Linear Precoding for Massive MIMO Systems with IQ Imbalance

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Abstract. The massive multiple-input multiple-output (MIMO) system is one of the most promising techniques, which extends degrees of freedom, increases the throughput of systems, supports more data streams and decreases transmit power. However, using cheap hardware in massive MIMO system can affect the overall performance of the system and deteriorate the user experience. The IQ imbalance caused by using cheap hardware is one of the important factors affecting system performance. To solve this problem, this paper proposes the design of precoding matrix based on the minimum mean square error (MMSE) criterion to suppress the influence of IQ imbalance on system performance. The numerical simulation results validate the effectiveness of the proposed algorithm, and show that the bit error rate (BER) performance of the proposed algorithm has obvious better than that of ZF, BD and WL-BD precoding.

Keywords: Massive MIMO · IQ imbalance · Minimum mean square error
Linear precoding · Bit error rate

1 Introduction

Massive multiple-input multiple-output (MIMO) extends degrees of freedom, increases the throughput of systems, supports more data streams and decreases transmit power by deploying excessive number of antennas at the base station (BS). Based on the above advantages, massive MIMO will become one of the key technologies of 5G wireless communication in the future [1–10].

However, due to the employment of an excessive number of transmit and receive antennas, the circuit power and cost of radio frequency (RF) chains in large-scale MIMO systems is much higher than that of conventional MIMO systems, which is one of its drawbacks. Fortunately, this problem can be solved by using cheap hardware. Because large-scale MIMO can limit performance degradation by providing sufficient degree of freedom in case of individual antenna units fail. Therefore, large-scale MIMO systems can relax the hardware accuracy requirements [8]. Unfortunately, the use of

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inexpensive hardware has a greater possibility of deteriorating system performance, such as in-phase and quadrature-phase (IQ) imbalance. IQ imbalance (IQI) refers to the mismatches between the real and imaginary parts of the complex signal. This paper focuses on the impact of IQI on system performance. In addition, the use of limited precision analog hardware will also produce IQ imbalance [10–12].

IQ imbalance degrades the overall performance of the system, therefore, deteriorates user experience. One of the ways to overcome IQ imbalance is measuring and compensating IQ imbalance parameters in each antenna [10, 12]. Reference [19] proposed a compensation algorithm for overcoming IQ imbalance in single-input single-output (SISO) system. However, due to large-scale MIMO systems are equipped with excessive antennas, the calculation of the compensation algorithm is too complicated, and the cost is too expensive in real implementations [10]. Therefore, some researchers have proposed to solve IQ imbalance by widely linear signal processing. Reference [14] proposed widely-linear block diagonal (WL-BD) precoding scheme. The numerical simulation results show that the WL-BD precoding scheme is superior to block diagonal (BD) precoding algorithm when the antennas of the BS occur IQ imbalance. Though reference [15] designs the precoding scheme based on the minimum mean square error (MMSE) criterion, its results are only for single user MIMO systems without IQI. Reference [12] proposed widely-linear regularized zero-forcing (WL-RZF) precoding scheme, which results indicate that when base station antennas are more than total user antennas, the proposed precoding scheme can eliminate the effect of IQ imbalance and the system sum rate close to the systems without IQ imbalance. In order to reduce the complexity of computing inverse of high-dimensional matrix, reference [18] proposed the reduced-rank widely linear precoding algorithm based on Krylov Subspace (KS), which greatly reduce the calculate complexity of widely linear precoding.

Based on the above analysis, this paper proposes a precoding algorithm based on MMSE in a single-cell downlink massive MIMO system to overcome IQ imbalance. Numerical simulation results illustrate that with the number of users increasing, the bit error rate (BER) performance is better than that of ZF, BD and WL-BD precoding algorithm. The structure of this article is described as below. The system model is introduced in Sect. 2. In Sect. 3, we can obtain the closed-form solution of the precoding matrix based on the MMSE criterion when the BS has IQ imbalances in large-scale MIMO systems. In Sect. 4, the simulation analysis of the proposed precoding algorithm and ZF, BD, WL-BD precoding algorithm at bit error ratio do the comparison. We also analysis bit error ratio of the four precoding schemes under different the number of base station antennas and users. Conclusions are drawn in Sect. 5.

