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Joint Precoding, Receive Combining, and Uplink Power Control for Full-Duplex Multi-User MIMO

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Abstract. To address the performance degradation in full-duplex multi-user multiple-input multiple-output (MIMO) systems caused by the coexistence of residual self-interference and multi-user interference, this paper investigates a joint transceiver design and power optimization method for full-duplex multi-user MIMO systems. Specifically, we consider a full-duplex multi-user MIMO scenario in which a base station (BS) performs downlink transmission and uplink reception simultaneously over the same time-frequency resource. With the objective of maximizing the weighted sum-rate of the uplink and downlink, a joint optimization problem is formulated over the downlink precoding matrix, the uplink receive combining matrix, and the uplink users' transmit powers. Owing to the non-convex nature of the original problem and the strong coupling among optimization variables, a solution framework combining fractional programming and alternating optimization is adopted. In particular, the original problem is transformed into a more tractable equivalent form by means of the Lagrangian dual transform and the quadratic transform, and all optimization variables are then updated iteratively. Simulation results show that the proposed method exhibits favorable convergence behavior. Compared with the fixed uplink power scheme and the ZF/MMSE baseline, the proposed method achieves higher weighted sum-rates under different transmit power levels and antenna configurations. The results demonstrate that jointly optimizing the transceiver beamforming and uplink transmit powers can effectively improve the spectral efficiency of full-duplex multi-user MIMO systems.

Keywords: full-duplex MIMO, multi-user MIMO, fractional programming, alternating optimization, uplink power control

1. Introduction

With the continuous growth of wireless service demands, future communication systems are expected to provide higher spectral efficiency, data rates, system capacity, and link reliability. Multiple-input multiple-output (MIMO) technology has become one of the key enablers for improving wireless system performance by exploiting spatial multiplexing and diversity gains. Through proper beamforming design, MIMO systems can not only enhance the desired signal but also suppress interference in the spatial domain, thereby effectively improving the signal-to-interference-plus-noise ratio (SINR) and the overall system throughput. Meanwhile, in dense connectivity scenarios with increasingly scarce spectrum resources, conventional half-duplex

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communication suffers from limited spectral efficiency due to the orthogonal separation of transmission and reception in either the time or frequency domain. In contrast, in-band full-duplex (FD) communication enables simultaneous transmission and reception over the same time-frequency resource, and therefore has the potential to further improve spectral efficiency [1].

However, the main bottleneck of full-duplex communication lies in self-interference [1]. Since the transmitter and receiver are co-located at the same node, the downlink transmit signal of the BS leaks to its own receiver through the coupling channel, which severely degrades uplink signal detection. Although antenna isolation, analog cancellation, and digital cancellation can suppress SI to a certain extent, the residual self-interference is still difficult to eliminate completely [1]. In multi-user MIMO scenarios, the system must cope not only with residual SI, but also with downlink multi-stream interference, uplink multi-user interference, and co-channel interference from uplink users to downlink users. As a result, the uplink and downlink links become strongly coupled.

Extensive research has been conducted on beamforming, self-interference suppression, and power allocation in full-duplex MIMO systems. One class of methods is mainly based on linear processing schemes such as zero-forcing and minimum mean-square error, where the transmitter and receiver are designed separately to improve system performance. Another class of methods adopts iterative approaches to solve the joint transceiver design problem under interference-coupled uplink and downlink links [1-3]. Although these methods improve the achievable performance of full-duplex systems to different extents, in multi-user full-duplex MIMO scenarios, fixing part of the variables or optimizing only one side of the link is often insufficient to fully exploit the overall system potential.

Recently, movable or position-reconfigurable antenna techniques have attracted increasing attention as a promising means of exploiting additional spatial degrees of freedom through antenna repositioning [4-6]. Existing studies have investigated joint beamforming and antenna-position optimization in spectrum-sharing and multiuser systems [7, 8], while full-duplex extensions with movable or position-reconfigurable antennas have also been reported in co-frequency co-time and secure multiuser scenarios [9, 10]. Our recent works further indicate the potential of joint position, beamforming, and power design for PRA-aided full-duplex MIMO systems [11, 12]. Related beamforming optimization for other emerging antenna architectures has also been explored in [13].

Different from these position-reconfigurable designs, this paper focuses on the full-duplex multi-user MIMO case and studies the gain obtainable from joint transceiver and uplink power optimization without antenna movement.

