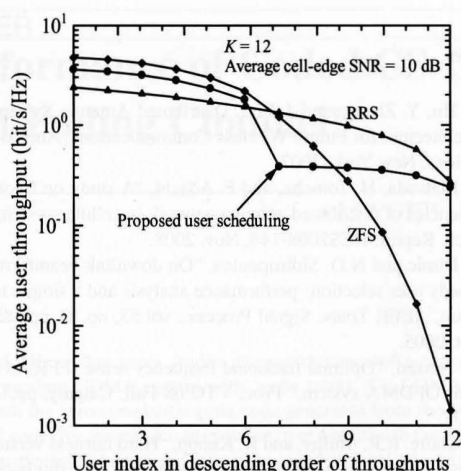


Fig. 15 Average user throughputs for various user scheduling schemes when $K = 12$.

provided the largest effective channel gain for each selection step. On the other hand, RRS exhibited the lowest average cell throughputs because it does not take the instantaneous channel conditions into account in the scheduling process. RRS is thus impractical for achieving high average cell throughputs. In contrast, the proposed user scheduling provided average cell throughputs that were at an intermediate between ZFS and RRS. In particular, when there is still room to select a user subset among the classified users, that is, when $K_H > N_U$, $K_L > N_U$, the proposed user scheduling achieved high average cell throughputs, e.g., 22.6 bps/Hz at an average cell-edge SNR of 10 dB, which was closer to the 26.5 bps/Hz obtained using ZFS.

5.4 Average User Throughput Comparison

Figures 15 and 16 show the average user throughput comparisons of RRS, ZFS, and the proposed user scheduling in the same simulation given in Figs. 13 and 14. For both $K = 12$ and 18, RRS exhibited the smallest disparity between the highest average user throughput and the lowest average user throughput, which is approximately 10 times. On the other hand, ZFS exhibited the largest average-user-throughput disparity, which is more than 1000 times, when $K = 12$. When $K = 18$, three users were not even scheduled. ZFS is thus impractical when trying to achieve some degree of user fairness. In contrast, the proposed user scheduling provided average user throughputs that were close to those obtained when using ZFS for high-throughput users and also provided average user throughputs that were close to those obtained when using RRS for low-throughput users. The average user throughput disparity was 15 times and 78 times, respectively, when $K = 12$ and 18. It can be seen from Figs. 12–15 that the proposed user scheduling can yield both high average cell throughputs and some degree of user fairness. When a larger K_H and a smaller K_L are used, the average cell throughput is expected to increase and the disparity of the average user throughputs is expected to enlarge.

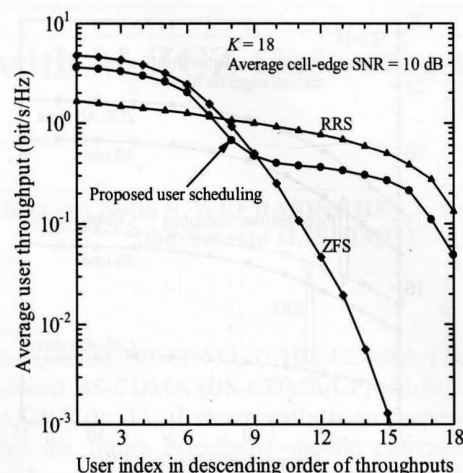


Fig. 16 Average user throughputs for various user scheduling schemes when $K = 18$.

5.5 Average Cell Throughputs and Average User Throughputs in the Presence of Cell-Edge Users

We evaluated the average cell throughputs for all users and cell-edge users, respectively, and average user throughputs as well in Case II. Note that the cell-edge users were not always classified as low-SIR users in the proposed user scheduling due to shadowing and instantaneous fading.

Figure 17 shows the average cell throughputs of RRS, ZFS, and the proposed user scheduling. The average cell throughputs of all the users were lower than those shown in Fig. 14 in all schemes, because Case II includes six users that were located at cell edges. Figure 17 also shows the average cell throughputs of the cell-edge users in RRS and the proposed user scheduling. ZFS was counted out for the cell-edge users' throughputs evaluation because those users were rarely scheduled in ZFS. The cell-edge users' average throughputs in RRS were kept low due to ICI. In contrast, the average cell throughputs of the cell-edge users were significantly improved by the proposed user scheduling and they were higher than those of all users in RRS.

Figure 18 shows the average user throughputs of RRS, ZFS, and the proposed user scheduling in the same case. In ZFS, four users were not even scheduled and the disparity between the average user throughputs was quite large. In RRS, the disparity between the average user throughputs was enlarged when compared with that shown in Fig. 16 because six users were located at the cell edges. In contrast, the proposed user scheduling provided high-throughput users with average cell throughputs that were close to those obtained with ZFS and also provided low-throughput users with higher average throughputs than RRS.

6. Conclusions

We described a user scheduling scheme that is suitable for ZFBF downlink MU-MIMO-OFDM transmission in

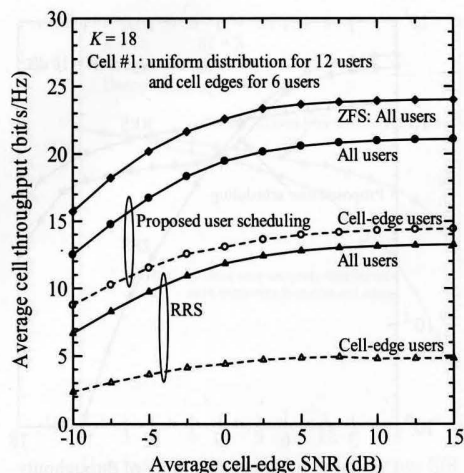


Fig. 17 Average cell throughputs for various user scheduling schemes when $K = 18$ including six users at cell edges.

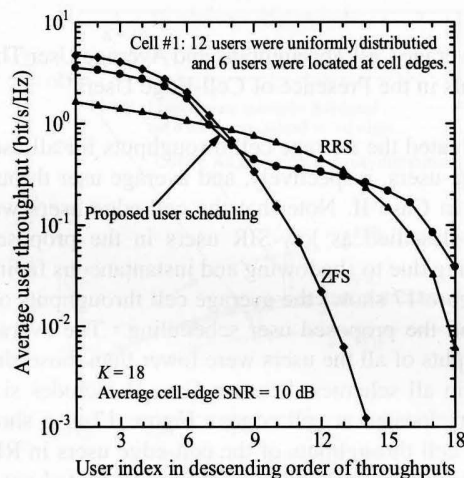


Fig. 18 Average user throughputs for various user scheduling schemes when $K = 18$ including six users at cell edges.

TDD-DAS. The user scheduling scheme consists of ICI-mitigation scheduling by FFR, PFS in the OFDM frequency domain, and high-capacity ZFBF-MU-MIMO scheduling by ZFS. SIR approximation values were used to classify users into inner-cell and cell-boundary users and they were assigned to subchannels where $FRF = 1$ and 3 , respectively. PFS scheduled each user to an RB where its channel gain was higher than the other RBs. By putting the user selected by PFS into an N_U -tuple user set as the first user, ZFS could then schedule the remaining $(N_U - 1)$ users. Our simulation results demonstrated that the proposed user scheduling scheme achieved high average cell throughputs that were close to that provided using ZFS only, and that it also achieved almost the same degree of user fairness as RRS.

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