The symbols used in this article are as follows: $(\boldsymbol{A})^T$, $(\boldsymbol{A})^H$ represent the matrix transpose and conjugate transpose; $tr\{\boldsymbol{A}\}$, $\|\boldsymbol{A}\|_F = \sqrt{tr\{\boldsymbol{A}^H\boldsymbol{A}\}}$ represent matrix trace and the Frobenius norm respectively. $E\{\bullet\}$ denotes expectation.

2 System Model

The research in this paper is carried out in downlink of a single cell with a base station (BS) and K users. The BS deploys N antennas and the k-th user has M_k antennas.

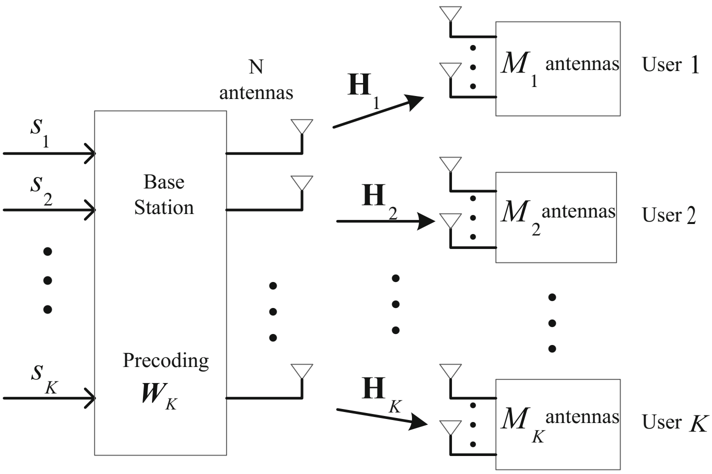

Fig. 1. System model

The number of users' antennas is $M = \sum_{k=1}^{K} M_k$. Assuming that BS has perfect channel state information (CSI), and users are distributed with the same power. The system model is shown in Fig. 1.

The MIMO channel of user k is denoted as $\boldsymbol{H}_k \in \mathbb{C}^{M_k \times N}$. The precoding matrix $\boldsymbol{W} \in \mathbb{C}^{N \times M}$ is defined for all users. The transmit signal and the precoding vector of k-th user are denoted respectively as $\boldsymbol{s}_k \in \mathbb{C}^{M_k \times L_k}$ and $\boldsymbol{W}_k \in \mathbb{C}^{N \times M_k}$, where L_k is the length of signal vector $\boldsymbol{s}_k$. Then, the combined precoding matrix and signal matrix are given by $\boldsymbol{W} = [\boldsymbol{W}_1, \cdots, \boldsymbol{W}_K]$, $\boldsymbol{s} = [\boldsymbol{s}_1^T, \cdots, \boldsymbol{s}_K^T]^T$. We assume the signal before precoding of users are independent, i.e.,$\forall k \neq j$, $E\{\boldsymbol{s}_k \boldsymbol{s}_j^H\} = 0$, $E\{\boldsymbol{s}_k \boldsymbol{s}_k^H\} = \boldsymbol{I}_{L_k}$.The precoded signal vector is $\boldsymbol{x} = \boldsymbol{W}\boldsymbol{s}$. The BS transmits the precoded signal $\boldsymbol{x}$ to the users, and then passes through the channel to the user terminal. Assume that there is IQ imbalance at the BS in a large-scale MIMO system. Then the precoded signal $\boldsymbol{x}_n$ transmit by the n-th antenna will become $a_{n1}\boldsymbol{x}_n + a_{n2}\boldsymbol{x}_n^*$, where a_{n1} and a_{n2} are imbalance parameters. We can obtain their values by applying the formula (1) [9]:

$$\begin{aligned} a_{n1} &= \cos(\theta_n/2) + jg_n \sin(\theta_n/2) \\ a_{n2} &= g_n \cos(\theta_2/2) - j \sin(\theta_n/2) \end{aligned} \tag{1}$$

where θ_n and g_n are relative phase error and gain error of I and Q, respectively. Generally, their values are 2°, 0.25 [9]. When θ_n and g_n are zero, the massive MIMO system without the presence of IQ imbalance at the BS.