Motivated by the above observations, this paper investigates the joint optimization of downlink transmit beamforming, uplink receive combining, and uplink users' transmit powers for a full-duplex multi-user MIMO system. The objective is to maximize the weighted sum-rate of the uplink and downlink. Based on the considered system model, the original weighted sum-rate maximization problem is gradually transformed into a more tractable equivalent form by combining fractional programming and alternating optimization, and a joint transceiver and power control design is subsequently developed.

2. System model and problem formulation

Consider a narrowband flat-fading FD multi-user MIMO system, where the BS performs downlink transmission and uplink reception simultaneously over the same time-frequency resource, which is a commonly adopted model for FD multi-user MIMO transceiver design [1, 10]. The BS is equipped with N_t transmit antennas and N_r receive antennas, respectively. The system consists of K_{DL} downlink users and K_{UL} uplink users, each of which is assumed to be a single-antenna terminal.

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The BS adopts fully digital beamforming, where the downlink precoding matrix is denoted by $W_{tx} \in \mathbb{C}^{N_t \times K_{DL}}$ and the uplink linear combining matrix is denoted by $W_{rx} \in \mathbb{C}^{N_r \times K_{UL}}$.

Let the downlink data symbol vector be $s_{DL} \in \mathbb{C}^{K_{DL} \times 1}$, satisfying $\mathbb{E}\left\{ s_{DL} s_{DL}^H \right\} = I$. Then, the downlink transmit signal at the BS can be expressed as

$$x = W_{tx} s_{DL} \tag{1}$$

For the ℓ-th uplink user, denote its transmitted symbol by $s_{u,l}$, and assume $\mathbb{E}\left\{ \left| s_{u,l} \right|^2 \right\} = 1$. Its transmit power is denoted by p_(u,l). The total BS downlink transmit power is constrained by

$$tr\left(W_{tx} W_{tx}^H \right) \le P_{BS} \tag{2}$$

For channel modeling, the downlink channel from the BS to the k-th downlink user is denoted by $H_{d,k} \in \mathbb{C}^{1 \times N_t}$, which is a row vector. The uplink channel from the ℓ-th uplink user to the BS is denoted by $G_{u,l} \in \mathbb{C}^{N_r \times 1}$, which is a column vector. Since the BS operates in full-duplex mode, a self-interference coupling channel exists between the transmit and receive arrays, denoted by $H_{SI} \in \mathbb{C}^{N_r \times N_t}$.

In addition, to maintain generality, co-channel interference from uplink users to downlink users is also taken into account. Let $h_{ud,kl}$ denote the scalar interference channel from the ℓ-th uplink user to the k-th downlink user. Then, the received signal of the k-th downlink user can be written as

$$y_{d,k} = H_{d,k} x + \sum_{l=1}^{K_{UL}} h_{ud,kl} \sqrt{p_{u,l}} s_{u,l} + n_{d,k} \tag{3}$$

where $n_{d,k}$~ $\mathcal{CN}\left(0, {\sigma_d}^2\right)$ denotes the receiver noise at the downlink user. Substituting (1) into (3), we obtain

$$y_{d,k} = H_{d,k} W_{tx} s_{DL} + \sum_{l=1}^{K_{UL}} h_{ud,kl} \sqrt{p_{u,l}} s_{u,l} + n_{d,k} \tag{4}$$

It can be seen that the received signal of the k-th downlink user consists of three components: the desired downlink signal, the multi-user interference from other downlink streams, and the uplink-to-downlink co-channel interference introduced by uplink users. If the uplink-to-downlink interference is neglected in subsequent analysis or simulations, one may simply set $h_{ud,kl} = 0$.

