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PAPER

Practical Uplink Multi-User MIMO Scheduling Based on Iterative Heuristic Search

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SUMMARY This paper proposes a low complexity scheduling for uplink multi-user multiple-input-multiple-output (MU-MIMO) that takes an approach of iterative heuristic search. The proposed scheduling randomly selects some of all the users in a cell, and searches the best combination of users in the possible combinations of the selected users for the MU-MIMO communication. The proposed scheduling iterates the above user search, while the best combination of the user is carried over to the user combination search at the next iteration. The performance of the proposed scheduling is evaluated in a three-dimensional wireless network by computer simulation. Even though the proposed scheduling can be implemented with approximately $\frac{1}{100}$ less complexity than the optimum scheduling which is regarded as a representative of conventional techniques, the performance of the proposed scheduling is shown to be near as superior as that of the optimum scheduling.
key words: *Multi-user multiple-input-multiple-output, scheduling, throughput minimum mean square error (MMSE) filter, low complexity*

1. Introduction

Network throughput has been demanded to raise in wireless access networks, for instance, the cellular networks based on the third generation partnership project (3GPP) and the IEEE 802.11 wireless local area networks (WLANs). Many cutting edge technologies have been applied for increasing network throughput. Among those technologies, multi-input-multiple-output (MIMO) has been playing the most important role in network throughput enhancement [1]–[3]. Since MIMO spatial multiplexing can raise the transmission speed of a wireless link in wireless networks by increasing the number of antennas on the transmitter and the receiver increases, many antennas have been installed in wireless access networks. Especially, the 5th generation cellular system (5G) applies lots of antennas on the base station, which is called "Massive MIMO" [4]–[6]. For further network throughput enhancement, multiuser MIMO (MU-MIMO) has been considered, because MU-MIMO enables to establish concurrent communications with several users at the same time in the same frequency band [7], which multiplies the network throughput. User scheduling is known to enable systems with MU-MIMO to exploit the user diversity gain, which improves the transmission performance and the network throughput [8], [9]. Because precoding is indispensable in the downlink MU-MIMO, precoding has been investigated in conjunction with scheduling [10]–[12]. However, base stations have to collect channel state information with all the users in most of those techniques. Because those scheduling techniques impose not only the overhead to collect channel state information but also complexity to select the best combination in all the candidate combinations on the base stations, the complexity and the overhead get quite high. The complexity reduction techniques for scheduling have been considered [13], [14]. Some of them take two-stage scheduling approach to reduce the complexity. For instance, users are divided into several user groups, and the best group is selected at the first stage. In the second stage, the optimum beamforming weight is searched among all the possible beamforming weights in the group. Heuristic algorithms are applied to the first stage for complexity reduction in some of the conventional techniques. On the other hand, higher frequency bands tend to be allocated to emerging wireless systems. To compensate for severe attenuation of wireless signals in such higher frequency bands, massive MIMO is going to be introduced in such systems. The massive MIMO causes user scheduling more complex [25]–[28]. To combat with the difficult problem, new approaches, for instance, application of machine learning, have been proposed [29]–[31]. For the beyond 5th generation cellular system, a new concept called "Cell-free radio access network (RAN)" has been proposed [32], where users select base stations to connect despite of a cell architecture of cellar systems. Because MIMO is indispensable even in systems with the cell-free RAN [33], user scheduling has also been investigated for cell-free massive MIMO systems [34]. Since MU-MIMO can be also implemented in the uplinks of wireless access systems, scheduling for MU-MIMO in the uplinks has been considered [15]–[19]. The greedy algorithm has been applied for the uplink MU-MIMO in the cellular system based on the long term evolution (LTE)-A standard. A smart routine was applied to solve the optimum scheduling problem with less computational complexity [19]. Moreover, uplink scheduling techniques are extended to multi-cell wireless networks [20]–[24].

This paper proposes a low complexity scheduling for uplink MU-MIMO that takes an approach of iterative heuristic search. We apply a utility function for the maximum sum throughput, which helps us reduce the computational complexity to select the users. The proposed scheduling requires only several users to send short packets for the sounding, and selects some promising users out of the users having sent the sounding packets. The proposed scheduling iter-

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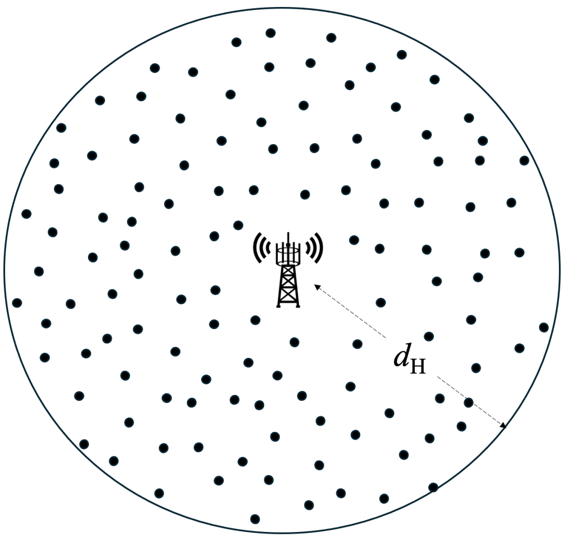

Fig. 1 User Distribution Around Base Station

ates the above simple signal processing. The performance is evaluated in 3-dimensional (3D) wireless networks which are going to be provided in the next generation wireless communication systems †.

