Antenna Selection Schemes in Bidirectional Full-Duplex MIMO Systems

Seokju Jang, Minki Ahn, Hoon Lee, and Inkyu Lee, *Fellow, IEEE*

***Abstract*—In this paper, we investigate antenna selection (AS) methods for bidirectional (BD) full-duplex multiple-input–multiple-output (MIMO) systems in which antennas at each node can be selected to either transmit or receive. In this configuration, we first analyze the average sum rate of the optimal AS scheme that finds the best antenna set solution by examining all the possible candidates. The result provides insight into which transmit and receive antenna configuration improves the average sum-rate performance of the AS scheme. Then, we present a new AS algorithm that achieves near-optimal sum-rate performance with much reduced complexity compared with the optimal AS scheme. From simulation results, we verify that our sum-rate analysis for the optimal AS scheme matches the numerical results and confirm that, by employing the proposed AS algorithm, a performance gain of 15% is achieved.**

***Index Terms*—Antenna selection (AS), full-duplex (FD), multiple-input multiple-output (MIMO).**

I. Introduction

Full-duplex (FD) communication systems have attracted much attention because they can provide better spectral efficiency than conventional half-duplex (HD) systems [1]. Since the FD protocol performs transmission and reception on the same frequency band at the same time, the performance may be degraded by self-interference (SI) generated from each node's own transmit antennas. Several recent studies described SI cancelation techniques and demonstrated the feasibility of FD systems experimentally [2], [3].

Based on these results, the FD protocol has been adopted in various network environments, such as relay systems [4] and bidirectional (BD) systems [5], [6], in which two radios communicate directly with each other. Specifically, in [5], upper and lower bounds were derived on the achievable sum rate, and then a transmission scheme based on the maximization of the sum-rate lower bound was proposed for BD FD systems. In addition, precoding methods that maximize the sum rate for BD FD systems were provided in [6].

In the meantime, multiple-input–multiple-output (MIMO) wireless systems have been widely studied to increase communication reliability and spectral efficiency [7]–[9]. Among several schemes for MIMO systems, antenna selection (AS) methods have been considered promising for improving system performance [10]. Many studies have reported adoption of the AS method in FD systems [11], [12]. The authors in [11] and [12] introduced a transmit–receive AS method for BD FD systems, assuming that each antenna can be set to transmit or receive. In particular, in [11], AS schemes that select a single transmit antenna and a single receive antenna for systems with two antennas at each node were provided. Extending this result, AS methods were proposed in [12] for multiple-antenna systems with more than two antennas at each node. However, the schemes in [11] and [12] were limited to single-stream transmission environments in which a single transmit and receive radio-frequency (RF) chain is deployed at each node; therefore, they are not easy to apply to general multiple-stream cases.

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S. Jang, H. Lee, and I. Lee are with the School of Electrical Engineering, Korea University, Seoul 136-701, South Korea (e-mail: seokju@korea.ac.kr; ihun1@korea.ac.kr; inkyu@korea.ac.kr).

M. Ahn is with LG Electronics, Seoul 150-721, South Korea (e-mail: minki.ahn@lge.com).

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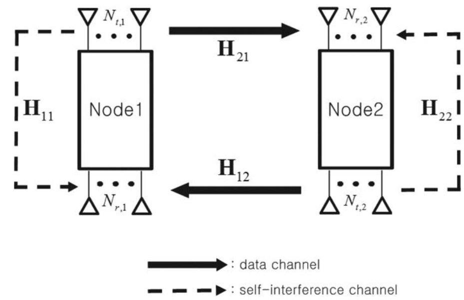

Fig. 1. BD FD MIMO system model.

In this paper, we investigate an AS method for BD FD MIMO systems in which each node has multiple transmit and receive antennas to improve the sum-rate performance. Unlike the works in [11] and [12], this paper considers a general multiple-stream transmission scenario in which each node has more than two RF chains. To provide an efficient AS method, we first analyze the average sum rate of the optimal AS scheme that selects the best antenna set by conducting an exhaustive search. The result provides insight into which transmit and receive antenna configuration maximizes the average sum-rate performance. Then, we propose a new AS algorithm that reduces the search complexity compared with that of the optimal AS scheme. Finally, simulation results confirm that our derived analysis matches the numerical simulations well. In addition, it is shown that the proposed AS algorithm provides near-optimal sum-rate performance and outperforms a conventional BD FD systems.