Accordingly, by treating the other downlink streams and the uplink co-channel interference as interference, the SINR of the k-th downlink user can be expressed as

$$SINR_{d,k} = \frac{\left| H_{d,k} w_{tx,k} \right|^2}{\sum_{j \ne k} \left| H_{d,k} w_{tx,j} \right|^2 + \sum_{l=1}^{K_{UL}} p_{u,l} \left| h_{ud,kl} \right|^2 + \sigma_d^2} \tag{5}$$

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The corresponding downlink achievable rate is

$$R_{d,k} = \log_2 (1 + SINR_{d,k}) \tag{6}$$

On the uplink, since the BS continues downlink transmission while receiving uplink signals, its receive vector contains not only the superposition of all uplink users' signals but also the self-interference caused by its own transmission. Hence, the received signal at the BS can be written as

$$y_{BS} = \sum_{l=1}^{K_{UL}} G_{u,l} \sqrt{p_{u,l}} s_{u,l} + H_{SI} x + n_{BS} \tag{7}$$

where n_{BS}~$\mathcal{CN}\left(0, \sigma^2 I\right)$ denotes the additive white Gaussian noise at the BS receiver. For the ℓ-th uplink user, the BS applies a linear combining vector $w_{rx,l}$ for detection, and the decision variable is given by

$$\hat{s}_{u,l} = w_{rx,l}^H y_{BS} \tag{8}$$

It should be noted that, in practical full-duplex systems, self-interference is usually suppressed by multiple stages, including antenna isolation, analog cancellation, and digital cancellation, yet a non-negligible residual component still remains [1, 11]. For analytical tractability, this paper adopts a commonly used linear residual SI model, in which the residual SI channel is represented as

$$H_{SI}^{(res)} = \sqrt{\alpha_{si}} H_{SI} \tag{9}$$

Here, $0 < \alpha_{si} \ll 1$ denotes the residual self-interference coefficient. Since $x = W_{tx} s_{DL}$ and $\mathbb{E}\left\{ s_{DL} s_{DL}^H \right\} = I$, we have

$$E\left\{ x x^H \right\} = W_{tx} E\left\{ s_{DL} s_{DL}^h \right\} W_{tx}^H = W_{tx} W_{tx}^H \tag{10}$$

Therefore, the covariance matrix of the residual self-interference at the BS receiver can be written as

$$R_{SI} = \alpha_{si} H_{SI} W_{tx} W_{tx}^H H_{SI}^H \tag{11}$$

On this basis, by treating the other uplink users, the residual self-interference, and the receiver noise as interference, the uplink SINR of user ℓ is given by

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$$SINR_{u,l} = \frac{p_{u,l}\left|w_{rx,l}^{H}G_{u,l}\right|^{2}}{\sum_{j\neq l}p_{u,j}\left|w_{rx,l}^{H}G_{u,j}\right|^{2}+w_{rx,l}^{H}R_{SI}w_{rx,l}+\sigma^{2}\left|\left|w_{rx,l}\right|\right|_{2}^{2}} \tag{12}$$

The corresponding uplink achievable rate is

$$R_{u,l} = \log_2\left(1+SINR_{u,l}\right) \tag{13}$$

From the above model, it can be observed that the uplink and downlink links are not independent. On the one hand, the downlink precoding matrix W_{tx} directly determines the reception performance of all downlink users. On the other hand, through the residual SI covariance matrix in (11), W_{tx} also affects the BS's detection performance for uplink users. Therefore, uplink and downlink transceiver design in full-duplex systems is inherently coupled, which is also the main reason why the ensuing optimization problem is difficult to solve directly. Similar variable coupling also appears in recent joint beamforming, power-control, and full-duplex optimization studies [8, 10-12].

Based on the above system model, the weighted sum-rate of the uplink and downlink is adopted as the system performance metric. Let $\mu_k \geq 0$ denote the service weight of the k-th downlink user and $\nu_l \geq 0$ denote the service weight of the ℓ-th uplink user. Then the weighted sum-rate can be written as

$$R_{sum} = \sum_{k=1}^{K_{DL}}\mu_k R_{d,k} + \sum_{l=1}^{K_{UL}}\nu_l R_{u,l} \tag{14}$$

Accordingly, the joint transceiver design problem can be formulated as (P1)

$$\max_{W_{tx}\,W_{rx}\,\{p_{u,l}\}} \sum_{k=1}^{K_{DL}}\mu_k R_{d,k} + \sum_{l=1}^{K_{UL}}\nu_l R_{u,l} \tag{15}$$

$$s.t. \quad tr\left(W_{tx}W_{tx}^{H}\right) \leq P_{BS},\ 0 \leq p_{u,l} \leq P_{u,l}^{max}, \forall l \tag{15a}$$

Here, the constraint $tr\left(W_{tx}W_{tx}^{H}\right) \leq P_{BS}$ limits the total BS downlink transmit power, while $0 \leq p_{u,l} \leq P_{u,l}^{max}$ represents the maximum uplink transmit power constraint for each uplink user. If all uplink user transmit powers are fixed, then $\{\ p_{u,l}\ \}$ can be regarded as known constants, and the optimization variables reduce to W_{tx} and W_{rx}.