When the BS has IQ imbalance, we can get the k-th received signal $\boldsymbol{y}_k \in \mathbb{C}^{M_k \times L_k}$:

$$\boldsymbol{y}_k = \beta \boldsymbol{H}_k \boldsymbol{A}_1 \boldsymbol{x} + \beta \boldsymbol{H}_k \boldsymbol{A}_2 \boldsymbol{x}^* + \boldsymbol{n}_k \tag{2}$$

From Eq. (2), we know that the k-th received signal is disturbed by its conjugate signal, so that the error of the received signal becomes larger, which is the adverse effect of IQ imbalance on massive MIMO system. The IQI parameters of all antennas at the BS side can be expressed as diagonal matrices $\boldsymbol{A}_1 = diag\{a_{11}, \cdots, a_{N1}\}$, $\boldsymbol{A}_2 = diag\{a_{12}, \cdots, a_{N2}\}$; The k-th additive white Gaussian noise vector can be denoted as $\boldsymbol{n}_k \sim CN(0, \boldsymbol{I}_{M_k})$, the entries of which are independent distributed variables with zero mean and variance 1.

3 Precoding Design

A transformation of a matrix or vector that transforms the complex matrix or vector into the real and imaginary parts is introduced in this section. Then we use this transformation to design the precoding matrix based on the MMSE criterion.

3.1 T Transformation

T transformation can separate the complex matrix or vector into the real and imaginary parts to form a new matrix or vector. It is defined as [20]:

$$\begin{aligned} T(\boldsymbol{x}) &= \begin{bmatrix} \mathrm{Re}(\boldsymbol{x}) \\ \mathrm{Im}(\boldsymbol{x}) \end{bmatrix}, \\ T(\boldsymbol{X}) &= \begin{bmatrix} \mathrm{Re}(\boldsymbol{X}) & -\mathrm{Im}(\boldsymbol{X}) \\ \mathrm{Im}(\boldsymbol{X}) & \mathrm{Re}(\boldsymbol{X}) \end{bmatrix} \end{aligned} \tag{3}$$

where $\mathrm{Re}(\bullet)$ represents the real parts and $\mathrm{Im}(\bullet)$ represents imaginary parts of a vector or matrix. From reference [20], we can get some properties of this transformation:

$$\begin{aligned} &T(\boldsymbol{AB}) = T(\boldsymbol{A})T(\boldsymbol{B}),\ T(\boldsymbol{A}^{-1}) = [T(\boldsymbol{A})]^{-1}, \\ &T(\boldsymbol{x}+\boldsymbol{y}) = T(\boldsymbol{x}) + T(\boldsymbol{y}),\ T(\boldsymbol{Ax}) = T(\boldsymbol{A})T(\boldsymbol{x}), \\ &T(\boldsymbol{A}+\boldsymbol{B}) = T(\boldsymbol{A}) + T(\boldsymbol{B}),\ T(\boldsymbol{A}^H) = [T(\boldsymbol{A})]^H, \\ &\det(T(\boldsymbol{A})) = [\det(\boldsymbol{A})]^2 = \det(\boldsymbol{AA}^H) \end{aligned} \tag{4}$$

Then we apply T transformation to rewrite the Eq. (2), and get $\widetilde{\boldsymbol{y}}_k$:

$$\begin{aligned} \widetilde{\boldsymbol{y}}_k &= T(\boldsymbol{y}_k) \\ &= T(\beta \boldsymbol{H}_k \boldsymbol{A}_1 \boldsymbol{x} + \beta \boldsymbol{H}_k \boldsymbol{A}_2 \boldsymbol{x}^* + \boldsymbol{n}_k) \\ &= T(\beta \boldsymbol{H}_k) T(\boldsymbol{A}_1 \mathbf{x} + \boldsymbol{A}_2 \boldsymbol{x}^*) + T(\boldsymbol{n}_k) \\ &= \beta T(\boldsymbol{H}_k)[T(\boldsymbol{A}_1) + T(\boldsymbol{A}_2)E_N]T(\boldsymbol{x}) + T(\boldsymbol{n}_k) \end{aligned} \tag{5}$$