This paper is organized as follows. Section II describes BD FD MIMO systems. In Section III, we analyze the average sum-rate performance of BD FD systems with the optimal AS scheme. Then, a low-complexity AS algorithm is proposed in Section IV. Section V presents the simulation results, and Section VI concludes this paper.

Throughout this paper, the following notation is used. Uppercase boldface, lowercase boldface, and normal letters represent matrices, vectors, and scalars, respectively. The operators $(\cdot)^H$, $\mathbb{E}[\cdot]$, and $\lceil\cdot\rceil$ stand for the conjugate transpose, expectation, and ceiling operation on the real value, respectively. Further, $|\cdot|$ and $\mathbf{I}_n$ indicate the determinant of a matrix and an $n \times n$ identity matrix, respectively.

II. System Model

As shown in Fig. 1, we consider BD FD MIMO systems in which two FD nodes transmit and receive signals on the same frequency band at the same time. It is assumed that each antenna can be set to either transmit or receive, as in [11]. Let us define a set of antennas at node i $(i = 1, 2)$ as $\mathcal{N}_i = \{1,2,\ldots,N_i\}$, where N_i represents the total number of antennas at node i. The sets of transmit and receive antennas at node i are denoted $\mathcal{T}_i \subset \mathcal{N}_i$ and $\mathcal{R}_i \subset \mathcal{N}_i$, respectively, and the numbers of transmit and receive antennas at node i are represented by $N_{t,i}$ and $N_{r,i}$, respectively, with $N_{t,i} + N_{r,i} = N_i$. Further, we use the notation $\mathcal{S} = \{\mathcal{T}_1, \mathcal{T}_2, \mathcal{R}_1, \mathcal{R}_2\}$ to indicate a certain antenna set selection candidate and denote $\mathcal{A}$ to represent the set of all possible antenna set candidates $\mathcal{S}$. The channel from node $\bar{i}$ to node i for a given $\mathcal{S}$ is modeled as $\mathbf{H}_{i\bar{i}}(\mathcal{S}) \in \mathbb{C}^{N_{r,i}\times N_{t,\bar{i}}}$ with $\bar{1} = 2$ and $\bar{2} = 1$, and the SI channel at node i is denoted by $\mathbf{H}_{ii}(\mathcal{S}) \in \mathbb{C}^{N_{r,i}\times N_{t,i}}$.

Then, the received signal at node i is given by

$$\mathbf{y}_i(\mathcal{S}) = \sqrt{P_{\bar{i}}}\mathbf{H}_{i\bar{i}}(\mathcal{S})\mathbf{x}_{\bar{i}}(\mathcal{S}) + \sqrt{P_i}\mathbf{H}_{ii}(\mathcal{S})\mathbf{x}_i(\mathcal{S}) + \mathbf{n}_i(\mathcal{S}) \quad (1)$$

where $\mathbf{x}_i(\mathcal{S}) \in \mathbb{C}^{N_{t,i}\times 1}$ defines the transmitted signal for a given $\mathcal{S}$ with $\mathbb{E}\{\mathbf{x}_i(\mathcal{S})\mathbf{x}_i(\mathcal{S})^H\} = (1/N_{t,i})\mathbf{I}_{N_{t,i}}$. Further, $\mathbf{n}_i(\mathcal{S}) \in \mathbb{C}^{N_{r,i}\times 1}$ denotes the additive white Gaussian noise with covariance $\mathbb{E}\{\mathbf{n}_i(\mathcal{S})\mathbf{n}_i(\mathcal{S})^H\} = \sigma_n^2\mathbf{I}_{N_{r,i}}$, and P_i stands for the transmit power. In (1), the first term represents the desired signal, and the second term indicates the SI signal. Then, the achievable rate at node i for a given $\mathcal{S}$ can be written as

$$R_i(\mathcal{S}) = \log_2 \Big|\mathbf{I}_{N_{r,i}} + \gamma_{\bar{i}}\mathbf{H}_{i\bar{i}}(\mathcal{S})\mathbf{H}_{i\bar{i}}(\mathcal{S})^H \times \left(\sigma_n^2\mathbf{I}_{N_{r,i}} + \gamma_i\mathbf{H}_{ii}(\mathcal{S})\mathbf{H}_{ii}(\mathcal{S})^H\right)^{-1}\Big| \quad (2)$$

where $\gamma_i \triangleq (P_i/N_{t,i})$.