It should be emphasized that problem (P1) is generally non-convex. On the one hand, downlink multi-stream interference, uplink multi-user interference, and uplink-to-downlink co-channel interference give rise to multiple coupled ratio terms in the rate expressions. On the other hand, the residual self-interference term R_{SI} is strongly dependent on W_{tx}, which further intensifies the coupling between the uplink and downlink. Hence, problem (15) does not admit a direct closed-form global optimum in general. It may be addressed by alternating optimization, WMMSE, or fractional

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programming, while fixed precoding/combining strategies may be adopted for baseline performance evaluation.

3. Proposed solution

As discussed in the previous section, the objective function of problem (P1) takes the typical weighted sum-rate maximization form, which is essentially a sum of multiple logarithmic ratio terms. Since the downlink precoding matrix W_{tx}, the uplink receive combining matrix W_{rx} , and the uplink users' transmit powers $\{ p_{u,\ell} \}$ all appear simultaneously in the desired-signal terms, interference terms, and residual SI terms, the optimization variables are strongly coupled. Similar coupled formulations have also been encountered in recent joint optimization studies for multiuser and full-duplex systems [8, 10-12].

Before introducing the specific transformations, we first discuss the scaling property of the uplink receive combining vector. For the ℓ-th uplink user, its achievable rate depends only on the direction of $w_{rx,\ell}$, rather than its overall amplitude. Therefore, the unit-norm constraint on the receive combining vector can be temporarily relaxed during optimization, and normalization may be performed afterwards once the optimal direction is obtained. This treatment preserves optimality while reducing the complexity of the ensuing optimization process.

3.1. Lagrangian dual transform

To handle the SINR ratio terms embedded inside the logarithm in the objective function, nonnegative real auxiliary variables are first introduced:

$$\gamma = [\gamma_{d,1}, \ldots, \gamma_{d,K_{DL}}, \gamma_{u,1}, \ldots, \gamma_{u,K_{UL}}]^T \geq 0$$

Here, $\gamma_{d,k}$ and $\gamma_{u,\ell}$ correspond to the effective SINR of the k-th downlink user and the ℓ-th uplink user, respectively. The purpose of introducing this set of variables is to explicitly unfold the nested structure $\log(1 + SINR)$ in the original objective, so that the desired signal and interference terms can be separated from the logarithm, thereby facilitating variable decoupling and block-wise optimization [2].

For notational convenience, define the total interference-plus-noise term of the k-th downlink user as

$$s_{d,k} = \sum_{j=1}^{K_{DL}} |H_{d,k} w_{tx,j}|^2 + \sum_{\ell=1}^{K_{UL}} p_{u,\ell} |h_{ud,k\ell}|^2 + \sigma_d^2 \tag{16}$$

The first term represents the total received power of all downlink streams at user k, the second term denotes the uplink-to-downlink co-channel interference power, and the third term is the receiver noise power. Similarly, the total interference-plus-noise term corresponding to the ℓ -th uplink user is defined as

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$$s_{u,l} = \sum_{j=1}^{K_{UL}} p_{u,j} \left| w_{rx,l}^H G_{u,j} \right|^2 + w_{rx,l}^H R_{SI} w_{rx,l} + \sigma^2 \left| \left| w_{rx,l} \right| \right|_2^2 \tag{17}$$

Here, the first term is the total uplink power after receive combining, the second term represents the residual self-interference projected onto the current receive vector, and the third term is the noise contribution. If the uplink-to-downlink co-channel interference is neglected in the system analysis, the second term in (16) may be removed.

