A Low Complexity User Selection Algorithm for Full-Duplex MU-MISO Systems

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***Abstract*— In this paper, we propose a new user selection algorithm for full-duplex (FD) multiuser multiple-input single-output (MU-MISO) systems, where an FD base station (BS) communicates with multiple half-duplex users in both downlink and uplink channels simultaneously. Due to self-interference at the BS and co-channel interference among users, a joint downlink and uplink user selection to maximize system performance incurs high search complexity. To reduce the complexity, we introduce a two-step user selection algorithm, which successively chooses downlink users followed by uplink users based on the decomposed sum rate of the FD systems. In addition, we analyze the average sum rate performance of our proposed user selection algorithm for FD MU-MISO systems and derive a tight approximation of the performance. From the numerical results, we confirm that our analysis matches well with simulation results, and the proposed user selection algorithm for the FD MU-MISO systems exhibits a small performance loss compared with the optimal user selection algorithm with much reduced complexity.**

***Index Terms*— MU-MISO, full-duplex, user selection, self-interference, co-channel interference.**

I. INTRODUCTION

MULTIUSER multiple-input and multiple-output (MU-MIMO) techniques have attracted considerable attentions as one of the core technologies of future generation wireless systems [2]–[4]. The MU-MIMO systems support multiple users and improve spectral efficiency by exploiting spatial multiplexing [5]. It is well known that dirty paper coding (DPC) can achieve the capacity region of the MU-MIMO systems [6], [7]. However, due to the difficulty of practical implementation of the DPC, linear beamforming schemes such as zero-forcing beamforming (ZFBF) have been widely used in the MU-MIMO systems. In addition, for the systems with a large number of users, the performance of the linear beamforming schemes approaches that of the DPC when a proper user selection algorithm is employed [8], [9].

Recently, a full-duplex (FD) protocol which allows simultaneous transmission and reception has been developed to further improve the capacity of the conventional half-duplex (HD) protocol where transmission and reception are performed separately in time or frequency domain [10]–[17]. The main challenge in implementing the FD systems is self-interference (SI) caused by its own transmission, since the SI may severely affect the performance of the uplink channel. It was shown in [10] and [18] that the SI can be efficiently suppressed by using advanced SI cancellation techniques.

Many researchers have studied the effectiveness of FD MU multiple-input single-output (MU-MISO) systems where a FD base station (BS) communicates with multiple HD users in both downlink and uplink channels simultaneously [12]–[14]. Specifically, in [13], iterative beamforming methods were provided to improve the spectral efficiency of the FD MU-MISO systems. Extending this result, the authors in [14] have proposed beamforming schemes for the practical scenario where co-channel interference (CCI) among users exists. However, all these works in [12]–[14] do not consider the systems with a large number of users. As in the case of the HD MU systems [19]–[21], a user selection gain is expected for the FD MU systems. To the best of our knowledge, user selection methods for the FD MU-MISO systems have not been investigated yet.

In this paper, our goal is to design a low complexity user selection algorithm which is applicable for practical systems. Since the sum rate of FD MU-MISO systems is affected by the SI and the CCI, the optimization problem requires a joint downlink and uplink user selection which incurs high search complexity. In order to reduce the complexity, the sum rate for the FD systems is decomposed into a sum of two performance metrics for high signal-to-interference-plus-noise ratio (SINR) regime, which are associated with the performance of the conventional HD systems and the attainable performance in the FD systems, respectively. Based on the decomposed performance metrics, we propose a two step user selection algorithm which successively selects the downlink users followed by the uplink users. From the simulation results, we confirm that the proposed user selection algorithm exhibits a small performance loss compared to the optimal user selection algorithm with much reduced complexity.

In addition, we analyze the average sum rate performance of the proposed user selection technique for the FD MU-MISO systems. To derive an analytical expression for the average

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sum rate, we focus on a case where a single downlink user and a single uplink user are selected. Then, we compute the probability density functions (PDFs) of the selected users' channel gain by employing the order statistics property in [22].

Based on the derived PDFs and a simple numerical algorithm in [23], we obtain a tight approximation of the average sum rate which enables us to predict the average performance gain efficiently. Also, we obtain the scaling law of our proposed algorithm by deriving the average sum rate performance in the large number of users regime. From the analysis, it is shown that the FD MU systems with the proposed user selection algorithm achieves twice higher scaling law than the HD MU systems.

The contributions of this paper can be summarized as follows: First, we propose a low complexity user selection algorithm for the FD MU-MISO systems, which shows a significant performance gain over the optimal user selection algorithm in the HD MU-MISO systems. Next, we derive a tight approximation for the average sum rate of our proposed user selection scheme which provides helpful insight for designing FD MU-MISO systems. Numerical results confirm that our analytical results match well with the simulation results in spite of adopted approximations.

This paper is organized as follows: The FD MU-MISO system model and problem formulation are presented in Section II. Section III describes the proposed user selection algorithm for the FD MU-MISO systems. Then, the performance of the proposed algorithm is analyzed in Section IV. Through the simulation results in Section V, we verify the effectiveness of our proposed scheme. Finally, this paper is terminated with conclusions in Section VI.

Throughout this paper, we use the following notations. Normal letters represent scalar quantities, boldface letters indicate vectors and boldface uppercase letters designate matrices. In addition, $(\cdot)^H$, $(\cdot)^{-1}$, and $\mathbb{E}[\cdot]$ stand for conjugate transpose, matrix inversion, and expectation, respectively. Also, $\otimes$ represents the Kronecker product and $\mathbb{C}^{m\times n}$ denotes the $m \times n$ complex matrix space. An identity matrix with size $N \times N$ is represented as $\mathbf{I}_N$.

II. System Model

As shown in Fig. 1, we consider FD MU-MISO systems where a FD BS is equipped with N_t transmit antennas for the downlink transmission and N_r receive antennas for the uplink reception. The FD BS communicates with $M \leq N_t$ single-antenna users in the downlink channels and $L \leq N_r$ single-antenna users in uplink channels at the same time over the same frequency band. In the FD systems, since both downlink and uplink transmissions are operated concurrently, SI at the FD BS and CCI at the downlink users are inevitable.[1] The set of all users within the cell is defined by $\mathcal{K} = \{1, 2, \cdots, K\}$ where K denotes the total number of users. Also, we represent the sets of selected downlink and uplink users as $\mathcal{K}_D = \{D_1, D_2, \cdots, D_M\}$ and $\mathcal{K}_U = \{U_1, U_2, \cdots, U_L\}$ where D_i and U_j stand for the i-th selected downlink user and the j-th selected uplink user, respectively.