In this paper, we aim to design the antenna set $\mathcal{S}$ that maximizes the sum rate $R(\mathcal{S}) \triangleq R_1(\mathcal{S}) + R_2(\mathcal{S})$ of the BD FD MIMO systems. It is clear that the optimal AS solution $\mathcal{S}^* = \arg\max_{\mathcal{S}\in\mathcal{A}} R(\mathcal{S})$ can be obtained by an exhaustive search that examines all the antenna set candidates. The search complexity of the optimal AS scheme is calculated as

$$\begin{aligned}\hat{N}_c &\triangleq |\mathcal{A}| \\ &= \sum_{N_{t,1}=1}^{N_1-1}\sum_{N_{t,2}=1}^{N_2-1}\binom{N_1}{N_{t,1}}\binom{N_2}{N_{t,2}} \\ &= (2^{N_1}-2)(2^{N_2}-2). \end{aligned} \quad (3)$$

Because (3) increases exponentially as N_1 and N_2 grow, the complexity becomes prohibitive in practice. For this reason, in this paper, we present an efficient AS method that decreases the search complexity of the optimal AS scheme. To understand how to reduce the complexity, we first analyze the average sum rate of the optimal AS scheme in the following.

III. Performance Analysis of the Optimal AS Scheme

Here, we analyze the average sum rate of the optimal AS scheme $\bar{R}_{\text{opt}} \triangleq \mathbb{E}[R(\mathcal{S}^*)]$. For notational convenience, let us define $\mathcal{S}_j \in \mathcal{A}$ as the jth element of $\mathcal{A}$ for $j = 1, \ldots, \hat{N}_c$. Then, the average sum rate of the optimal AS scheme can be expressed as

$$\begin{aligned}\bar{R}_{\text{opt}} &= \mathbb{E}\left[\max_{j=1,\ldots,\hat{N}_c} R(\mathcal{S}_j)\right] \\ &\approx \mathbb{E}\left[\log_2\sum_{j=1}^{\hat{N}_c} 2^{R(\mathcal{S}_j)}\right] \quad (4) \\ &= \mathbb{E}\left[\log_2\sum_{j=1}^{\hat{N}_c}\prod_{i=1}^{2} D_i(\mathcal{S}_j)\right] \quad (5)\end{aligned}$$

where (4) comes from the max-log approximation, which is tight in the high-SNR regime [13], and $D_i(\mathcal{S}_j) \triangleq |\mathbf{I}_{N_{r,i}} + \gamma_{\bar{i}}\mathbf{H}_{i\bar{i}}(\mathcal{S}_j)\mathbf{H}_{i\bar{i}}(\mathcal{S}_j)^H(\sigma_n^2\mathbf{I}_{N_{r,i}} + \gamma_i\mathbf{H}_{ii}(\mathcal{S}_j)\mathbf{H}_{ii}(\mathcal{S}_j)^H)^{-1}|$.

Since (5) still has a complicated form, it is difficult to obtain any insight into the optimal AS scheme. Thus, by applying the relation between the arithmetic and geometric means to (5), we further derive (5) as

$$\begin{aligned}\bar{R}_{\text{opt}} &\approx \log_2\hat{N}_c + \mathbb{E}\left[\frac{1}{\hat{N}_c}\sum_{j=1}^{\hat{N}_c}\log_2\prod_{i=1}^{2}D_i(\mathcal{S}_j)\right] \\ &= \log_2\hat{N}_c + \mathbb{E}\left[\frac{1}{\hat{N}_c}\sum_{j=1}^{\hat{N}_c}\{R_1(\mathcal{S}_j) + R_2(\mathcal{S}_j)\}\right] \\ &= \log_2\hat{N}_c + \bar{R}_{\text{conv}} \end{aligned} \quad (6)$$

where $\bar{R}_{\text{conv}} \triangleq \mathbb{E}[(1/\hat{N}_c)\sum_{j=1}^{\hat{N}_c} R(\mathcal{S}_j)]$ represents the average sum rate of conventional BD FD systems that select an antenna set randomly over $\hat{N}_c$ candidates. From (6), we conclude that the optimal AS scheme provides an average sum-rate performance gain of $\log_2\hat{N}_c$ compared with conventional BD FD systems. Note that this average sum-rate gain is independent of the SI power and increases as the number of antennas N_i grows. In Section V, we will verify that this observation is valid in the high-SNR regime. Moreover, note that (6) is independent of the channel statistics; thus, these results are also valid in a general correlated channel scenario.