Throughout the paper, $\arg\min_{n \in B} [f(n)]$ denotes a value of n included in a set B that minimizes a function $f(n)$. Superscript T and H indicate transpose and Hermitian transpose of a matrix or a vector. In addition, $\mathbf{A}^{-1}$ and $\mathrm{tr}[\mathbf{A}]$ denote inverse and a trace of a matrix $\mathbf{A}$, respectively.

2. System Model

We assume an uplink of a wireless access system where users with N_{T} antennas are scattered around a base station with N_{R} antennas. N_{U} users are randomly moving in a cell with the diameter $d_{\mathrm{H}} \in \mathbb{R}$ where the base station is located at the center. The system model is drawn in figure 1, which is regarded as a single cell network. Though the user locations are drawn in the 2-dimensional picture, we assume that the user locations are also distributed in the vertical direction. In fact, the users are located below the height of $d_{\mathrm{V}} \in \mathbb{R}$ in the cell. The user location is uniformly distributed in the 3D cell, which causes that the injection angle of the signals received at the base station is distributed not only in the horizontal axis but also in the vertical axis. To cope with the received signals, we apply a uniform planar array antenna with N_{V} by N_{H} elements where N_{V} and N_{H} represent the number of antenna elements in the vertical axis and in the horizontal axis, respectively.

The information bit stream is encoded with an error correction code and fed to a modulator via a bit interleaver. The modulator output signals are divided into N_{T} streams and every stream is provided to the inverse Fourier transform (IFFT) for the OFDM. The IFFT output signal stream is emitted from each antenna after the cyclic prefix (CP) is added as a header of the IFFT output signals. While N_{U} users exist in the 3D cell, the N_{P} users are allowed to simultaneously send their packets for the base station. Let $\mathbf{x}_p(n) \in \mathbb{C}^{N_{\mathrm{T}}}$ denote an nth transmission signal vector in the packet sent from the pth user, which is defined as $\mathbf{x}_p(n) = \left(x_{p,0}(n) \cdots x_{p,N_{\mathrm{T}}-1}(n)\right)^{\mathrm{T}}$ where $x_{p,m}(n) \in \mathbb{C}$ denotes a transmission signal sent from the mth antenna of the pth user at time index n, a signal vector received at the base station is represented as,

$$\mathbf{y}(n) = \sum_{p=0}^{N_{\mathrm{P}}-1} \sum_{i=0}^{N_\tau-1} \mathbf{T}_p(i)\, \mathbf{x}_p(n-i) + \mathbf{n}(n) \tag{1}$$

In (1), $N_\tau \in \mathbb{Z}$, $\mathbf{y}(n) \in \mathbb{C}^{N_{\mathrm{R}}}$, $\mathbf{n}(n) \in \mathbb{C}^{N_{\mathrm{R}}}$, and $\mathbf{T}_p(i) \in \mathbb{C}^{N_{\mathrm{R}} \times N_{\mathrm{T}}}$ denote a channel impulse response length, a received signal vector at the base station, an additive white Gaussian noise (AWGN) vector, and a channel matrix of the ith path between the base station and the pth user. As is described above, since we use a uniform planar array antennas at the base station, the channel matrix $\mathbf{T}_p(i)$ is defined as,

$$\mathbf{T}_p(i) = \mathbf{V}\left(\phi_p(i)\right) \otimes \mathbf{H}\left(\theta_p(i)\right) h_p(i). \tag{2}$$

In (2), $\mathbf{V}(\phi)$ and $\mathbf{H}(\theta)$ represent array steering vectors in the vertical axis and in the horizontal axis, respectively, where $\phi \in \mathbb{R}$ and $\theta \in \mathbb{R}$ represent an injection angle of an input signal in the vertical axis and that in the horizontal axis. In addition, $\otimes$, $h_p(i)$, $\phi_p(i)$, and $\theta_p(i)$ denote the operator of the Kronecker's product, a complex channel gain of the ith path from the pth user, injection angles of the ith path from the pth user in the vertical axis and in the horizontal axis, respectively. On the other hand, let $D_{\mathrm{V}} \in \mathbb{R}$, $D_{\mathrm{H}} \in \mathbb{R}$, and $\lambda \in \mathbb{R}$ denote antenna spacing in the vertical axis and in the horizontal axis, and a wavelength of the carrier signal, the array steering vectors $\mathbf{V}(\theta)$ and $\mathbf{H}(\theta)$ are defined as follows.