Under the above notation, the original problem (P1) can be equivalently rewritten as (P2):

$$\max_{W_{tx}, W_{rx}, \{p_{u,l}\}, \gamma} \sum_{k=1}^{K_{DL}} \mu_k \left(\ln\left(1+\gamma_{d,k}\right) - \gamma_{d,k} \right) + \sum_{l=1}^{K_{UL}} \nu_l \left(\ln\left(1+\gamma_{u,l}\right) - \gamma_{u,l} \right) + S_1 + S_2 \tag{18}$$

$$s.t. \quad tr\left(W_{tx} W_{tx}^H\right) \le P_{BS,}\ 0 \le p_{u,l} \le P_{u,l}^{max}, \forall l, \gamma \ge 0 \tag{18a}$$

Here,

$$S_1 = \sum_{k=1}^{K_{DL}} \mu_k \left(1+\gamma_{d,k}\right) \frac{\left| H_{d,k} w_{tx,k} \right|^2}{s_{d,k}} \tag{19}$$

$$S_2 = \sum_{l=1}^{K_{UL}} \nu_l \left(1+\gamma_{u,l}\right) \frac{p_{u,l} \left| w_{rx,l}^H G_{u,l} \right|^2}{s_{u,l}} \tag{20}$$

It can be seen that after the Lagrangian dual transform, the logarithmic terms and the ratio terms in the original objective are effectively separated: the former appears explicitly in the form $\ln(1+\gamma)-\gamma$, while the latter is expressed as ratios directly related to the desired signal and interference powers. This reformulation does not alter the optimal value of the original problem, but significantly improves the problem structure. In particular, when W_{tx}, W_{rx}, and $\{p_{u,l}\}$ are fixed, problem (P2) is convex with respect to the auxiliary variable γ, and hence a closed-form update can be obtained from the first-order optimality condition. Specifically, the optimal auxiliary variables are exactly the instantaneous SINRs under the current variable configuration:

$$\gamma_{d,k}^{*} = \frac{\left| H_{d,k} w_{tx,k} \right|^2}{\sum_{j \ne k} \left| H_{d,k} w_{tx,j} \right|^2 + \sum_{l=1}^{K_{UL}} p_{u,l} \left| h_{ud,kl} \right|^2 + \sigma_d^2} \tag{21}$$

$$\gamma_{u,l}^{*} = \frac{p_{u,l} \left| w_{rx,l}^H G_{u,l} \right|^2}{\sum_{j \ne l} p_{u,j} \left| w_{rx,l}^H G_{u,j} \right|^2 + w_{rx,l}^H R_{SI} w_{rx,l} + \sigma^2 \left| \left| w_{rx,l} \right| \right|_2^2} \tag{22}$$

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Therefore, the main role of the Lagrangian dual transform is to explicitly unfold the sum-log-ratio structure in the original weighted sum-rate problem, thereby converting it into an equivalent form that can be further processed.

3.2. Quadratic transform

Although the above transformation has separated the SINR terms from the logarithm, the reformulated problem still contains multiple coupled ratio terms, and thus cannot yet be optimized directly in a block-wise manner. To further decouple the numerators and denominators, a set of complex auxiliary variables is introduced [3]:

$$y = [y_{d,1}, \ldots, y_{d,K_{DL}}, y_{u,1}, \ldots, y_{u,K_{UL}}]^T$$

Here, $y_{d,k}$ and $y_{u,l}$ correspond to the auxiliary variables associated with the downlink and uplink links, respectively. From an optimization perspective, this set of variables may be interpreted as receive filters introduced by the quadratic transform for converting the fractional terms into quadratic forms that are easier to optimize with respect to each variable block.

By applying the quadratic transform, problem (P2) can be further rewritten as (P3):

$$\max_{W_{tx},W_{rx},\{p_{u,l}\},\gamma,y} \sum_{k=1}^{K_{DL}} \mu_k \left(\ln\left(1+\gamma_{d,k}\right)-\gamma_{d,k}\right)+\sum_{l=1}^{K_{UL}} \nu_l \left(\ln\left(1+\gamma_{u,l}\right)-\gamma_{u,l}\right)+T_1+T_2 \tag{23}$$

$$s.t. tr(W_{tx}W_{tx}^H) \le P_{BS}, 0 \le p_{u,l} \le P_{u,l}^{max}, \forall l, \gamma \ge 0 \tag{23a}$$

where

$$T_1 = \sum_{k=1}^{K_{DL}} \left[2\sqrt{\mu_k\left(1+\gamma_{d,k}\right)}\, \Re\left\{y_{d,k}^{*} H_{d,k} w_{tx,k}\right\} - |y_{d,k}|^2 s_{d,k}\right] \tag{24}$$

$$T_2 = \sum_{l=1}^{K_{UL}} \left[2\sqrt{\nu_l\left(1+\gamma_{u,l}\right)p_{u,l}}\, \Re\left\{y_{u,l}^{*} w_{rx,l}^H G_{u,l}\right\} - |y_{u,l}|^2 s_{u,l}\right] \tag{25}$$