For simplicity, we define $\widetilde{\boldsymbol{H}_k} = T(\boldsymbol{H}_k)$, $\widetilde{\boldsymbol{A}} = [T(\boldsymbol{A}_1) + T(\boldsymbol{A}_2)\boldsymbol{E}_N]$, $\widetilde{\boldsymbol{x}} = T(\boldsymbol{x})$, $\widetilde{\boldsymbol{n}_k} = T(\boldsymbol{n}_k)$, where $\boldsymbol{E}_N = diag\{\boldsymbol{I}_N, -\boldsymbol{I}_N\}$. Equation (5) can be equivalent:

$$\widetilde{\boldsymbol{y}}_k = \beta\widetilde{\boldsymbol{H}_k}\widetilde{\boldsymbol{A}}\widetilde{\boldsymbol{x}} + \widetilde{\boldsymbol{n}_k} \tag{6}$$

From above analysis, we know that the precoded signal is $\boldsymbol{x} = \boldsymbol{Ws}$. Applying T transformation to $\boldsymbol{x}$ gives $\widetilde{\boldsymbol{x}} = T(\boldsymbol{Ws}) = T(\boldsymbol{W})T(\boldsymbol{s}) = \widetilde{\boldsymbol{W}}\widetilde{\boldsymbol{s}}$, where $\widetilde{\boldsymbol{W}} = [\widetilde{\boldsymbol{W}_1}, \cdots, \widetilde{\boldsymbol{W}_K}]$, $\widetilde{\boldsymbol{s}} = [\widetilde{\boldsymbol{s}_1^T}, \cdots, \widetilde{\boldsymbol{s}_K^T}]^T$, β is power limiting factor which satisfied $E\left\{\|\beta\widetilde{\boldsymbol{x}}\|^2\right\} = E\left\{\left\|\beta\widetilde{\boldsymbol{W}}\widetilde{\boldsymbol{s}}\right\|^2\right\} = P$, that is, $E\left\{\left\|\beta\widetilde{\boldsymbol{W}}\right\|^2\right\} = P$, P is the total user's transmit power. We can rewrite (6):

$$\widetilde{\boldsymbol{y}}_k = \beta\widetilde{\boldsymbol{H}_k}\widetilde{\boldsymbol{A}}\widetilde{\boldsymbol{W}}\widetilde{\boldsymbol{s}} + \widetilde{\boldsymbol{n}_k} \tag{7}$$

We denote $\widetilde{\boldsymbol{y}} = [\widetilde{\boldsymbol{y}}_1^T, \cdots, \widetilde{\boldsymbol{y}}_K^T]^T$, $\widetilde{\boldsymbol{H}} = [\widetilde{\boldsymbol{H}_1^T}, \cdots, \widetilde{\boldsymbol{H}_K^T}]^T$, $\widetilde{\boldsymbol{n}} = [\widetilde{\boldsymbol{n}_1^T}, \cdots, \widetilde{\boldsymbol{n}_K^T}]^T$, then the received signal of all users is:

$$\widetilde{\boldsymbol{y}} = \beta\widetilde{\boldsymbol{H}}\widetilde{\boldsymbol{A}}\widetilde{\boldsymbol{W}}\widetilde{\boldsymbol{s}} + \widetilde{\boldsymbol{n}} \tag{8}$$

3.2 Precoding Algorithm

Based on MMSE criterion, the problem of precoding matrix can be formulated as:

$$\begin{aligned} &\min_{\widetilde{W}} E\left\{\left\|\beta^{-1}\widetilde{\boldsymbol{y}} - \widetilde{\boldsymbol{s}}\right\|^2\right\} \\ &s.t \quad \beta^2\left\|\widetilde{\boldsymbol{A}}\widetilde{\boldsymbol{W}}\right\|^2 = P \end{aligned} \tag{9}$$