$$\begin{aligned} \mathbf{V}(\phi) &= \left(1 \cdots \mathrm{e}^{-\mathrm{j}2\pi(N_{\mathrm{V}}-1)\frac{D_{\mathrm{V}}}{\lambda}\sin((\phi))}\right)^{\mathrm{T}} \\ \mathbf{H}(\theta) &= \left(1 \cdots \mathrm{e}^{-\mathrm{j}2\pi(N_{\mathrm{H}}-1)\frac{D_{\mathrm{V}}}{\lambda}\cos((\theta))}\right)^{\mathrm{T}} \end{aligned} \tag{3}$$

The received signal vector is fed to the fast Fourier transform (FFT) after the CP is removed. Let $N_{\mathrm{F}} \in \mathbb{Z}$ indicate an FFT point, the FFT output signal vector $\mathbf{z}(m) \in \mathbb{C}^{N_{\mathrm{R}}}$ is described as,

$$\begin{aligned} \mathbf{z}(m) &= \frac{1}{\sqrt{N_{\mathrm{F}}}} \sum_{n=0}^{N_{\mathrm{F}}-1} \mathbf{y}(n) \mathrm{e}^{-\mathrm{j}2\pi\frac{nm}{N_{\mathrm{F}}}} \\ &= \sum_{p=0}^{N_{\mathrm{P}}-1} \dot{\mathbf{T}}_p(m)\, \dot{\mathbf{x}}_p(m) + \dot{\mathbf{n}}(m) \end{aligned}$$

† We hope that our proposed scheduling is applied to the beyond 5th generation (B5G) cellular system. Although the parameter set of the B5G cellular system has not been determined yet, the orthogonal frequency division multiplexing (OFDM) is expected to be applied to the B5G cellular system. Moreover, many B5G test beds have been implemented dedicated to three-dimensional cells. We expect that the beyond 5th generation wireless communication would be going to be provided in three-dimensional cells with the air interface in the use of the OFDM. The performance is evaluated in such communication environment.

$$= \dot{\mathbf{T}}_{\Omega_0}(m)\,\dot{\mathbf{X}}_{\Omega_0}(m) + \dot{\mathbf{n}}(m)\,. \quad (4)$$

$\dot{\mathbf{T}}_p(m) \in \mathbb{C}^{N_\mathrm{R}\times N_\mathrm{T}}$, $\dot{\mathbf{x}}_p(m) \in \mathbb{C}^{N_\mathrm{T}}$, and $\dot{\mathbf{n}}(m) \in \mathbb{C}^{N_\mathrm{R}}$ in (3) represent an mth frequency response matrix in the channel between the base station and the pth user, an mth frequency spectrum of the transmission signals sent from the pth user, and the mth instantaneous spectrum of the AWGN vector in the mth subcarrier, which are defined as $\dot{\mathbf{T}}_p(m) = \sum_{i=0}^{N_\tau-1}\mathbf{T}_p(i)\,\mathrm{e}^{-\mathrm{j}2\pi\frac{im}{N_\mathrm{F}}}$, $\dot{\mathbf{x}}_p(m) = \frac{1}{\sqrt{N_\mathrm{F}}}\sum_{n=0}^{N_\mathrm{F}-1}\mathbf{x}_p(n)\,\mathrm{e}^{-\mathrm{j}2\pi\frac{nm}{N_\mathrm{F}}}$, and $\dot{\mathbf{n}}(m) = \frac{1}{\sqrt{N_\mathrm{F}}}\sum_{n=0}^{N_\mathrm{F}-1}\mathbf{n}(n)\,\mathrm{e}^{-\mathrm{j}2\pi\frac{nm}{N_\mathrm{F}}}$, respectively. In addition, $\dot{\mathbf{T}}_{\Omega_0}(m) \in \mathbb{C}^{N_\mathrm{R}\times N_\mathrm{T}N_\mathrm{P}}$ and $\dot{\mathbf{X}}_{\Omega_0}(m) \in \mathbb{C}^{N_\mathrm{T}N_\mathrm{P}}$ represent a composite frequency response matrix and a composite transmission signal vector in the mth subcarrier, which are defined as $\dot{\mathbf{T}}_{\Omega_0}(m) = \left(\dot{\mathbf{T}}_0(m)\cdots\dot{\mathbf{T}}_{N_\mathrm{P}-1}(m)\right)$ and $\dot{\mathbf{X}}_{\Omega_0}(m) = \left(\dot{\mathbf{x}}_0(m)^\mathrm{T}\cdots\dot{\mathbf{x}}_{N_\mathrm{P}-1}(m)^\mathrm{T}\right)^\mathrm{T}$ where $\mathbf{\Omega}_0$ indicates a user combination index. The received signal $\mathbf{z}(m)$ is provided for the frequency response matrix estimation, called "sounding". The sounding period precedes the signal detection period in the proposed scheduling.