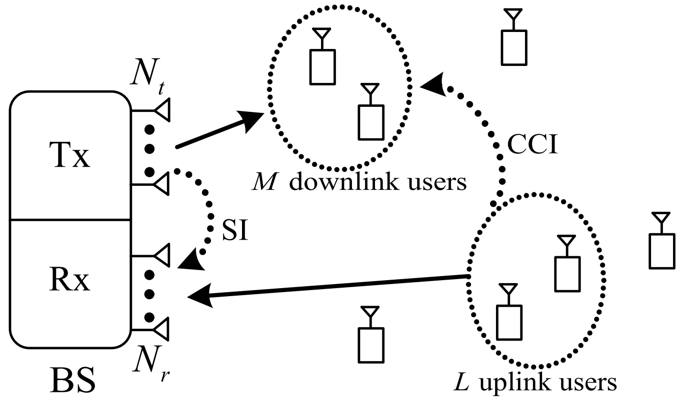

Fig. 1. System description for FD MU-MISO systems.

In the downlink transmission, the transmitted data symbol s_{D_i} for user D_i is multiplied by the beamforming vector $\mathbf{w}_{D_i} \in \mathbb{C}^{N_t\times 1}$. Here, the transmit power for user D_i is expressed by $P_{D_i} = \mathbb{E}[|s_{D_i}|^2]$ and the total transmit power at the BS is given by $P_T = \sum_{i=1}^{M} P_{D_i}$. Then, the received signal at user D_i is written as

$$y_{D_i} = \mathbf{h}_{D_i}^H \mathbf{w}_{D_i} s_{D_i} + \sum_{k\neq i}^{M} \mathbf{h}_{D_i}^H \mathbf{w}_{D_k} s_{D_k} + \sum_{j=1}^{L} g_{j,i} s_{U_j} + n_{D_i}, \tag{1}$$

where $\mathbf{h}_{D_i} \in \mathbb{C}^{N_t\times 1}$ indicates the complex downlink channel vector from the BS to user D_i, $g_{j,i}$ equals the complex channel coefficient from user U_j to user D_i, s_{U_j} stands for the data symbol transmitted from user U_j, and n_{D_i} is the additive white Gaussian noise (AWGN) with zero mean and unit variance. In (1), the second term accounts for multiuser interference (MUI) and the third term represents the CCI among downlink and uplink users.

In this paper, we adopt the ZFBF for the downlink transmission to remove the MUI [8]. Then, the rate in the downlink channel is expressed by

$$R_D = \sum_{i=1}^{M} \log_2\left(1 + \frac{P_{D_i} |\mathbf{h}_{D_i}^H \mathbf{w}_{D_i}|^2}{1 + \sum_{j=1}^{L} P_{U_j} |g_{j,i}|^2}\right),$$

where $P_{U_j} = \mathbb{E}[|s_{U_j}|^2]$ is the transmit power at uplink user U_j. For notational simplicity, we assume that all uplink users have the same transmit power P_U.

Next, in the uplink transmission, the received signal vector at the FD BS is given by

$$\mathbf{y}_U = \sum_{j=1}^{L} \bar{\mathbf{h}}_{U_j} s_{U_j} + \sum_{i=1}^{M} \mathbf{H}_{SI} \mathbf{w}_{D_i} s_{D_i} + \mathbf{n}_U,$$

[1] Recently, one can use an active antenna system (AAS) that helps in getting more control on antenna elements individually [24]. In the AAS, each array element is integrated with a separate radio-frequency transceiver unit which provides remote control to the elements electronically. By employing AAS at the FD BS, the vertical radiation pattern can also be adjusted dynamically in each sector, and multiple elevation beams can also be generated to support vertical sectors. Then, inner sector and outer sector can be used to support downlink users and uplink users, respectively. Thus, CCI among users may be marginal which can be considered as a special case of Fig. 1.

where $\bar{\mathbf{h}}_{U_j} \in \mathbb{C}^{N_r \times 1}$ denotes the complex uplink channel vector from user U_j to the BS, $\mathbf{H}_{SI} \in \mathbb{C}^{N_r \times N_t}$ equals the residual SI channel from the transmit antennas to the receive antennas at the FD BS where its entries are determined by the SI cancellation techniques, and $\mathbf{n}_U$ indicates the AWGN vector with zero mean and $\mathbb{E}[\mathbf{n}_U \mathbf{n}_U^H] = \mathbf{I}_{N_r}$.

We assume that the elements of the channel $\mathbf{h}_{D_i}$, $\bar{\mathbf{h}}_{U_i}$, and $g_{j,i}$ have an independent and identically distributed (i.i.d.) complex Gaussian distribution with zero mean and unit variance. Note that the residual SI channel after SI cancellation mechanisms can be characterized by the Rician distribution [10]. Therefore, we assume the distribution of the residual SI channel $\mathbf{H}_{SI}$ as $\mathbf{H}_{SI} \sim \mathcal{CN}(\sqrt{\sigma_{SI}^2 \kappa/(1+\kappa)}\bar{\mathbf{H}}_{SI}, (\sigma_{SI}^2/(1+\kappa))\mathbf{I}_{N_r} \otimes \mathbf{I}_{N_t})$ where $\bar{\mathbf{H}}_{SI}$ is a constant matrix, κ denotes the Rician factor, and σ_{SI}^2 represents the SI power. In this case, σ_{SI}^2 indicates the ratio of the average power before and after the SI cancellation process [14].[2] Also, we assume that channel state information (CSI) of all links is known at the FD BS via CSI feedback. For example, the downlink channel $\mathbf{h}_{D_i}$ and the co-channel $g_{j,i}$ are estimated at each user and then the FD BS can obtain the CSI through the feedback from the users.

For the uplink case, we adopt the minimum mean square error and successive interference cancellation (MMSE-SIC) receiver at the BS which achieves the capacity with an affordable decoding complexity [26]. By treating the SI as the background noise, the rate of the uplink channel is given by

$$R_U = \sum_{j=1}^{L} \log_2 \left(1 + P_U \bar{\mathbf{h}}_{U_j}^H \left(\mathbf{I}_{N_r} + \sum_{m>j}^{L} P_U \bar{\mathbf{h}}_{U_m} \bar{\mathbf{h}}_{U_m}^H + \mathbf{H}_{SI} \mathbf{Q}_D \mathbf{H}_{SI}^H \right)^{-1} \bar{\mathbf{h}}_{U_j} \right),$$

where $\mathbf{Q}_D \triangleq \sum_{i=1}^{M} P_{D_i} \mathbf{w}_{D_i} \mathbf{w}_{D_i}^H$.