Compared with problem (P2), the key advantage of (P3) lies in the fact that the fractional structures originally appearing in S_1 and S_2 are now equivalently rewritten as standard quadratic expressions. Consequently, when the other variables are fixed, the subproblems corresponding to W_{tx} , W_{rx}, and $\{p_{u,l}\}$ become much more regular, which facilitates block-wise optimization under the subsequent alternating optimization framework. Similar block-wise design ideas are also consistent with recent joint optimization works in multiuser or full-duplex settings [8, 10–12].

Likewise, when W_{tx}, W_{rx}, $\{p_{u,l}\}$, and γ are fixed, problem (P3) is separable and convex with respect to y, and therefore the optimal y can be obtained in closed form:

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$$y_{d,k}^{*}=\frac{\sqrt{\mu_k(1+\gamma_{d,k})}\,H_{d,k}w_{tx,k}}{s_{d,k}} \tag{26}$$

$$y_{u,l}^{*}=\frac{\sqrt{\nu_l\left(1+\gamma_{u,l}\right)p_{u,l}}\,w_{rx,l}^{H}G_{u,l}}{s_{u,l}} \tag{27}$$

The above results can be obtained directly from the first-order optimality condition. It can be observed that the auxiliary variables $y_{d,k}$ and $y_{u,l}$ essentially characterize the matching relationship between the desired signal and the total interference under the current variable configuration. As these variables are updated iteratively, the original fractional terms are repeatedly reconstructed into local quadratic forms that are easier to handle, thereby providing the basis for subsequent closed-form or semi-closed-form solutions of the subproblems.

In summary, after the Lagrangian dual transform and the quadratic transform, the original weighted sum-rate maximization problem is converted into an equivalent problem that is more suitable for alternating optimization. Specifically, in each iteration, the auxiliary variables γ and y are first updated according to the current W_{tx}, W_{rx}, and $\{p_{u,l}\}$. Then, with the auxiliary variables fixed, the downlink precoding matrix, the uplink receive combining matrix, and the uplink transmit powers are updated sequentially. Since each update step corresponds to an equivalent reformulation or a locally optimal update of the original objective, this framework can effectively reduce the difficulty of the original problem while ensuring monotonic improvement of the objective value.

4. Simulation results

4.1. Simulation settings

This section provides numerical results to verify the effectiveness of the proposed joint optimization method for full-duplex multi-user MIMO systems. The system performance metric is the weighted sum-rate of the uplink and downlink. To highlight the performance advantage of the proposed method, the following three schemes are considered for comparison: 1) Proposed FP-AO, in which the downlink precoding matrix, the uplink receive combining matrix, and the uplink transmit powers are jointly optimized; 2) FP-AO (fixed UL power), in which the uplink user transmit powers are fixed and only the BS transceiver beamformers are iteratively optimized; and 3) ZF/MMSE baseline, in which ZF precoding is employed for the downlink and MMSE linear combining is used for the uplink as a low-complexity benchmark [1, 8].

Unless otherwise specified, the simulations are conducted under $N_t = N_r = N$ and $K_D = K_U = K$. For each independent channel realization, a finite number of AO iterations is performed, and the results are averaged over multiple random channel realizations in order to reduce the fluctuation caused by small-scale fading. The adopted residual self-interference setting is also consistent with the commonly used full-duplex residual-interference modeling framework [1, 11].

4.2. Convergence evaluation

Fig. 1 illustrates the AO convergence behavior of the considered schemes under the default parameter setting. It can be observed that the proposed FP-AO scheme achieves a rapid performance

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improvement within the first few iterations and then gradually converges to a stable value, indicating favorable convergence behavior under the considered system model. In contrast, the FP-AO scheme with fixed uplink power also converges, but its final weighted sum-rate is evidently lower than that of the proposed joint optimization method. Since the ZF/MMSE baseline does not involve iterative optimization, its performance remains approximately constant over the iteration axis. This result indicates that, in the considered full-duplex multi-user scenario, joint optimization of the uplink transmit powers provides an additional performance gain [11, 12].