A minimum mean square error (MMSE) filter is applied for the signal detection for the proposed scheduling being practical. As is well-known, the MMSE filter can detect the N_R signal streams with high detection performance. When every user sends N_T streams without any precoding, the number of those users should be limited to $N_\mathrm{S} = \frac{N_\mathrm{R}}{N_\mathrm{T}}$. This implies that the number of the users sending the signal simultaneously during the sounding period is possibly different from that during the detection period.

Let $\mathbf{\Omega}_k$ indicate an index of a user combination, the MMSE filter $\mathbf{W}_{\Omega_k}(m) \in \mathbb{C}^{N_\mathrm{R}\times N_\mathrm{R}}$ for the user combination in the mth subcarrier is defined as,

$$\mathbf{W}_{\Omega_k}(m) = \left(\bar{\dot{\mathbf{T}}}_{\Omega_k}(m)\,\bar{\dot{\mathbf{T}}}_{\Omega_k}(m)^\mathrm{H} + \frac{2\sigma^2}{\sigma_\mathrm{D}^2}\mathbf{I}\right)^{-1}\bar{\dot{\mathbf{T}}}_{\Omega_k}(m)\,. \quad (5)$$

In (5), σ^2, σ_D^2, $\mathbf{I} \in \mathbb{R}^{N_\mathrm{R}\times N_\mathrm{R}}$, and $\bar{\dot{\mathbf{T}}}_{\Omega_k}(m) \in \mathbb{C}^{N_\mathrm{R}\times N_\mathrm{T}N_\mathrm{S}}$ denote a single side band noise spectrum density, power of the modulation symbols, the N_R-dimensional identity matrix, and an estimated composite response matrix in the mth subcarrier between the base station and the users. The signal detection is carried out as,

$$\bar{\dot{\mathbf{X}}}_{\Omega_k} = \mathbf{W}_{\Omega_k}(m)^\mathrm{H}\,\mathbf{z}(m), \quad (6)$$

where $\bar{\dot{\mathbf{X}}}_{\Omega_k} \in \mathbb{C}^{N_\mathrm{T}N_\mathrm{P}}$ denotes an estimate of the composite transmission signal vector in the mth subcarrier, $\dot{\mathbf{X}}_{\Omega_0}(m)$. Since the scheduling has to select the best combination of the users among all the possible combinations of the users, the scheduling gets seriously complex as the number of the users N_U increases.

This paper proposes a scheduling technique to find suboptimum combination of the users with small computational complexity, which is presented in the following section.

3. Low Complexity Scheduling

While all the users send their packets for the base station to estimate the frequency response matrices with all of them in the optimum scheduling, only N_P users are randomly selected to send the packets for the sounding in the proposed scheduling, because the base station has no knowledge about the frequency response with the users. Since packets usually convey some control bits, only a part of all the subcarriers are occupied by pilot signals for the channel estimation. The base station carries out the channel estimation for the subcarriers conveying the pilot signals. In the proposed scheduling, the least square channel estimation is applied, which is summarized as follows.

(a) Channel estimation is performed only for the subcarriers conveying the pilot signals.
(b) Channel impulse responses in the time domain are estimated by means of the IFFT from the frequency responses estimated in (a).
(c) Frequency response for all the subcarriers are obtained through the FFT from the channel impulse responses estimated in (b).

On the other hand, we apply a utility function for maximizing the sum throughput. In other words, the scheduler searches the best combination of the users that maximizes the sum throughput. The sum throughput maximization can be approximately achieved by selecting the user combination that maximizes the sum of the signal to interference and noise power ratio (SINR) at the subcarriers †. Besides, when the MMSE filter is used for the signal detection, the desired signal is amplified to the desired signal level as far as the SINR is high enough ††. We can only focus on the noise in the output from the MMSE filter for evaluating the SINR. In addition, because the MMSE filter is expected to orthogonalize the output signals, the sum throughput maximization can be approximately achieved by selecting the user combination that minimizes the sum of the noise power of the MMSE output signals.

Let an estimated composite frequency response matrix in the mth subcarrier be denoted by $\bar{\dot{\mathbf{T}}}_{\Omega_k}(m) \in \mathbb{C}^{N_\mathrm{R}\times N_\mathrm{T}N_\mathrm{S}}$, the proposed scheduling searches the best combination of the users as follows.

†The adaptive modulation and channel coding (AMC) enables wireless systems to achieve near capacity based on the SINR or the SNR, which has been shown, for instance, in [39].