Then, we define the sum rate of the FD systems as

$$\begin{aligned} R_{FD} &\triangleq R_D + R_U \\ &= \sum_{i=1}^{M} \log_2 \left(1 + \frac{P_{D_i} |\mathbf{h}_{D_i}^H \mathbf{w}_{D_i}|^2}{1 + \sum_{j=1}^{L} P_U |g_{j,i}|^2} \right) \\ &\quad + \sum_{j=1}^{L} \log_2 \left(1 + P_U \bar{\mathbf{h}}_{U_j}^H \left(\mathbf{I}_{N_r} + \sum_{m>j}^{L} P_U \bar{\mathbf{h}}_{U_m} \bar{\mathbf{h}}_{U_m}^H + \mathbf{H}_{SI} \mathbf{Q}_D \mathbf{H}_{SI}^H \right)^{-1} \bar{\mathbf{h}}_{U_j} \right). \end{aligned} \tag{2}$$

Since the sum rate in (2) which employs the ZFBF for the downlink and the MMSE-SIC for the uplink transmissions is still contaminated by the CCI and the SI, the FD system may not yield better performance than the conventional HD system which only considers the downlink transmission.[3] However, by properly choosing users in MU environments, we can improve the performance of the FD MU-MISO systems.

Our goal is to find the set of downlink and uplink users that maximizes the sum rate. Then, we can formulate the user selection problem as

$$\{\hat{\mathcal{K}}_D, \hat{\mathcal{K}}_U\} = \underset{\{\mathcal{K}_D, \mathcal{K}_U\} \in \mathcal{K}}{\arg\max}\; R_{FD}(\{\mathcal{K}_D, \mathcal{K}_U\}). \tag{3}$$

The optimal solution $\{\hat{\mathcal{K}}_D, \hat{\mathcal{K}}_U\}$ of (3) can be obtained by comparing the sum rate of all possible candidate sets. However, the optimal user selection algorithm based on exhaustive search has prohibitively high complexity. Thus, to reduce the search complexity, we provide an efficient user selection algorithm for the FD systems in the following section.

III. Low Complexity User Selection Algorithm

In this section, we propose a low complexity user selection algorithm for FD MU-MISO systems. As shown in (2), the sum rate of the FD systems is affected by the SI and the CCI, and thus the optimization problem in (3) requires a joint downlink and uplink user selection which incurs high search complexity. To tackle this problem, we employ a high SINR approximation for the sum rate of the FD system as

$$\begin{aligned} R_{FD} &\approx \sum_{i=1}^{M} \log_2 \left(\frac{P_{D_i} |\mathbf{h}_{D_i}^H \mathbf{w}_{D_i}|^2}{1 + \sum_{j=1}^{L} P_U |g_{j,i}|^2} \right) \\ &\quad + \sum_{j=1}^{L} \log_2 \left(1 + P_U \bar{\mathbf{h}}_{U_j}^H \left(\mathbf{I}_{N_r} + \sum_{m>j}^{L} P_U \bar{\mathbf{h}}_{U_m} \bar{\mathbf{h}}_{U_m}^H + \mathbf{H}_{SI} \mathbf{Q}_D \mathbf{H}_{SI}^H \right)^{-1} \bar{\mathbf{h}}_{U_j} \right) \\ &= \sum_{i=1}^{M} \log_2 \left(P_{D_i} |\mathbf{h}_{D_i}^H \mathbf{w}_{D_i}|^2 \right) \\ &\quad - \sum_{i=1}^{M} \log_2 \left(1 + \sum_{j=1}^{L} P_U |g_{j,i}|^2 \right) + \sum_{j=1}^{L} \log_2 \left(1 + P_U \bar{\mathbf{h}}_{U_j}^H \left(\mathbf{I}_{N_r} + \sum_{m>j}^{L} P_U \bar{\mathbf{h}}_{U_m} \bar{\mathbf{h}}_{U_m}^H + \mathbf{H}_{SI} \mathbf{Q}_D \mathbf{H}_{SI}^H \right)^{-1} \bar{\mathbf{h}}_{U_j} \right). \end{aligned} \tag{4}$$

We can see that the first term in (4) is associated with the performance of the HD system at high SNR regime and the other terms can be regarded as the attainable performance in the FD system with the given downlink users. For the case of the HD systems, it is worth noting that the successive user selection method in [8] shows negligible performance loss

[2] Receiver chains in radios are saturated if the input signal is beyond a particular level that is determined by their ADC resolution. It has been reported in many studies that analog cancellation in a FD system can provide a sufficient self-interference reduction [11], [25]. Thus, we assume that the possibility of the front-end saturation would be zero in this paper.

[3] In this paper, we refer to the downlink transmission only for the HD system, since the downlink channel and the uplink channel can achieve the same performance due to the downlink and uplink duality [7].

$$\Omega_U(\mathcal{K}_U) = \sum_{j=1}^{L} \log_2 \left(P_U \bar{\mathbf{h}}_{U_j}^H \left(\mathbf{I}_{N_r} + \sum_{m>j}^{L} P_U \bar{\mathbf{h}}_{U_m} \bar{\mathbf{h}}_{U_m}^H + \mathbf{H}_{SI} \mathbf{Q}_D \mathbf{H}_{SI}^H \right)^{-1} \bar{\mathbf{h}}_{U_j} \right) - \sum_{i=1}^{M} \log_2 \left(1 + \sum_{j=1}^{L} P_U |g_{j,i}|^2 \right). \tag{6}$$

compared to the opitmal user selection method [19]. From these observations, we develop the successive user selection method for the FD systems by leveraging the decomposed performance metrics in (4).