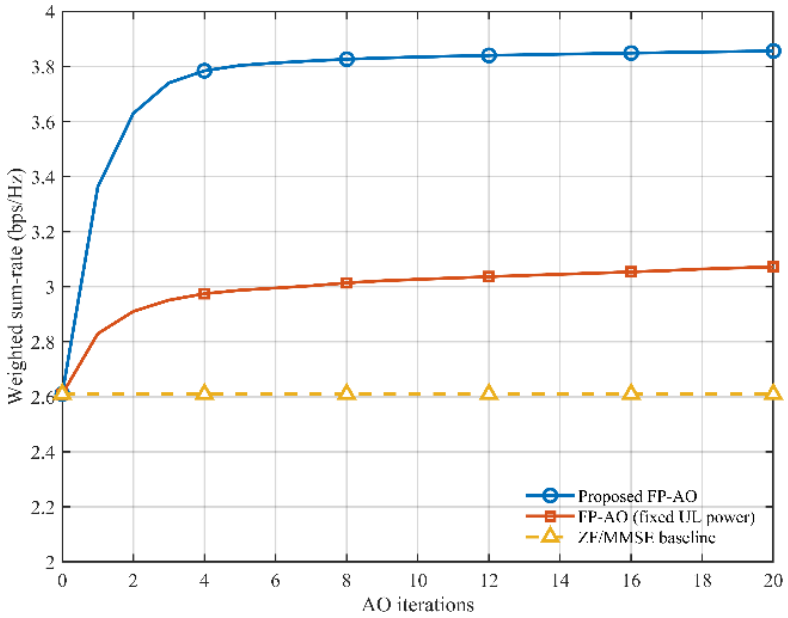

Figure 1. AO convergence behavior of different schemes

4.3. Performance evaluation under different conditions

Fig. 2 shows the weighted sum-rate as a function of the BS transmit power. As the BS transmit power increases, the performance of all three schemes improves, which indicates that, within the considered parameter range, increasing the transmit power can effectively enhance the overall transmission efficiency of the system. Meanwhile, the proposed FP-AO scheme consistently outperforms the other two schemes over the entire power range. This demonstrates that the joint optimization of transceiver beamforming and uplink power can better coordinate the coupling between the uplink and downlink links, thereby yielding a higher system weighted sum-rate. Compared with the FP-AO scheme with fixed uplink power, the persistent performance advantage of the proposed method further confirms the importance of uplink power control in full-duplex multi-user systems [8, 11].

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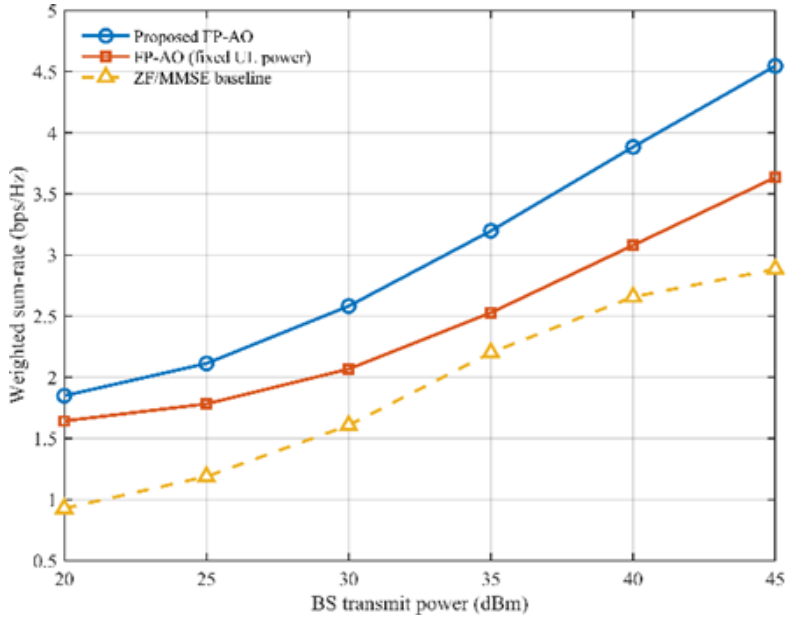

Figure 2. Weighted sum-rate versus BS transmit power

Fig. 3 presents the weighted sum-rate as a function of the number of BS antennas. It can be seen that, as $N_t = N_r = N$ increases, the performance of all schemes improves gradually. This is because a larger number of transmit and receive antennas offers more spatial degrees of freedom, thereby enhancing downlink multi-user separation and improving the suppression of uplink interference as well as residual self-interference. Over the entire antenna range considered, the proposed FP-AO scheme consistently achieves the best performance, which indicates that the proposed method can exploit the additional spatial dimensions more effectively. Overall, Figs. 2 and 3 show from two different perspectives that the proposed joint optimization method exhibits stable and significant performance advantages under varying system parameters [1, 8].