When the number of transmit and receive antennas is given, i.e., $N_{t,i}$ and $N_{r,i}$ for $i = 1, 2$ are fixed, we can rewrite (6) as

$$\bar{R}_{\text{opt}}(N_{t,i}, N_{r,i}) \approx \log_2 N_c(N_{t,i}, N_{r,i}) + \bar{R}_{\text{conv}}(N_{t,i}, N_{r,i}) \quad (7)$$

where $\bar{R}_{\text{opt}}(N_{t,i}, N_{r,i})$ and $\bar{R}_{\text{conv}}(N_{t,i}, N_{r,i})$ denote the average sum rate of BD FD systems with the optimal AS scheme and conventional BD FD systems for a given $N_{t,i}$ and $N_{r,i}$, respectively, and $N_c(N_{t,i}, N_{r,i}) = \binom{N_{t,1}+N_{r,1}}{N_{t,1}}\binom{N_{t,2}+N_{r,2}}{N_{t,2}}$ indicates the number of antenna set candidates.

From (7), we can see that the performance of the AS scheme can be improved by maximizing the number of antenna set candidates $N_c(N_{t,i}, N_{r,i})$. Utilizing Pascal's triangle [14], it can be shown that $N_{t,i}$ and $N_{r,i}$ maximizing $N_c(N_{t,i}, N_{r,i})$ under the antenna constraint $N_{t,i} + N_{r,i} = N_i$ ($i = 1, 2$, are obtained as

$$\{N_{t,i}^*, N_{r,i}^*\} = \begin{cases}\left\{\frac{N_i}{2}, \frac{N_i}{2}\right\}, & \text{if } N_i \text{ is even} \\ \left\{\frac{N_i\pm 1}{2}, \frac{N_i\mp 1}{2}\right\}, & \text{if } N_i \text{ is odd.}\end{cases} \quad (8)$$

It is interesting to note that if the number of transmit and receive antennas is set according to (8), we cannot only improve the performance of BD FD systems compared with conventional BD FD systems but also reduce the search size of the optimal AS scheme to $\binom{N_1}{N_1/2}\binom{N_2}{N_2/2}$ for even N_1 and N_2. Thus, based on the results in (8), we propose a low-complexity AS algorithm in the following.

IV. Proposed Low Complexity AS Algorithm

Here, we provide a new AS algorithm that reduces the search complexity. As discussed earlier, we assume that the transmit and receive antenna configuration satisfies (8). To reduce the complexity, we apply a greedy search concept to BD FD systems. The greedy search algorithm has been widely applied to the AS problem in conventional HD MIMO systems to decrease the search complexity [15], [16]. However, the methods in [15] and [16] cannot be directly applied to BD FD systems because of the SI term in (2). By considering these issues, we propose an efficient AS algorithm for BD FD systems based on greedy search.

First, let us define n as the iteration index and $\bar{\mathcal{S}}^{(n)} = \{\bar{\mathcal{T}}_1^{(n)}, \bar{\mathcal{T}}_2^{(n)}, \bar{\mathcal{R}}_1^{(n)}, \bar{\mathcal{R}}_2^{(n)}\}$ as the antenna set determined at the nth step. In the proposed AS algorithm, we initialize $\bar{\mathcal{T}}_{\bar{i}}^{(0)} = \bar{\mathcal{R}}_i^{(0)} = \phi$, $\bar{\mathcal{R}}_{\bar{i}}^{(0)} = \mathcal{N}_{\bar{i}}$, and $\bar{\mathcal{T}}_i^{(0)} = \mathcal{N}_i$. At the nth iteration, one transmit and one receive antenna that maximize the sum rate $R(\bar{\mathcal{S}})$ are added to $\bar{\mathcal{T}}_{\bar{i}}^{(n)}$ and $\bar{\mathcal{R}}_i^{(n)}$, whereas they are removed from $\bar{\mathcal{R}}_{\bar{i}}^{(n)}$ and $\bar{\mathcal{T}}_i^{(n)}$, respectively. This is because in BD FD systems, $\bar{\mathcal{R}}_{\bar{i}}^{(n)}$ and $\bar{\mathcal{T}}_i^{(n)}$ can be directly obtained as $\left(\bar{\mathcal{T}}_i^{(n)}\right)^c = \bar{\mathcal{R}}_i^{(n)}$, where $(\cdot)^c$ stands for a complementary set. We repeat this process until the antenna set $\bar{\mathcal{S}}$ satisfies the condition in (8). The proposed AS algorithm is summarized as Algorithm 1 for $N_1 = N_2$. The algorithm can be described in a similar way when N_1 is not equal to N_2.

