An Efficient User Selection Technique for Full-Duplex MU-MISO Systems

Minki Ahn*, Han-Bae Kong†, Hun Min Shin*, Hoon Lee* and Inkyu Lee*

*School of Electrical Eng., Korea University, Seoul, Korea
†School of Computer Eng., Nanyang Technological University, Singapore
Email: *{amk200, semo0617, hun1, inkyu}@korea.ac.kr, †hbkong@ntu.edu.sg

***Abstract*—In this paper, we propose a new user selection algorithm for full-duplex (FD) multiuser multiple-input single-output (MU-MISO) systems where a FD base station (BS) communicates with multiple half-duplex (HD) 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. From the numerical results, we confirm that the proposed user selection algorithm for the FD MU systems exhibits a small performance loss compared to the optimal user selection algorithm with much reduced complexity.**

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 [1]–[3]. The MU-MIMO systems support multiple users and improve spectral efficiency by exploiting spatial multiplexing [4]. It is well known that dirty paper coding (DPC) can achieve the capacity region of the MU-MIMO systems [5] [6]. 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 [7] [8].

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 [9]–[14]. 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 [9] and [15] that the SI can be efficiently suppressed by using advanced SI cancellation techniques.

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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 [11]–[13]. Specifically, in [12], iterative beamforming methods were provided to improve the spectral efficiency of the FD MU-MISO systems. Extending this result, the authors in [13] have proposed beamforming schemes for the practical scenario where co-channel interference (CCI) among users exists. However, all these works in [11]–[13] do not consider the systems with a large number of users. As in the case of the HD MU systems [16]–[18], 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.

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 $\mathbf{I}_N$.

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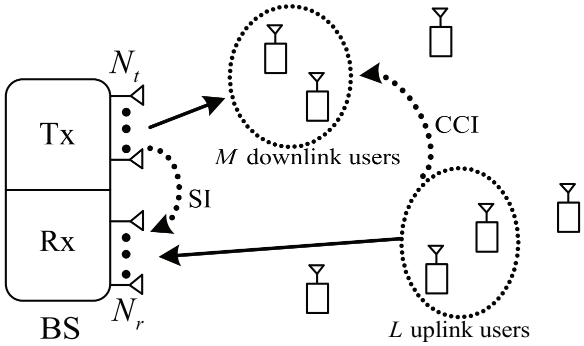

Fig. 1. System description for FD MU-MISO systems

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. 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.

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

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

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 [7]. 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

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

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 [9]. 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 [13].

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. By treating the SI as the background noise, the rate of the uplink channel is given by

$$\begin{aligned} R_U = \sum_{j=1}^{L} \log_2 \Bigg(1 + P_U \bar{\mathbf{h}}_{U_j}^H \\ \times (\mathbf{I}_{N_R} + \sum_{m>j}^{L} P_U \bar{\mathbf{h}}_{U_m} \bar{\mathbf{h}}_{U_m}^H + \mathbf{H}_{SI} \mathbf{Q}_D \mathbf{H}_{SI}^H)^{-1} \bar{\mathbf{h}}_{U_j} \Bigg), \end{aligned}$$

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

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

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.[1] 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

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

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

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

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 [7] can achieve the performance of the opitmal user selection method [16]. 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 two performance metrics which will be adopted in choosing downlink users and uplink users as

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

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

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 [19] to compute the performance metric in (6). Then, we can rewrite the performance metric in (6) as

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

where

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

with $\mathbf{\Lambda}_1 = (\mathbf{I}_{N_R} + \mathbf{H}_{SI}\mathbf{Q}_D\mathbf{H}_{SI}^H)^{-1}$. We can see that the inverse operation of $\mathbf{\Lambda}_k$ is carried out only once at $k=1$.

Algorithm 1 : Proposed user selection algorithm

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

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

[1] 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 [6].

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.[2]

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 $\sum_{n=1}^{N_t} \sum_{m=1}^{N_r} \binom{K}{n+m}\binom{n+m}{m}$.

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 IV, we will confirm that the proposed user selection algorithm exhibits a small performance loss to the optimal one with much reduced complexity.

IV. 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. We assume that the transmit power at uplink users is set to $P_U = \frac{P_T}{L}$ for fairness between the downlink and the uplink performances. Also, we set $\kappa = 1$ and $\bar{\mathbf{H}}_{SI}$ to be the matrix of all ones. From Fig. 2 to Fig. 3, the SI power for $\mathbf{H}_{SI}$ is fixed as $\sigma_{SI}^2 = -30$ dB, as in [9] and [13].