††Because the desired signal level is not amplified to the desired signal level when the SINR is low, the average desired signal power is affected by the low SINR channel. The average SINR might not be exactly evaluated by only the MMSE output noise power. Besides, if the SINR in a channel with the base station and a user is that low enough, the MMSE filter outputs huge noise power. When such a user is included in a combination of users, the combination gets the sum of the noise power so high. The combination of users including such a user can't be selected by the proposed scheduling. Hence, we don't need to take care of such a user or such a channel.

$$\bar{\Omega}(n) = \underset{\Omega_k \in B_{C(n)}}{\arg\min}\left[\mathrm{tr}\left[\sum_{m=0}^{N_F-1}\left(\bar{\mathbf{T}}_{\Omega_k}(m)\,\bar{\mathbf{T}}_{\Omega_k}(m)^{\mathrm{H}} + \frac{2\sigma^2}{\sigma_D^2}\mathbf{I}\right)^{-1}\right]\right] \quad (7)$$

In (7), $\bar{\Omega}(n)$ and indicates the best combination of the users at the nth round, which is defined below. In addition, $B_{C(n)}$ represents a set accommodating the indexes of the possible user combinations, $B_{C(n)} = \{\Omega_k |\, k = 0, \cdots, {}_{N_P+N_S}C_{N_S} - 1\}$ at the nth round †.

Since the N_P users are not probably the optimum from the view point of the transmission performance, the proposed scheduling repeats the channel estimation and the best user combination selection many rounds, where one sequence of the channel estimation and the user combination selection is regarded as signal processing a round. Actually, the proposed scheduling iterates the sequence with a procedure described below, many rounds, for improving the transmission performance.

The user indexes searched in (7) are stored in the user set $B_{u(n+1)}$. In addition to those, the indexes of the N_P users sending their packets at the $n+1$ round are also stored in the user set $B_{u(n+1)}$, which increases the entries of the set $B_{u(n+1)}$ to N_P+N_S. For the search in (7) at the $n+1$ round, the N_S user indexes out of the N_P+N_S indexes are grouped in a candidate combination index. Since the N_P+N_S user indexes are stored in the user set $B_{u(n+1)}$, ${}_{N_P+N_S}C_{N_S}$ candidate indexes can be generated, and all of them are stored in $B_{C(n+1)}$, which is applied to the search in (7) at the $n+1$ round. Finally, the proposed scheduler outputs the user combination searched at the final round for the signal detection. The proposed scheduling is summarized as follows.

① The sounding period starts with $n = 0$.
② The N_P users are allowed to send their packets simultaneously.
③ The base station estimates the frequency response matrix $\mathbf{T}_p(m)$ from the received signal vector, and they are stored in the set $B_{T(n)}$.
④ As the users' indexes are stored in the set $B_{u(n)}$, any N_S user indexes in the $B_{u(n)}$ are grouped into a candidate combination index, all of which are stored in the set $B_{C(n)}$.
⑤ The best combination is searched based on (7), which minimizes the sum of the noise power.
⑥ The user indexes in the best combination are stored in the set $B_{u(n+1)}$.
⑦ Return to the step ② with $n = n+1$ until the final round.
⑧ The sounding period ends and the detection period starts.
⑨ The combination of the users searched at the final round is output from the proposed scheduler, and the users in the combination are allowed to send the packet.
⑩ The MMSE filter is generated by picking up the frequency response matrices of the scheduler output user indexes from the set $N_{T(N_M)}$ for the signal detection.
⑪ The signal detection is performed with the MMSE filter.

† The number of the entries in the set $B_{C(n)}$ is clearly explained when the proposed scheduling is summarized afterwards.