The solution of the (9) is the optimal solution of the proposed precoding algorithm. From (8), we can get:

$$\begin{aligned} E\left\{\left\|\beta^{-1}\widetilde{\boldsymbol{y}} - \widetilde{\boldsymbol{s}}\right\|^2\right\} &= E\left\{\left\|\widetilde{\boldsymbol{H}}\widetilde{\boldsymbol{A}}\widetilde{\boldsymbol{W}}\widetilde{\boldsymbol{s}} + \beta^{-1}\widetilde{\boldsymbol{n}} - \widetilde{\boldsymbol{s}}\right\|^2\right\} \\ &= E\left\{\left\|\widetilde{\boldsymbol{H}}\widetilde{\boldsymbol{A}}\widetilde{\boldsymbol{W}}\widetilde{\boldsymbol{s}} - \widetilde{\boldsymbol{s}}\right\|^2 + \beta^{-2}\|\boldsymbol{n}\|^2\right\} \end{aligned} \tag{10}$$

From (9), we can obtain $\beta^2 = P\Big/\left\|\widetilde{\boldsymbol{A}}\widetilde{\boldsymbol{W}}\right\|^2$. Then, (11) is given by:

$$\begin{aligned} E\{\|\beta^{-1}\widetilde{\boldsymbol{y}} - \widetilde{\boldsymbol{s}}\|^2\} &= E\{\left\|\widetilde{\boldsymbol{H}}\widetilde{\boldsymbol{A}}\widetilde{\boldsymbol{W}}\widetilde{\boldsymbol{s}} - \widetilde{\boldsymbol{s}}\right\|^2\} + \frac{\left\|\widetilde{\boldsymbol{A}}\widetilde{\boldsymbol{W}}\right\|^2}{P}M\sigma_n^2 \\ &= E\{tr(\widetilde{\boldsymbol{H}}\widetilde{\boldsymbol{A}}\widetilde{\boldsymbol{W}}\widetilde{\boldsymbol{s}} - \widetilde{\boldsymbol{s}})(\widetilde{\boldsymbol{H}}\widetilde{\boldsymbol{A}}\widetilde{\boldsymbol{W}}\widetilde{\boldsymbol{s}} - \widetilde{\boldsymbol{s}})^H\} + \frac{\left\|\widetilde{\boldsymbol{A}}\widetilde{\boldsymbol{W}}\right\|^2}{P}M\sigma_n^2 \\ &= tr(\widetilde{\boldsymbol{W}}^H\widetilde{\boldsymbol{A}}^H\widetilde{\boldsymbol{H}}^H\widetilde{\boldsymbol{H}}\widetilde{\boldsymbol{A}}\widetilde{\boldsymbol{W}} - \widetilde{\boldsymbol{H}}\widetilde{\boldsymbol{A}}\widetilde{\boldsymbol{W}} - \widetilde{\boldsymbol{W}}^H\widetilde{\boldsymbol{A}}^H\widetilde{\boldsymbol{H}}^H + \boldsymbol{I}_M + \frac{\widetilde{\boldsymbol{W}}^H\widetilde{\boldsymbol{A}}^H\widetilde{\boldsymbol{A}}\widetilde{\boldsymbol{W}}}{P}M\sigma_n^2) \end{aligned} \tag{11}$$

We define:

$$f(\tilde{\boldsymbol{W}}) = \widetilde{\boldsymbol{W}}^H\widetilde{\boldsymbol{A}}^H\widetilde{\boldsymbol{H}}^H\widetilde{\boldsymbol{H}}\widetilde{\boldsymbol{A}}\widetilde{\boldsymbol{W}} - \widetilde{\boldsymbol{H}}\widetilde{\boldsymbol{A}}\widetilde{\boldsymbol{W}} - \widetilde{\boldsymbol{W}}^H\widetilde{\boldsymbol{A}}^H\widetilde{\boldsymbol{H}}^H + \boldsymbol{I}_M + \frac{\widetilde{\boldsymbol{W}}^H\widetilde{\boldsymbol{A}}^H\widetilde{\boldsymbol{A}}\widetilde{\boldsymbol{W}}}{P}M\sigma_n^2 \quad (12)$$