Then, we define the performance metric which will be adopted in choosing downlink users as

$$\Omega_D(\mathcal{K}_D) = \sum_{i=1}^{M} \log_2 \left(P_{D_i} |\mathbf{h}_{D_i}^H \mathbf{w}_{D_i}|^2 \right) \tag{5}$$

Similarly, the metric for selecting uplink users is defined as (6) which is shown in top of this page. Note that the performance metric in (6) requires the matrix inverse operation to compare every uplink user candidates. In order to reduce the complexity, we employ the Sherman-Morrison formula in [27] to compute the performance metric in (6). Then, we can rewrite the performance metric in (6) as

$$\Omega_U(\mathcal{K}_U) = \sum_{j=1}^{L} \log_2 \left(P_U \bar{\mathbf{h}}_{U_j}^H \Lambda_{L-j+1} \bar{\mathbf{h}}_{U_j} \right) - \sum_{i=1}^{M} \log_2 \left(1 + \sum_{j=1}^{L} P_U |g_{j,i}|^2 \right), \tag{7}$$

where

$$\Lambda_k = \Lambda_{k-1} - \frac{P_U \Lambda_{k-1} \bar{\mathbf{h}}_{U_{L-k+2}} \bar{\mathbf{h}}_{U_{L-k+2}}^H \Lambda_{k-1}}{1 + P_U \bar{\mathbf{h}}_{U_{L-k+2}}^H \Lambda_{k-1} \bar{\mathbf{h}}_{U_{L-k+2}}},$$

with $\Lambda_1 = (\mathbf{I}_{N_r} + \mathbf{H}_{SI} \mathbf{Q}_D \mathbf{H}_{SI}^H)^{-1}$. We can see that the inverse operation of Λ_k is carried out only once at $k = 1$.

Utilizing the performance metrics in (5) and (7), we propose a two step user selection algorithm which selects the downlink users followed by the uplink users as follows: The proposed algorithm performs a successive procedure initiated by choosing the downlink user with the maximum channel gain. After each downlink user is selected, a new downlink user will be chosen sequentially from the remaining user set until an addition of one more user reduces the downlink performance metric in (5). After the downlink users are determined, the uplink users are selected sequentially by using the uplink performance metric in (7). The whole process is summarized in Algorithm 1.[4]

Next, we compare the search complexity of our proposed user selection algorithm with the optimal user selection algorithm. First, the search complexity of the optimal user selection algorithm is calculated as follows: Considering the case of n selected downlink and m selected uplink users, the required number of candidates is $\binom{K}{n+m}$ to determine a selected user set among K users, and $\binom{n+m}{m}$ is needed to select the uplink users among the selected user set. Since $1 \leq n \leq N_t$ and $1 \leq m \leq N_r$, we can compute the search complexity of the optimal user selection algorithm as $\sum_{n=1}^{N_t} \sum_{m=1}^{N_r} \binom{K}{n+m} \binom{n+m}{m}$.

Algorithm 1 : Proposed User Selection Algorithm

Find a user $D_1 = \arg\max_{i \in \mathcal{K}} \|\mathbf{h}_i\|^2$
Set $\mathcal{S}_1^D = \{D_1\}$ and $M = 1$
For $M = 2 : N_t$
  Find a user $D_M = \arg\max_{i \in \mathcal{K} \setminus \mathcal{S}_{M-1}^D} \Omega_D(\mathcal{S}_{M-1}^D \cup \{i\})$
  Set $\mathcal{S}_M^D = \mathcal{S}_{M-1}^D \cup \{D_M\}$
  If $\Omega_D(\mathcal{S}_M^D) \leq \Omega_D(\mathcal{S}_{M-1}^D)$
    Set $M \leftarrow M - 1$ and break
  end
end
Find a user $U_1 = \arg\max_{i \in \mathcal{K} \setminus \mathcal{S}_M^D} \Omega_U(i)$
Set $\mathcal{S}_1^U = \{U_1\}$ and $L = 1$
For $L = 2 : N_r$
  Find a user $U_L = \arg\max_{i \in \mathcal{K} \setminus \{\mathcal{S}_{L-1}^U \cup \mathcal{S}_M^D\}} \Omega_U(\mathcal{S}_{L-1}^U \cup \{i\})$
  Set $\mathcal{S}_L^U = \mathcal{S}_{L-1}^U \cup \{U_L\}$
  If $\Omega_U(\mathcal{S}_L^U) \leq \Omega_U(\mathcal{S}_{L-1}^U)$
    Set $L \leftarrow L - 1$ and break
  end
end
Obtain $\hat{\mathcal{K}}_D = \mathcal{S}_M^D$ and $\hat{\mathcal{K}}_U = \mathcal{S}_L^U$

In contrast, the proposed user selection method successively chooses users, and this leads to the search complexity of $K + (K-1) + \cdots + (K - (N_t + N_r) + 1)$ in the worst case. Therefore, the search complexity of our proposed user selection algorithm is given by $\frac{1}{2}(2K - N_t - N_r + 1)(N_t + N_r)$. For instance, when $N_t = 2$, $N_r = 2$, and $K = 15$, the search candidates of the proposed algorithm and the optimal algorithm equal 50 and 11130, respectively. Thus, the proposed method achieves a significant complexity reduction compared to the optimal method. In Section V, we will confirm that the proposed user selection algorithm exhibits a small performance loss to the optimal one with much reduced complexity.

IV. Performance Analysis

In this section, we analyze the average sum rate performance of the proposed user selection algorithm for the FD MU systems. In general, the difficulty in analyzing the performance of successive user selection algorithms arises from the fact that a user selection procedure is dependent on the previous

[4]Our proposed user selection algorithm is easily extended to the case where a downlink user is selected and then a uplink user is chosen alternately. Since the system performance of this algorithm is comparable with the proposed algorithm, we omit it in this paper.

selection and this incurs a complicated joint PDF expression for the scheduled users' channel gain [8], [28]. For this reason, it is extremely hard to analyze the average performance of the successive user selection algorithms in general. For analytical simplicity, we focus on a special case of $M = L = 1$ (i.e., a single downlink user and a single uplink user are selected) in this section.[5]

When $M = L = 1$, we can rewrite the selected downlink and uplink users as

$$\hat{\mathcal{K}}_D = \arg\max_{k\in\mathcal{K}} ||\mathbf{h}_k||^2 \tag{8}$$

$$\hat{\mathcal{K}}_U = \arg\max_{k\in\mathcal{K}\setminus D_1} \frac{P_U \bar{\mathbf{h}}_k^H (\mathbf{I} + P_T \mathbf{H}_{SI}\mathbf{h}_{D_1}\mathbf{h}_{D_1}^H \mathbf{H}_{SI}^H)^{-1}\bar{\mathbf{h}}_k}{1 + P_U|g_{k,D_1}|^2}. \tag{9}$$

To evaluate the average sum rate performance, we first need to compute the PDF of $X_{\max} = \max_{k\in\mathcal{K}} X_k$ and $Y_{\max} = \max_{k\in\mathcal{K}\setminus D_1} Y_k$ where $X_k \triangleq ||\mathbf{h}_k||^2$ and $Y_k \triangleq \frac{P_U \bar{\mathbf{h}}_k^H (\mathbf{I}+P_T \mathbf{H}_{SI}\mathbf{h}_{D_1}\mathbf{h}_{D_1}^H \mathbf{H}_{SI}^H)^{-1}\bar{\mathbf{h}}_k}{1+P_U|g_{k,D_1}|^2}$. Note that $X_k = ||\mathbf{h}_k||^2$ is a chi-square random variable with N_t degree-of-freedom and its PDF and cumulative density function (CDF) are given by

$$f_{X_k}(x) = \frac{x^{N_t-1}\exp(-x)}{(N_t-1)!} \text{ and } F_{X_k}(x) = \frac{\gamma(N_t, x)}{(N_t-1)!}, \tag{10}$$

where $\gamma(M, \upsilon) = \int_0^{\upsilon} t^{M-1}\exp(-t)dt$ is the incomplete lower gamma function.