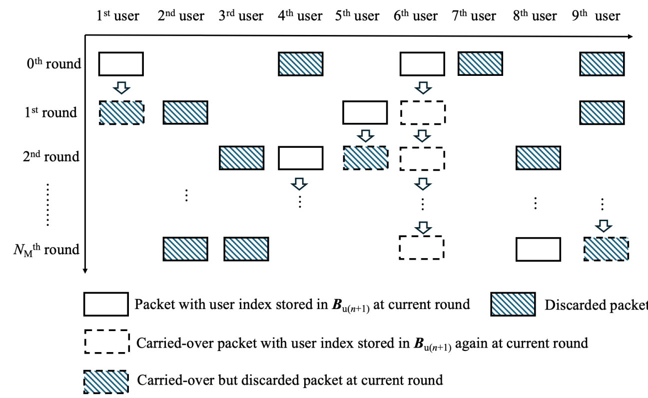

Fig. 2 Multi Round Packet Transmission

The sequence from ② to ⑦ is regarded as signal processing a round in the sounding period. However, to achieve better performance with the same complexity, the $N_P + N_S$ users are allowed to simultaneously send their packets at the initial round, because the set $\mathbf{B}_{u(0)}$ is null before the initial round. The repetitive sounding packets transmission in the proposed scheduling is named "Multi round packet transmission" in this paper, which is illustrated in figure 2. The horizontal axis and the vertical axis are the user index and the round number, respectively. This is an example of $N_P = 3$, $N_S = 2$, and $N_U = 9$. The 1st, 4th, 6th, 7th, and 9th users are permitted to send the packets at the initial round, i.e., 0th round ($n = 0$). The 1st and 6th users are selected by the procedure in (7). The shaded blocks mean the packets that are not selected. The selected user indexes, i.e., 1st and 6th user indexes, are carried over to the next round by storing them in the set $B_{u(1)}$. The box with the broken line edges means a packet carried over from the previous round. While the 2md, 5th, and 9th users send their packets, only the combination of the 5th and 6th users is selected among the ${}_5C_2$ combinations, and the other user indexes are discarded at the 1st round. Those signal transmission and the selection are repeated up to the final round of the N_Mth round. As a result, the combination of the 6th and 8th users is selected, which is scheduled to communicate with the base station.

As the number of the rounds is increased, the sounding period becomes longer, which is regarded as overhead of the proposed scheduling. As is explained later, if the value of N_P is increased, the proposed scheduling achieves higher transmission performance improvement with small number of the rounds, which could reduce the overhead. However, the increase in the value of N_P causes the computational complexity higher. In other words, the overhead can be reduced at the cost of the computational complexity. This means that there is a trade-off between the performance and the complexity.

Table 1 Simulation Parameters

Multicarrier transmission	OFDM
The carrier frequency f	4 GHz
The number of subcarriers, N_F	64
Subcarriers conveying pilot signals	$8k$th subcarrier, $k = 0, ..7$
The number of the round N_M	10
The number of antennas on a terminal and a base station, (N_T, N_R)	(2, 6)
The BS planar array antenna configuration and spacing, (N_H, N_V, d_h, d_v)	(3, 2, 0.5, 0.5)
The height of the antennas on the base station, d_{BS}	6 m
Antenna spacing (d_v, d_h)	$(\frac{\lambda}{2}, \frac{\lambda}{2})$
NLOS channel model	4-path Rayleigh fading
LOS channel model	Rice fading with K-factor of 5 dB
Cell size, d_H	100 m
The maximum height of the users, d_V	10 m
The number of users sending the packet per round, N_P	6
The number of the users to select, N_S	3
The number of all users, N_U	66
The normalized maximum Doppler frequency, $f_D T$	2.3×10^{-5}

4. Simulation

The performance of the proposed scheduling is confirmed by computer simulations in a 3D cellular system where many terminals try to communicate with a base station in a cell †. While the base station is located at the height of 6 meters, the user location is distributed uniformly in the 3D cell. The channel model depends on the height of the users. When the users are located higher than the base station, because the line of sight (LOS) signal can arrive at the base station, the instantaneous signal fading is modeled as the rice fading. That channel is called "LOS channel". Otherwise, the instantaneous signal fading is reduced to the Rayleigh fading based on Jakes' model [38], because the LOS signal from the user is difficult to arrive at the base station. That channel is called "NLOS channel". The path loss models are also dependent on the height of the users. The following path loss models are applied to the LOS channel and the NLOS channel in the performance evaluation [35]–[37] ††.

$$L_{\mathrm{NLOS}} = 39.08 \log_{10}\left(\frac{d}{d_0}\right) + 20 \log_{10}(f) - 0.6\,(h_{\mathrm{UE}} - 1.5)\ [\mathrm{dB}] \qquad (8)$$

$$L_{\mathrm{LOS}} = 25 \log_{10}\left(\frac{d}{d_0}\right) + 20 \log_{10}(f)\ [\mathrm{dB}] \qquad (9)$$

In (8) and (9), $f \in \mathbb{R}$, $d \in \mathbb{R}$, L_{NLOS}, and L_{LOS} represent carrier frequency, distance between the base station and one of the users, path loss in dB for the NLOS channel and that for the LOS channel, respectively. In addition, $d_0 \in \mathbb{R}$ indicates distance from the base station, at which the average energy per bit to noise density ratio (E_b/N_0) is defined, instead of defining the transmission power and the noise figure. The average E_b/N_0 is set to 10 dB at the distance d_0 of 10 m. We apply two types of user distributions to the performance evaluations. The one is that all the users are located below the base station, which means that the channels between all the users and the base station are modeled as the NLOS channels. The other is that some of the users are located above the base station and the other users are below the base station, which channel is described as a (LOS α%, NLOS $100 - \alpha$ %) channel in this paper. On the other hand, we evaluate the performance of the optimum scheduling as a reference, which is one of conventional scheduling †††. Simulation parameters are listed in Table 1 ††††.