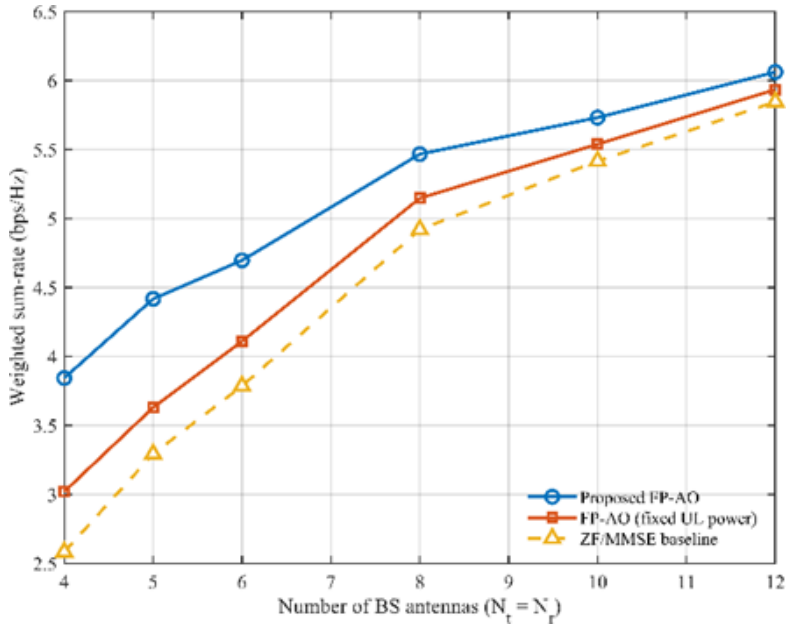

Figure 3. Weighted sum-rate versus the number of BS antennas

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5. Conclusion

This paper investigated the joint transceiver optimization problem in full-duplex multi-user MIMO systems. In the considered scenario, the BS performs downlink transmission and uplink reception simultaneously over the same time-frequency resource, and the system is affected simultaneously by downlink multi-stream interference, uplink multi-user interference, uplink-to-downlink co-channel interference, and residual self-interference. To address this setting, a joint optimization problem over the downlink precoding matrix, the uplink receive combining matrix, and the uplink users' transmit powers was formulated with the weighted sum-rate of the uplink and downlink as the optimization objective, and the corresponding SINR and achievable rate expressions were derived on the basis of the system model.

To cope with the sum-log-ratio structure and the strong coupling among variables, a solution approach combining fractional programming and alternating optimization was developed. By introducing auxiliary variables, the original weighted sum-rate maximization problem was gradually reformulated into an equivalent problem that is more amenable to block-wise optimization, thereby enabling sequential updates of the downlink transmit beamforming, uplink receive combining, and uplink transmit powers in each iteration. Compared with the iterative scheme with fixed uplink power and the ZF/MMSE baseline, the proposed method can coordinate the coupling between uplink and downlink links more effectively and thus achieve a higher weighted sum-rate while maintaining favorable convergence behavior.

Simulation results demonstrated the advantage of the proposed joint optimization method from multiple perspectives. First, under the default parameter setting, the proposed method reaches a stable performance level within a relatively small number of iterations. Second, as the base-station transmit power increases, the proposed scheme consistently outperforms the two benchmark schemes, indicating that the joint optimization framework can make better use of the available power resources. Third, as the number of base-station antennas increases, the system performance improves continuously, and the proposed method remains superior over the entire antenna range, showing that it can effectively exploit the additional spatial degrees of freedom to suppress multi-user interference and residual self-interference. Overall, the results verify that the joint optimization of transceiver beamforming and uplink transmit power is of significant importance for improving the performance of full-duplex multi-user MIMO systems, which is also in line with recent developments in full-duplex and related joint optimization studies [2, 3].

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