Also, from the order statistics property in [22], for arbitrary random variables Ψ_n, the PDF of $\Psi_{\max} = \max_{1\le n\le N}\Psi_n$ is calculated as $f_{\Psi_{\max}}(x) = N(F_{\Psi_n}(x))^{N-1} f_{\Psi_n}(x)$ where $F_{\Psi_n}(x)$ and $f_{\Psi_n}(x)$ denote the CDF and the PDF of Ψ_n, respectively. Combining these results, the PDF of $X_{\max}$ becomes

$$f_{X_{\max}}(x) = K\left(\frac{\gamma(N_t, x)}{(N_t-1)!}\right)^{K-1} \frac{x^{N_t-1}\exp(-x)}{(N_t-1)!}. \tag{11}$$

Next, we will derive the PDF of $Y_{\max}$. Computing the CDF of Y_k is very difficult due to the SI term in the numerator in (9). To allow tractable analysis, we assume $(\mathbf{I} + P_T \mathbf{H}_{SI}\mathbf{h}_{D_1}\mathbf{h}_{D_1}^H \mathbf{H}_{SI}^H)^{-1} \approx \frac{1}{1+P_T\sigma_{SI}^2}\mathbf{I}$, i.e., $\mathbf{H}_{SI}\mathbf{h}_{D_1}\mathbf{h}_{D_1}^H \mathbf{H}_{SI}^H = \sigma_{SI}^2\mathbf{I}$. We will confirm from the simulation results that this assumption does not affect the system performance. Then, we obtain the PDF of $Y_{\max}$ in the following lemma.

Lemma 1: The PDF of $Y_{\max}$ is derived as

$$\begin{aligned} &f_{Y_{\max}}(y) \\ &= (K-1)\left(1 - \sum_{i=0}^{N_r}\sum_{j=0}^{i} \frac{\omega_1^{j-i+1}}{\omega_2^{j-i}(i-j)!}\frac{y^i\exp(-\frac{\omega_1}{\omega_2}y)}{(y+\omega_1)^{j+1}}\right)^{K-2} \\ &\quad\times\Bigg(\sum_{i=0}^{N_r}\sum_{j=0}^{i} \frac{\omega_1^{j-i+1}}{\omega_2^{j-i}(i-j)!}\frac{y^{i-1}\exp(-\frac{\omega_1}{\omega_2}y)}{(y+\omega_1)^{j+1}} \\ &\qquad\qquad\times\Big(-i + \frac{\omega_1}{\omega_2}y + \frac{(j+1)y}{y+\omega_1}\Big)\Bigg). \end{aligned} \tag{12}$$

[5]Due to the analytical difficulty, the analysis to general K user cases remains as a future work.

Proof: By assuming $(\mathbf{I} + P_T \mathbf{H}_{SI}\mathbf{h}_{D_1}\mathbf{h}_{D_1}^H \mathbf{H}_{SI}^H)^{-1} \approx \frac{1}{1+P_T\sigma_{SI}^2}\mathbf{I}$, Y_k can be expressed as

$$Y_k = \frac{\frac{P_U}{1+P_T\sigma_{SI}^2}||\bar{\mathbf{h}}_k||^2}{P_U|g_{k,\hat{K}_D}|^2+1} = \frac{\omega_1 X}{Z+\omega_2},$$

where $\omega_1 \triangleq \frac{1}{1+P_T\sigma_{SI}^2}$, $\omega_2 \triangleq \frac{1}{P_U}$, X and Z are chi-square random variables with N_r and 2 degree-of-freedoms, respectively. The CDF of X and the PDF of Z are given by $F_X(x) = \frac{\gamma(N_r,x)}{(N_r-1)!}$ and $f_Z(z) = \exp(-z)$, respectively.

Employing the results, the CDF of Y_k can be obtained by

$$\begin{aligned} F_{Y_k}(y) &= Pr(Y_k < y) \\ &= \int_0^{\infty} Pr\left(X < \left(\frac{z+\omega_2}{\omega_1}\right)y\right) f_Z(z)dz \\ &= 1 - \sum_{i=0}^{N_r}\sum_{j=0}^{i}\frac{\omega_1^{j-i+1}}{\omega_2^{j-i}(i-j)!}\frac{y^i\exp(-\frac{\omega_1}{\omega_2}y)}{(y+\omega_1)^{j+1}}. \end{aligned} \tag{13}$$

Applying the order statistics to (13), the PDF of $Y_{\max}$ can be computed as in (12), and then the proof is completed. ■

Adopting the derived PDFs in (11) and (12), we can obtain the average sum rate of the proposed user selection algorithm for the FD MU-MISO systems. From (4), the sum rate R_{FD} at high SINR is expressed as

$$\begin{aligned} R_{FD} &\approx \log_2(P_T||\mathbf{h}_{D_1}||^2) \\ &\quad + \log_2\left(\frac{P_U\bar{\mathbf{h}}_{U_1}^H(\mathbf{I}+P_T\mathbf{H}_{SI}\mathbf{h}_{D_1}\mathbf{h}_{D_1}^H\mathbf{H}_{SI}^H)^{-1}\bar{\mathbf{h}}_{U_1}}{1+P_U|g_{U_1,D_1}|^2}\right), \end{aligned}$$

and, the average sum rate becomes $\mathbb{E}[R_{FD}]$.

Then, the average sum rate at high SINR can be computed as

$$\begin{aligned} \mathbb{E}[R_{FD}] \approx &\int_0^{\infty}\log_2(P_T x) f_{X_{\max}}(x)dx \\ &+ \int_0^{\infty}\log_2(x) f_{Y_{\max}}(x)dx. \end{aligned} \tag{14}$$

By utilizing the multinomial theorem and evaluating the integral from the standard identities in [29], the average sum rate in (14) can be directly calculated. However, this approach incurs high computational complexity when the number of users K is large. To reduce the computational complexity, we will apply tight approximations to the average sum rate in (14).