Fig. 2 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 without user selection. It is observed that without user selection, the FD systems outperform the conventional HD systems since the FD systems exploit the additional spatial multiplexing at the uplink channel. We can see that the systems with user selection schemes provide a significant performance gain over the systems without user selection. 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 since 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 27% at $P_T = 20$ dB over the HD systems with the optimal user selection algorithm.

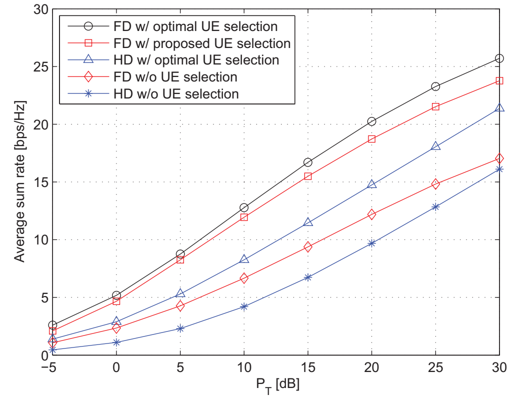

Fig. 2. Average sum rate performance comparison as a function of P_T for MU-MISO systems

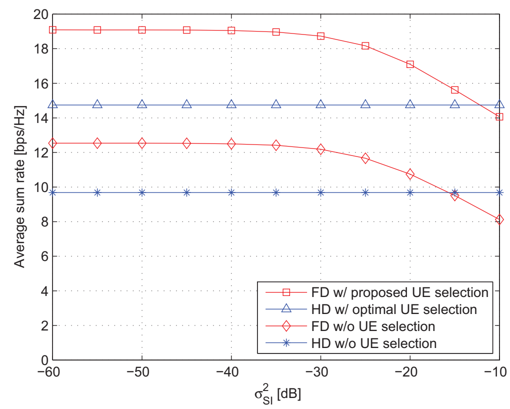

Fig. 3. Average sum rate performance comparison as a function of σ_{SI}^2 for MU-MISO systems

In Fig. 3, we present the average sum rate performance with various SI power σ_{SI}^2 for $N_t = N_r = 2$ and $P_T = 20$ dB to evaluate the effect of the SI on the performance of the FD systems. It is seen that a performance gain of the proposed user selection algorithm is 30% over the conventional HD system at $\sigma_{SI}^2 = -45$ dB. As can be expected, this performance gap between the FD system and the conventional HD system is increased as the SI power becomes smaller. Also, we can observe that the proposed user selection algorithm for the FD systems provides a larger user selection gain compared to the HD systems. The plot shows that the SI power should be less than -12.5 dB to guarantee a performance advantage of the

[2]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.

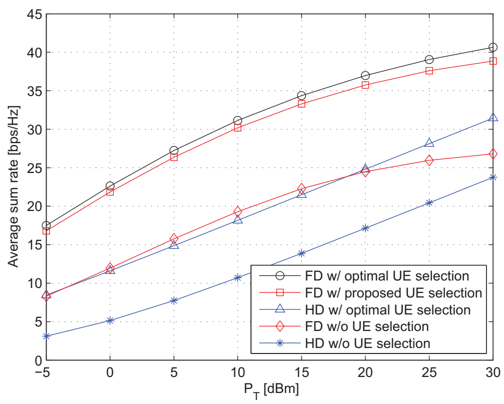

Fig. 4. Average sum rate performance comparison for MU-MISO systems in the realistic channel

FD systems over the HD systems, and this can be achieved by adopting a SI cancellation technique in [13]. Also, we can see that $\sigma_{SI}^2 = -40$ dB is sufficient to achieve the performance of the perfect SI cancellation case.

Until now, the channels $\mathbf{h}_{D_i}$, $\bar{\mathbf{h}}_{U_i}$, and $g_{j,i}$ are assumed to be 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. In this scenario, the SI power is assumed to be $\sigma_{SI}^2 = -100$ dB and other parameters are set as in [13].

Fig. 4 illustrates the average sum rate performance with respect to P_T for $N_t = N_r = 2$ and $K = 15$ in the realistic channel model. Similar to the Rayleigh fading channel in Fig. 2, we can observe that the systems with user selection show a large performance gain over the systems without user selection. In particular, the proposed user selection scheme exhibits a performance loss of 3.3% at $P_T = 20$ dBm compared to the optimal user selection scheme for the FD systems. In addition, the FD systems with the proposed algorithm show a throughput gain of 44% at $P_T = 20$ dBm over the HD systems with the optimal user selection algorithm. Throughout the simulations, we confirm that our proposed user selection algorithm is efficient for FD MU-MISO systems.

V. 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. The sum rate for the FD systems has been decomposed 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. From numerical results, we have confirmed that the proposed user selection algorithm for the FD MU systems exhibits a small performance loss compared to the optimal user selection algorithm with much reduced complexity.

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