Now, we compare the complexity of the proposed AS algorithm with that of the optimal AS scheme. When $N_i \le N_{\bar{i}}$ and both N_i and $N_{\bar{i}}$ are even, the search complexity of the proposed AS algorithm is computed as[1]

$$\begin{aligned}\bar{N}_c &= \sum_{k=1}^{\frac{N_i}{2}} (N_i - (k-1))\,(N_{\bar{i}} - (k-1)) \\ &\quad + \sum_{k=\frac{N_i}{2}+1}^{\frac{N_{\bar{i}}}{2}} (N_{\bar{i}} - (k-1)) \\ &= \frac{1}{2}(N_{\bar{i}}+1)\left(N_i^2 + N_{\bar{i}}\right) \\ &\quad - \frac{1}{24}N_i(N_i+2)\,(2N_i + 3N_{\bar{i}} + 2) - \frac{1}{8}N_{\bar{i}}(N_{\bar{i}}+2)\end{aligned}$$

which is given by a polynomial of the number of antennas N_i. Note that when $N_i = N_{\bar{i}}$, $\bar{N}_c$ is on the order of $\mathcal{O}(N_i^3)$. The search size of the optimal AS scheme in (3) increases exponentially with increasing N_i and $N_{\bar{i}}$. For instance, for $N = 8$ and $N_{t,1} = N_{t,2} = 4$, the search size of the optimal AS scheme is 64 516, whereas that of the proposed AS algorithm is 174, which is only 0.27% that of the optimal AS scheme. It is clear that the proposed AS algorithm achieves a significant complexity reduction compared with that of the optimal AS scheme. In the simulation results, we will confirm that the proposed AS algorithm provides performance almost identical to that of the optimal AS scheme with much reduced complexity.

Algorithm 1: Proposed AS algorithm

Initialize $\bar{\mathcal{T}}_1^{(0)} = \{1, \ldots, N_1\}, \bar{\mathcal{T}}_2^{(0)} = \phi$,
$\bar{\mathcal{R}}_1^{(0)} = \phi, \bar{\mathcal{R}}_2^{(0)} = \{1, \ldots, N_2\}$,
and $\bar{\mathcal{S}}^{(0)} = \{\bar{\mathcal{T}}_1^{(0)}, \bar{\mathcal{T}}_2^{(0)}, \bar{\mathcal{R}}_1^{(0)}, \bar{\mathcal{R}}_1^{(0)}\}$.
For $n = 1 : \lceil N_1/2 \rceil$
Find the antenna $\hat{t}_n, \hat{r}_n$ such that
$\{\hat{t}_n, \hat{r}_n\} = \arg\max_{t \in \bar{\mathcal{T}}_1^{(n-1)}, r \in \bar{\mathcal{R}}_2^{(n-1)}} R(\bar{\mathcal{S}}^{(n)})$.
Update $\bar{\mathcal{T}}_1^{(n)} = \bar{\mathcal{T}}_1^{(n-1)} \setminus \{t_n\}, \bar{\mathcal{T}}_2^{(n)} = \bar{\mathcal{T}}_2^{(n-1)} \bigcup \{r_n\}$,
$\bar{\mathcal{R}}_1^{(n)} = \bar{\mathcal{R}}_1^{(n-1)} \bigcup \{t_n\}, \bar{\mathcal{R}}_2^{(n)} = \bar{\mathcal{R}}_2^{(n-1)} \setminus \{r_n\}$.
End

V. Simulation Results

Here, numerical results are provided to evaluate the performance of the proposed AS algorithm in BD FD MIMO systems. Now, we set $P_1 = P_2 = P$ and $N_1 = N_2 = N$, and the SNR is defined as P/σ_n^2. We assume a spatially uncorrelated Rayleigh fading model for the channel matrices between two nodes $\mathbf{H}_{i\bar{i}}$ with zero mean and unit variance. Moreover, we consider the Rician fading environment for the SI channel such that the elements of the SI channel matrix $\mathbf{H}_{ii}$ are independent and identically distributed (i.i.d.) complex Gaussian random variables with mean $\sqrt{\sigma_{SI}^2 K/(1+K)}$ and variance $\sigma_{SI}^2/(1+K)$, where σ_{SI}^2 is the SI power, and K equals the Rician factor, which is set to $K = 1$ [18]. For a practical SI channel model, σ_{SI}^2 is determined by adopting proper SI cancelation techniques [19].