For a random variable Z with the CDF $F_Z(x)$ and the largest order statistic Z_K, the following approximation [30] holds as

$$E[Z_K] \approx F_Z^{-1}\left(\frac{1}{1+\exp(-\sum_{i=1}^{K-1}\frac{1}{i})}\right),$$

where F^{-1} indicates the inverse function of F. Note that this approximation has been shown to be tight for a Gaussian distribution [22].

Applying this result and Jensen's inequality, we can obtain

$$\mathbb{E}[R_{FD}] \approx \log_2(P_T\psi) + \log_2(\xi), \tag{15}$$

where $\psi = F_{X_k}^{-1}(\frac{1}{1+\exp(-\sum_{i=1}^{K-1}\frac{1}{i})})$ and $\xi = F_{Y_k}^{-1}(\frac{1}{1+\exp(-\sum_{i=1}^{K-2}\frac{1}{i})})$. To compute (15), we still require the inverse functions of $F_{X_k}(x)$ and $F_{Y_k}(x)$ in ψ and ξ, respectively. Unfortunately, due to the complicated form of the CDFs $F_{X_k}(x)$ and $F_{Y_k}(x)$, it is difficult to compute the inverse CDFs. Therefore, in order to evaluate ψ, we employ a simple numerical algorithm in [23] as

$$\psi_{j+1} = \log_e(N(K)) + \log_e(1 - F_{X_k}(\psi_j)) + \psi_j, \quad (16)$$

where ψ_j is the j-th iteration value with an initial iteration value $\psi_0 = 1$ and $N(K) = 1 + \exp(\sum_{i=1}^{K-1}\frac{1}{i})$.

In a similar way in (16), ξ can be determined with the following update algorithm

$$\xi_{j+1} = \log_e(N(K-1)) + \log_e(1 - F_{Y_k}(\xi_j)) + \xi_j, \quad (17)$$

where ξ_j is the j-th iteration value with $\xi_0 = 1$. Note that the algorithms in (16) and (17) converge, since additional iterations result in additional nested logarithms [23]. In addition, we have confirmed from the simulations that the numerical algorithms in (16) and (17) converge quite rapidly. For example, the algorithms converge within a few iterations when $N_t = N_r = 2$, $P_T = P_U = 5$ dB, and $K = 10$.

Let us denote ψ_{conv} and ξ_{conv} as the converged values from the numerical algorithms in (16) and (17), respectively. Substituting the results into (15), we finally derive an approximation for average sum rate of the proposed user selection algorithm as

$$\mathbb{E}[R_{FD}] \approx \log_2(P_T \psi_{conv}) + \log_2(\xi_{conv}). \quad (18)$$

The result in (18) can be calculated efficiently, and thus provides helpful guidelines for designing the FD MU-MISO systems. In Section V, we will confirm that the analytical result in (18) matches well with the Monte-Carlo simulations in the practical SNR range. From now on, we will investigate the average sum rate performance of the proposed user selection algorithm in the large K regime.

Theorem 1: For a large K, the average sum rate for the FD MU-MISO systems with the proposed algorithm is given by

$$\begin{aligned}\mathbb{E}[R_{FD}] &= 2\log_2(\log_e K) + \log_2 P_T + \log_2\left(1 - \frac{\log_e((N_t-1)!)}{\log_e K}\right) \\ &\quad + \log_2\left(1 + \frac{1}{\log_e K}\left(1 + (2-N_r)\log_e \frac{P_U}{1+P_T\sigma_{SI}^2}\right.\right. \\ &\quad \left.\left. - \log_e(P_U(N_r-1)!) - \frac{1+P_T\sigma_{SI}^2}{P_U}\right)\right). \quad (19)\end{aligned}$$

Proof: By applying the result from order statistics [22] to (15), the average sum rate in (15) for large K becomes

$$\begin{aligned}\mathbb{E}[R_{FD}] \approx \log_2\left(P_T F_{X_k}^{-1}\left(\frac{K}{K+1}\right)\right) \\ + \log_2\left(F_{Y_k}^{-1}\left(\frac{K-1}{K}\right)\right). \quad (20)\end{aligned}$$

This implies that for large K, we need only consider the CDFs $F_{X_k}(x)$ and $F_{Y_k}(x)$ in the high x regime since the input term in the inverse functions in (20) approaches one.

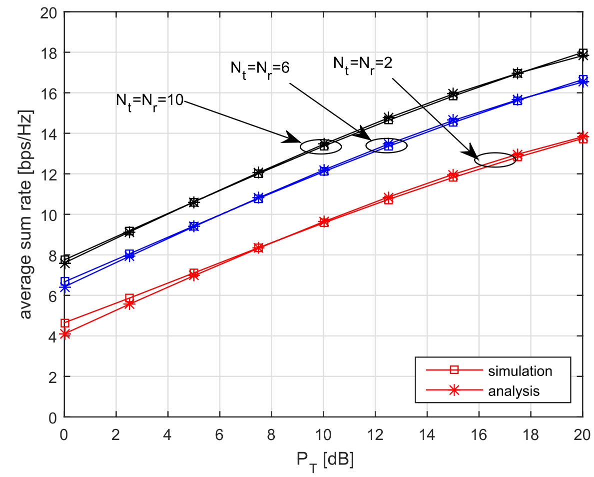

Fig. 2. Average rate performance comparison as a function of P_T for FD MU-MISO systems.

By examining the expression for the largest exponent of x, we can rewrite the CDFs of X_k in (10) and Y_k in (13) as

$$F_{X_k}(x) = 1 - \exp(-x)\frac{x^{N_t-1}}{(N_t-1)!}, \quad (21)$$

$$F_{Y_k}(x) = 1 - \exp\left(-\frac{\omega_1}{\omega_2}x\right)\frac{\omega_1^{2-Nr}}{\omega_2^{1-Nr}(N_r-1)!}x^{N_r-2}, \quad (22)$$

where (21) comes from the fact that the lower incomplete gamma function $\gamma(N_t, x)$ in (10) can be rewritten by $(1 - \exp(-x)(\sum_{m=0}^{N_t-1}\frac{x^m}{m!}))(N_t-1)!$ [29].