4.1 SNR Distribution

The performance of the proposed scheduling is confirmed in terms of the SNR in Fig. 3. This figure shows a cumulative distribution function (CDF) of the SNR defined in every subcarrier. All the channels are modeled as the NLOS channels. In the figure, the proposed scheduling with the rounds of 0, 5, 10 are compared with that of the optimum scheduling. The performance of the random scheduling is added for comparison. The SNR performance is improved as the number

†The communication environment is illustrated in Fig. 1, even though the figure is drawn as the two dimensional picture. Actually, only one cell is taken into account in the performance evaluation. As is written in Table 1, the scenario is similar as that in urban-macro cells.

††The path loss models are borrowed from the research on channel propagation for a small cell in an urban micro-street canyon scenario and a macro scenario, because we assume that the proposed scheduling is applied to the urban macro cell.

†††Since the optimum scheduling is regarded as a representative of conventional scheduling as described in Sec. 1, the performance of the proposed scheduling is compared with that of the optimum scheduling in this paper.

††††We are not sure if the parameter setting is applied to the B5G cellular system. Among the parameters, the value of N_P plays a crucial role in the proposed scheduling. The value of N_P can be determined independently of the other parameters. However, while higher transmission performance improvement is achieved with small number of the rounds as the value of N_P is raised, the complexity of the proposed scheduling is increased. This paper puts a priority on the complexity. We select the value so as to make the complexity of the proposed scheduling much less complex. The optimization of the value is one of our future works.

of the rounds increases. The proposed scheduling with the 10 rounds achieves the performance only 3dB inferior to the optimum scheduling.

Fig. 4 shows the performance of the proposed scheduling in the (LOS 20 % and NLOS 80 %) channel. The performances of the random scheduling and the optimum scheduling are added for comparison in the figure. Obviously, the proposed scheduling achieves better SNR performance than the random scheduling. Similar as the performance in Fig. 3, the performance of the proposed scheduling comes close to that of the optimum scheduling as the number of the rounds increases. The proposed scheduling with the 10 rounds is only 2dB inferior to the optimum scheduling at the CDF of 10^{-2}.

The performance in Fig. 4 is better than that in Fig. 3, which means that the performance can be improved as the percentage of the LOS channels is increased. The performance can be understood as follows. NLOS channels attenuates transmission signals more severely than LOS channels, because the path loss model of NLOS channel is different from that of LOS channel. In fact, the path loss models written in (8) and (9) are used in the performance evaluation.. Since the users are located randomly in the cell, the received signal power is attenuated with higher probability as the percentage of the NLOS channels increases. This causes the performance gap between the NLOS channels and the LOS channels. Fig. 5 confirms the performance where the SNR is evaluated with respect to the percentage of the LOS channels. The CDF of the SNR is shown in the figure when the percentage of the LOS is changed from 0 % (NLOS channel) to 100 % (complete LOS channel). As is inferred in the previous observation, the performance is improved as the percentage of the LOS channels increases.