[1]Our proposed scheme is a run-time technique [17]. As the proposed scheme is based on a greedy search method, there might exist a delay related to the search size.

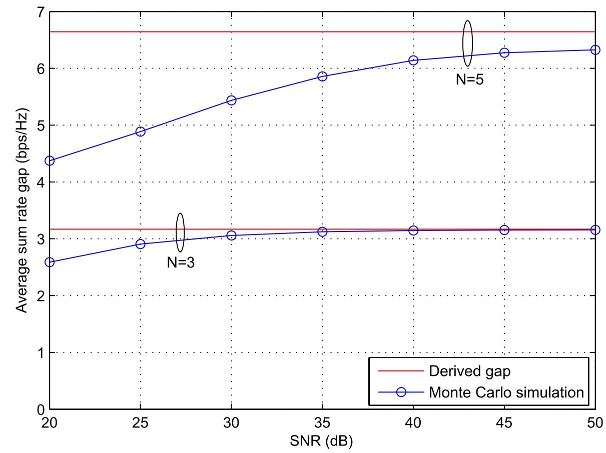

Fig. 2. Performance gain of the optimum AS scheme over conventional BD FD systems with $\sigma_{SI}^2 = -20$ dB.

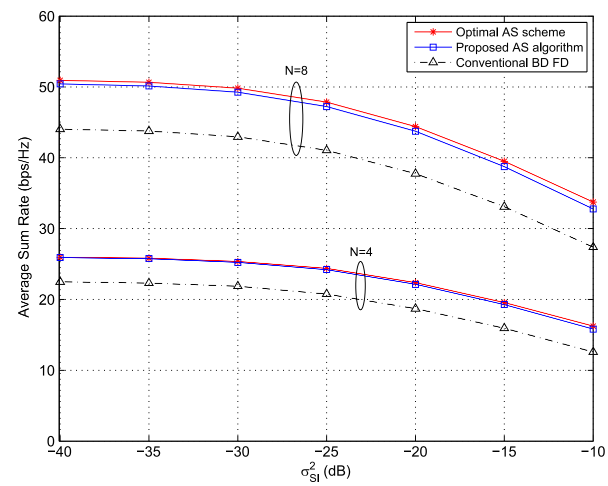

Fig. 3. Average sum rate for various σ_{SI}^2 at an SNR of 20 dB.

Fig. 2 depicts the average sum rate gap between the optimal AS scheme and conventional BD FD systems with $\sigma_{SI}^2 = -20$ dB. Note that the conventional BD FD systems, which select the antenna set randomly, have the same performance as the systems utilizing a fixed antenna set. The sum rate gap is defined as $\log_2 N_c(N_{t,i}, N_{r,i})$ from (7). The plot shows that our derived gap $\log_2 N_c$ agrees well with the Monte Carlo simulations in the high-SNR regime, as the max-log approximation in (4) is more accurate at high SNR. Moreover, we can see that the gain grows as the number of antenna at each node increases. Thus, we can conclude that our analytical results agree well with the simulation results at high SNR.

In Fig. 3, we present the average sum rate of BD FD systems with respect to σ_{SI}^2 for an SNR of 20 dB. The proposed AS algorithm exhibits significant performance gains over conventional BD FD systems for all simulated σ_{SI}^2. Moreover, the performance of the proposed AS algorithm is close to that of the optimal AS scheme. It can be shown that the performance difference between the optimal AS scheme and conventional BD FD systems remains constant as σ_{SI}^2 varies, as we have verified in (7).