Also, the terms $F_{X_k}^{-1}\left(\frac{K}{K+1}\right)$ and $F_{Y_k}^{-1}\left(\frac{K-1}{K}\right)$ in (20) can be solved by substituting $N(K) = K + 1$ and $N(K-1) = K$ into the iterations in (16) and (17), respectively. As K becomes large, no iteration is required in both algorithms, since more iterations would produce nested log terms which have a negligible effect [23]. After some manipulations, we finally obtain the average sum rate for large K as in (19). This concludes the proof. ■

The above result shows that the proposed user selection algorithm for the FD MU-MISO systems can achieve a scaling law of $2\log(\log K)$. Then, it can be seen that our user selection algorithm for the FD systems provides twice higher scaling law than the time-division-multiple-access scheme for HD MU-MISO systems which achieves a scaling law of $\log(\log K)$ in [9]. With this large K analysis, we demonstrate that the FD MU systems is efficient in terms of the scaling law compared to the HD MU systems. In the following section, we will confirm that the analysis of the scaling law in (19) agrees well with the Monte-Carlo simulations.

V. Simulation Results

In this section, we compare the average sum rate performance of the FD systems with the proposed user selection algorithm to the conventional HD systems with the optimal user selection algorithm. For simulation, we set $\kappa = 1$ and $\bar{\mathbf{H}}_{SI}$ as a matrix of all ones as in [14]. From Fig. 2 to Fig. 4, we assume that the SI power for $\mathbf{H}_{SI}$ is fixed as $\sigma_{SI}^2 = -25$ dB

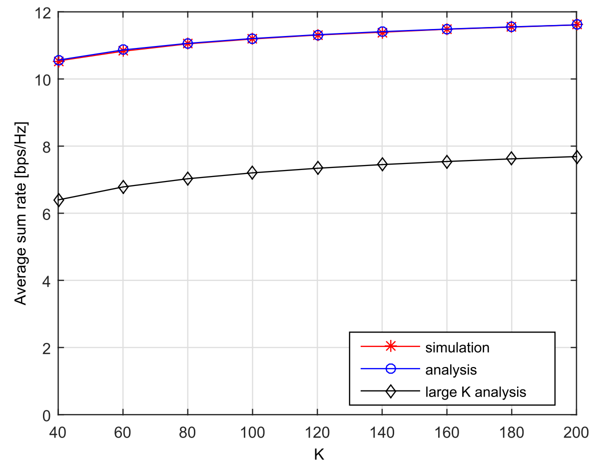

Fig. 3. Average rate performance comparison as a function of K for FD MU-MISO systems.

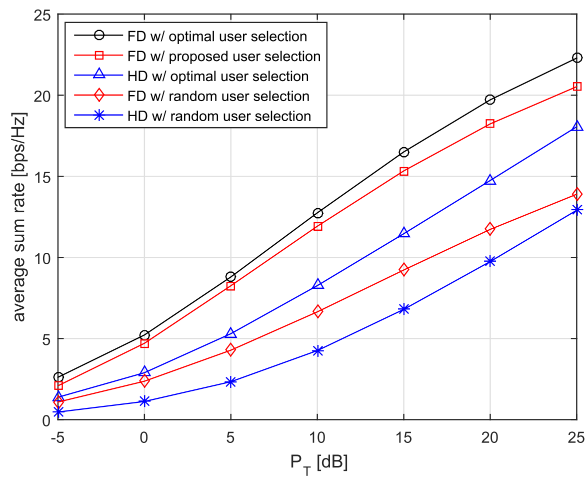

Fig. 4. Average sum rate performance comparison as a function of P_T for MU-MISO systems.

and the transmit power at uplink users is set to $P_U = \frac{P_T}{L}$ for fairness between the downlink and the uplink performance.

Fig. 2 exhibits the average rate performance by comparing the Monte-Carlo simulation with the analysis in (18) when $M = L = 1$. First the analytical result in (18) for the FD systems with the proposed user selection algorithm agrees will with the simulation for high SNR, since the analytical result is obtained with a high SINR approximation. Also, we can see that our analysis is quite accurate over various N_t and N_r.

Next, in order to verify our large K analysis in (19), Fig. 3 shows the average rate performance with respect to K for $N_t = N_r = 2$. In this plot, it is observed that the average sum rates for the FD systems increase as the number of users becomes larger due to multiuser diversity [20], [31]. Comparing the slope of the curves in the figure, it can be seen that our analytical result in (19) predicts the scaling law of the proposed user selection algorithm. Also, we can check that our analysis in (18) is well matched with the simulation.

Fig. 4 demonstrates the average rate performance with respect to P_T for $N_t = N_r = 2$ and $K = 15$. Also, we compare the average rate performance for the FD and the HD systems with a random user selection algorithm where users are chosen at random. In this plot, we can see that a proper

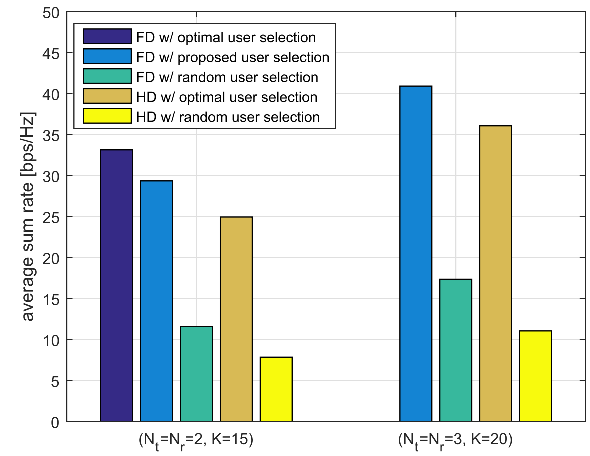

Fig. 5. Average sum rate performance comparison for MU-MISO systems in realistic channels.

TABLE I

SIMULATION PARAMETERS FOR THE REALISTIC CHANNEL MODEL

Carrier frequency	2 GHz
System bandwidth	10 MHz
Cell radius	173 m
Thermal noise	-174 dBm/Hz
Tx power	24 dBm
Rx power	23 dBm
Receiver noise figure (at BS)	5 dB
Receiver noise figure (at downlink users)	9 dB
Path loss model [dB]	$PL_{\text{LOS}} = 103.8 + 20.9 \log_{10} d$, $PL_{\text{NLOS}} = 145.4 + 37.5 \log_{10} d$,

choice of users provides a substantial performance gain. It is worthwhile to note that the proposed user selection algorithm for the FD systems achieves a significant complexity reduction of 99.6% compared to the optimal user selection algorithm, considering that of the number of the search candidates of the proposed algorithm and the optimal algorithm are 50 and 11130, respectively. Nevertheless, the proposed algorithm shows a small performance loss of 7.5% at $P_T = 20$ dB. Also, the FD systems with the proposed user selection algorithm provide a performance improvement of 24% at $P_T = 20$ dB over the HD systems with the optimal user selection algorithm.