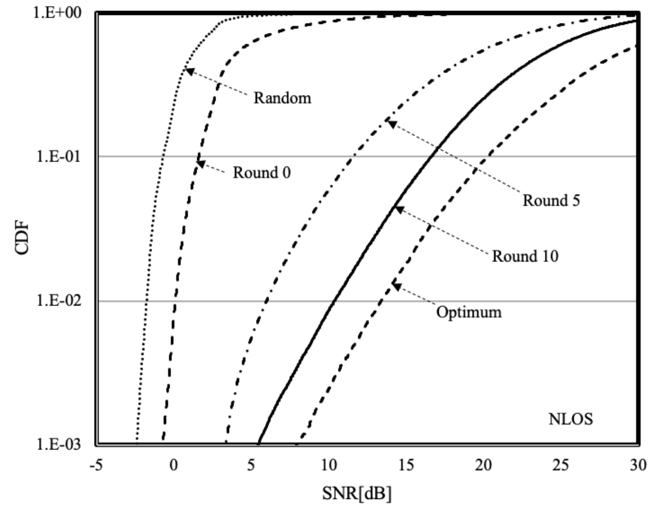

Fig. 3 CDF of SNR in NLOS channels

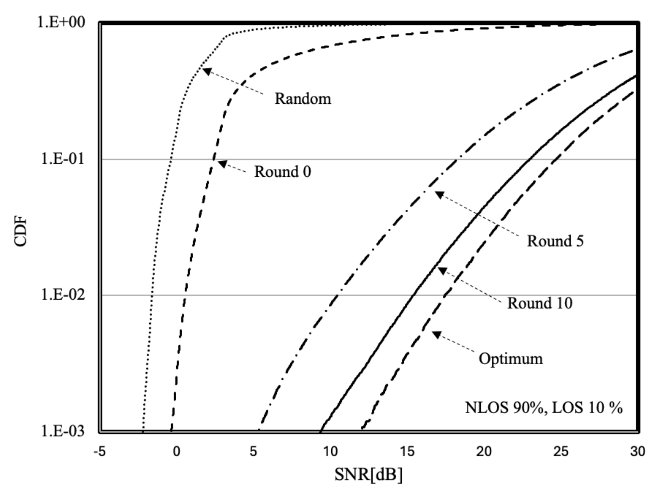

Fig. 4 CDF of SNR in (LOS 20 % and NLOS 80 %) channels

4.2 Complexity

Fig. 6 shows the complexity of the proposed scheduling with respect to the number of the rounds. In the figure, the complexity is evaluated in terms of the number of the complex multiplications needed for the proposed scheduling. The complexity of the optimum scheduling is also added in the figure. Since the optimum scheduling is regarded as a representative of conventional scheduling, the figure compares the proposed scheduling with the conventional scheduling in terms of the computational complexity. Although the complexity of the proposed scheduling is increasing in proportion to the number of the rounds, the complexity is much less than that of the optimum scheduling as long as the number of the rounds is less than 10. In fact, the complexity of the proposed scheduling with the 10 rounds is approximately $\frac{1}{100}$ as much as that of the optimum scheduling. Since the optimum scheduling collects all the frequency response matrices and searches the best combination of the users among all the combinations, i.e., ${}_{N_\mathrm{U}}\mathrm{C}_{N_\mathrm{S}}$ combinations, with the brute force search technique, the complexity is quite high. On the other hand, although the proposed scheduling applies the brute force technique to search the best combination, the number of the possible combinations a round is reduced to ${}_{N_\mathrm{S}+N_\mathrm{P}}\mathrm{C}_{N_\mathrm{S}}$. This is the reason why the complexity of the proposed scheduling is much less than that of the optimum scheduling, even if the proposed scheduling iterates the searches many rounds.

5. Conclusion

This paper proposes a low complexity scheduling for uplink MU-MIMO that takes an approach of iterative heuristic user selection. If a sequence of a random user selection, channel estimation, and the best user combination search is defined as a round, the proposed scheduling iterates the round many times. Actually, the user indexes in the best combination at a round are carried over to the next round. The proposed scheduling selects the users from the carried over users and some of all the users every round, assuming that an MMSE filter is used for the signal detection.

The performance of the proposed scheduling is evalu-

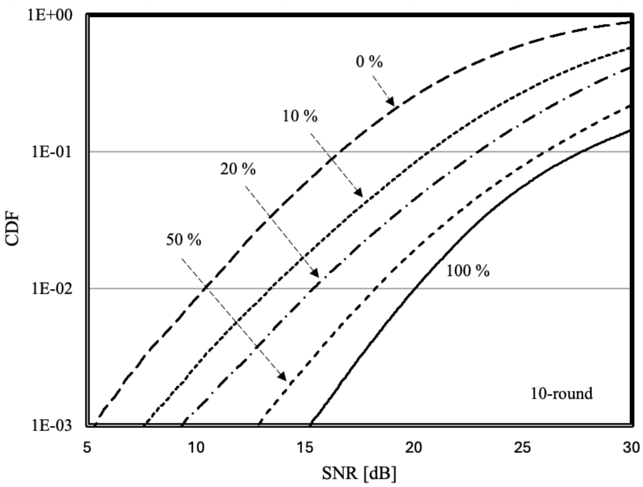

Fig. 5 CDF of SNR With Respect to User Percentage in LOS Channels

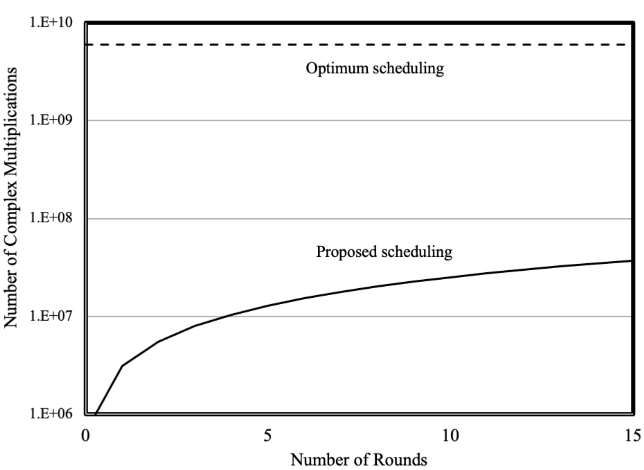

Fig. 6 Complexity

ated by computer simulations in a 3D cell where the user location is distributed uniformly in the cell. When the number of the users with 2 antennas is 66 and only the base station with 6 antennas exists in the center of the cell at the height of 6 m, the proposed scheduling achieves the performance only 2 dB inferior to the optimum scheduling in the 3D cell where some of the users are located above the base station. However, the complexity of the proposed scheduling is approximately $\frac{1}{100}$ as much as that of the optimum scheduling.

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