Fig. 4 shows the average sum-rate performance of the optimal AS scheme and the proposed algorithm with perfect and imperfect channel state information (CSI). Here, we employ the additive Gaussian channel estimation error model [20], i.e., the estimated channel $\hat{\mathbf{H}}_{i\bar{i}}$ and the SI channel $\hat{\mathbf{H}}_{ii}$ are given by $\hat{\mathbf{H}}_{i\bar{i}} = \mathbf{H}_{i\bar{i}} + \mathbf{E}_{i\bar{i}}$ and $\hat{\mathbf{H}}_{ii} = \mathbf{H}_{ii} + \mathbf{E}_{ii}$, respectively, where the elements of $\mathbf{E}_{i\bar{i}}$ and $\mathbf{E}_{ii}$ are i.i.d. complex Gaussian random variables with zero mean and variance σ_e^2.

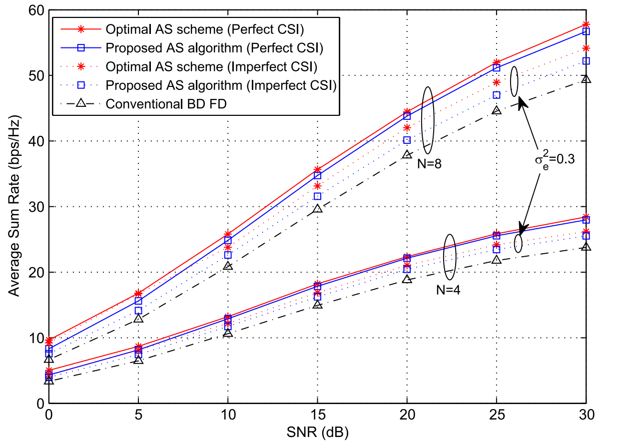

Fig. 4. Average sum rate as a function of SNR with $\sigma_{SI}^2 = -20$ dB in the perfect and imperfect CSI cases.

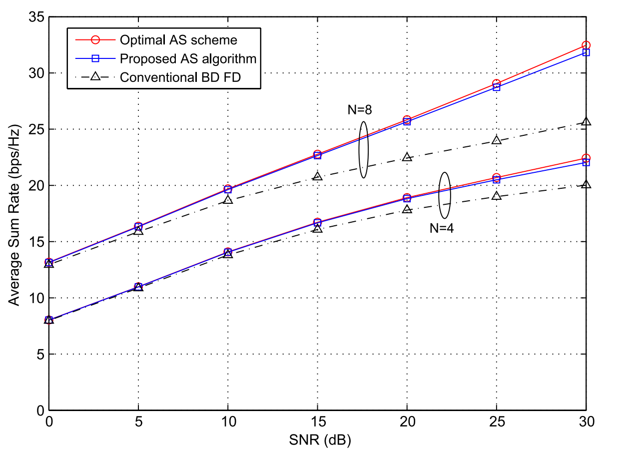

Fig. 5. Average sum rate as a function of SNR with $\sigma_{SI}^2 = -20$ dB in the correlated channel model with $\rho = 0.9$.

In the perfect CSI case, we observe that the proposed AS algorithm exhibits almost the same performance with much reduced complexity compared to the optimal AS scheme and outperforms conventional BD FD systems for all simulated cases. When SNR = 30 dB and $N = 8$, the proposed AS algorithm provides a performance gain of 15% compared with conventional BD FD systems, and the performance gap increases with increasing N. Moreover, we can see that the proposed AS algorithm exhibits good performance compared with the optimal AS scheme for the imperfect CSI case. It would be interesting future work to analyze the performance and its robust design under an imperfect CSI scenario.

Fig. 5 presents the average sum rate of BD FD systems with respect to SNR when $N = 4$ and 8 with $\sigma_{SI}^2 = -20$ dB in correlated channels. For the simulation, we apply the Kronecker exponential correlation model that defines the (i, j)th component of the correlation matrix as $\rho^{|i-j|}$ with ρ denoting the correlation coefficient [21]. It can be observed that the proposed algorithm still provides a larger sum rate than the conventional BD FD systems under the correlated channel environment and achieves almost identical performance to that of the optimal AS scheme. Therefore, as discussed in Section III, the proposed algorithm is also effective in the correlated channel case.

VI. Conclusion

In this paper, we have proposed a low-complexity AS technique for BD FD MIMO systems. We have first analyzed the performance of BD FD MIMO systems with the optimal AS scheme. By using this result, an efficient AS algorithm has been provided, which utilizes the greedy search method. From the numerical simulations, we have demonstrated that the analytical result agrees well with the simulation results. Moreover, we have confirmed that BD FD systems that use the proposed AS algorithm outperform conventional BD FD systems and exhibit near-optimal sum-rate performance with much reduced complexity.

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