So far, we have assumed that the channels $\mathbf{h}_{D_i}$, $\bar{\mathbf{h}}_{U_i}$, and $g_{j,i}$ are i.i.d. complex Gaussian distributed with zero mean and unit variance. Next, we compare the performance of the user selection algorithms for a more realistic channel model which adopts the 3GPP LTE specifications for small cell deployments as in [14]. Users are randomly generated and placed uniformly with the cell radius. Also, the channels are replaced by $\sqrt{\gamma_{D_i}}\mathbf{h}_{D_i}$, $\sqrt{\gamma_{U_i}}\bar{\mathbf{h}}_{U_i}$, and $\sqrt{\gamma_{j,i}}g_{j,i}$ where $\gamma_{(\cdot)}$ denotes the path loss in [32]. Here, $\gamma_{(\cdot)} = 10^{-PL/10}$ is calculated from the path loss model in Table I where the path loss model PL can be either line-of-sight (LOS) or non LOS (NLOS) according to the probability of LOS as follows:

$$P_{\text{LOS}} = 0.5 - \min\left(0.5, 5\exp\left(-\frac{0.156}{d}\right)\right) + \min\left(0.5, 5\exp\left(-\frac{d}{0.03}\right)\right),$$

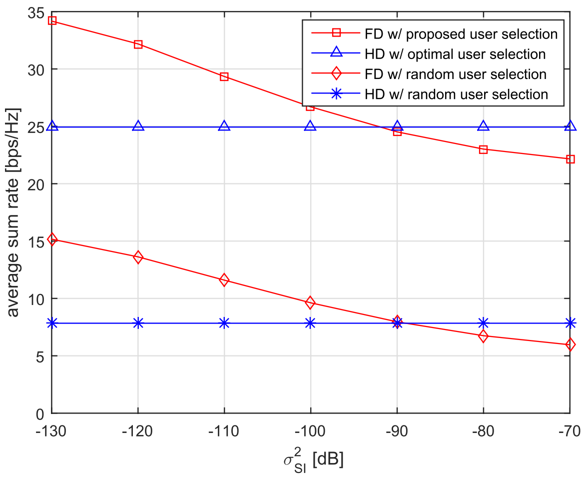

Fig. 6. Average sum rate performance comparison as a function of σ_{SI}^2 for MU-MISO systems in realistic channels.

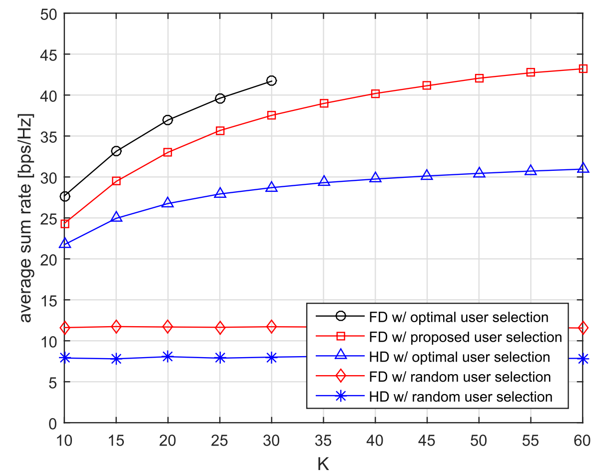

Fig. 7. Average sum rate performance comparison as a function of K for MU-MISO systems in realistic channels.

where d is the distance (in kilometers). In this scenario, the SI power is assumed to be $\sigma_{SI}^2 = -110$ dB as in [14] and other parameters are listed in Table I.

Fig. 5 illustrates the average sum rate performance for two different system configurations in the realistic channel model. The performance of the FD systems with the optimal user selection scheme is plotted only for the system with $N_t = N_r = 2$, $K = 15$ due to long simulation time. Similar to the Rayleigh fading channel case in Fig. 4, we can observe that the systems with a proper user selection scheme show a large performance gain over the systems with random user selection. In particular, the FD systems with the proposed algorithm exhibit a throughput gain of 18% and 13% over the HD systems with the optimal user selection algorithm.

In Fig. 6, we present the average sum rate performance with various SI power σ_{SI}^2 for $N_t = N_r = 2$ to evaluate the effect of the SI on the FD systems. It is seen that a performance gain of the proposed user selection algorithm is 29% over the conventional HD system at $\sigma_{SI}^2 = -120$ dB. As expected, this performance gap between the FD system and the conventional HD system is increased as the SI power becomes smaller. The plot shows that the SI power should be less than -93 dB to guarantee a performance advantage of the FD systems over the HD systems, and this can be achieved by adopting a practical SI cancellation technique in [11] and [25].

Fig. 7 illustrates the average sum rate performance with various K for $N_t = N_r = 2$. The performance of the FD systems with the optimal user selection scheme is plotted only for $K \leq 30$ due to long simulation time. Our proposed user selection scheme for the FD systems exhibits a significant performance gain over the optimal user selection scheme for the HD systems. In addition, we can check that for a large K, the slope of our proposed user selection scheme for the FD systems is identical to that of the optimal user selection scheme for the FD systems. Throughout the simulations, we confirm that our proposed user selection algorithm is efficient for FD MU-MISO systems.

VI. Conclusion

In this paper, we have proposed a low complexity user selection algorithm for FD MU-MISO systems. Due to SI and CCI for the FD MU-MISO systems, the joint downlink and uplink user selection problem requires high search complexity. In order to make the problem more tractable, we have decomposed the sum rate for the FD systems into a sum of two performance metrics. Based on the decomposed metrics, we have provided a successive user selection algorithm which achieves a significant complexity reduction compared to the optimal user selection algorithm. Also, we have analyzed the average rate performance of our proposed user selection algorithm. The analytical result has been derived as a tight approximation of the system performance which is calculated efficiently. Moreover, we have provided the large number of users analysis which predicts the scaling law of the proposed user selection algorithm. From numerical results, we have confirmed that our analytical results match well with the simulation results, and the proposed user selection algorithm for the FD MU systems exhibits only a small performance loss compared to the optimal user selection algorithm with much reduced complexity. Extending the joint user selection, power allocation and even optimized beamforming design remains as an interesting future work.

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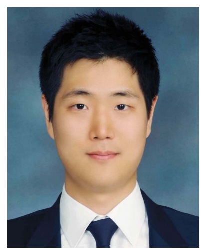

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