In order to get $\widetilde{\boldsymbol{W}}$, we assume that $\widetilde{\boldsymbol{W}}$ is dependent on $\widetilde{\boldsymbol{W}}^H$. Then, the first order derivatives of (12) on $\widetilde{\boldsymbol{W}}$ is given by:

$$\frac{\partial f(\widetilde{\boldsymbol{W}})}{\partial \widetilde{\boldsymbol{W}}} = \widetilde{\boldsymbol{W}}^H\widetilde{\boldsymbol{A}}^H\widetilde{\boldsymbol{H}}^H\widetilde{\boldsymbol{H}}\widetilde{\boldsymbol{A}} - \widetilde{\boldsymbol{H}}\widetilde{\boldsymbol{A}} + \frac{\widetilde{\boldsymbol{W}}^H\widetilde{\boldsymbol{A}}^H\widetilde{\boldsymbol{A}}}{P}M\sigma_n^2 \quad (13)$$

Letting the above formula be equal to zero, we can obtain the solution of the $\widetilde{\boldsymbol{W}}$:

$$\begin{aligned}
&\widetilde{\boldsymbol{W}}^H\widetilde{\boldsymbol{A}}^H\widetilde{\boldsymbol{H}}^H\widetilde{\boldsymbol{H}}\widetilde{\boldsymbol{A}} - \widetilde{\boldsymbol{H}}\widetilde{\boldsymbol{A}} + \frac{\widetilde{\boldsymbol{W}}^H\widetilde{\boldsymbol{A}}^H\widetilde{\boldsymbol{A}}}{P}M\sigma_n^2 = 0 \\
&\widetilde{\boldsymbol{W}}^H(\widetilde{\boldsymbol{A}}^H\widetilde{\boldsymbol{H}}^H\widetilde{\boldsymbol{H}}\widetilde{\boldsymbol{A}} + \frac{\widetilde{\boldsymbol{A}}^H\widetilde{\boldsymbol{A}}}{P}M\sigma_n^2) = \widetilde{\boldsymbol{H}}\widetilde{\boldsymbol{A}} \\
&\widetilde{\boldsymbol{W}}^H = \widetilde{\boldsymbol{H}}\widetilde{\boldsymbol{A}}(\widetilde{\boldsymbol{A}}^H\widetilde{\boldsymbol{H}}^H\widetilde{\boldsymbol{H}}\widetilde{\boldsymbol{A}} + \frac{\widetilde{\boldsymbol{A}}\widetilde{\boldsymbol{A}}^H}{P}M\sigma_n^2)^{-1} \\
&\widetilde{\boldsymbol{W}} = (\widetilde{\boldsymbol{A}}^H\widetilde{\boldsymbol{H}}^H\widetilde{\boldsymbol{H}}\widetilde{\boldsymbol{A}} + \frac{\widetilde{\boldsymbol{A}}\widetilde{\boldsymbol{A}}^H}{P}M\sigma_n^2)^{-1}\widetilde{\boldsymbol{A}}^H\widetilde{\boldsymbol{H}}^H
\end{aligned} \quad (14)$$

4 Numerical Results

This section analyzes the proposed algorithm in the previous section by numerical simulating in the downlink of a single-cell with IQ imbalance. The BER of the proposed precoding algorithm is comparable to that of ZF, BD, WL-BD algorithms in this section. It is assumed that the total number of antennas at the BS is $N = 100$, the total number of users is $K = 50$, and each user has $M_k = 2$ antennas. According to reference [9], we know the general value of IQ imbalance parameters g_n and θ_n are 0.25, 2°, respectively. The definition of signal to noise ratio (SNR) is $P_k/M_k\sigma_n^2$. Based on the modulation of quadrate phase shift keying (QPSK), we can calculate the bit error ratio (BER).

Figure 2 shows the BER comparison of the proposed precoding scheme, ZF, BD, and WL-BD in the single-cell multi-user scenarios under the presence of IQ imbalance at the BS. We can clearly see that the BER of the proposed precoding scheme and ZF, BD and WL-BD are decreasing with the increase of SNR from Fig. 2. When the SNR is less than 8 dB, the gap between the proposed algorithm and other algorithms is gradually widening; When the SNR is greater than 8 dB and less than 10 dB, the gap between the proposed algorithm and WL-BD algorithms is narrow. Although the BER of the proposed algorithm is inferior to the algorithm when the value of signal to noise ratio is more than 10 dB, the BER of the proposed precoding scheme is superior to ZF, BD and the calculate complexity of WL-BD is too high.

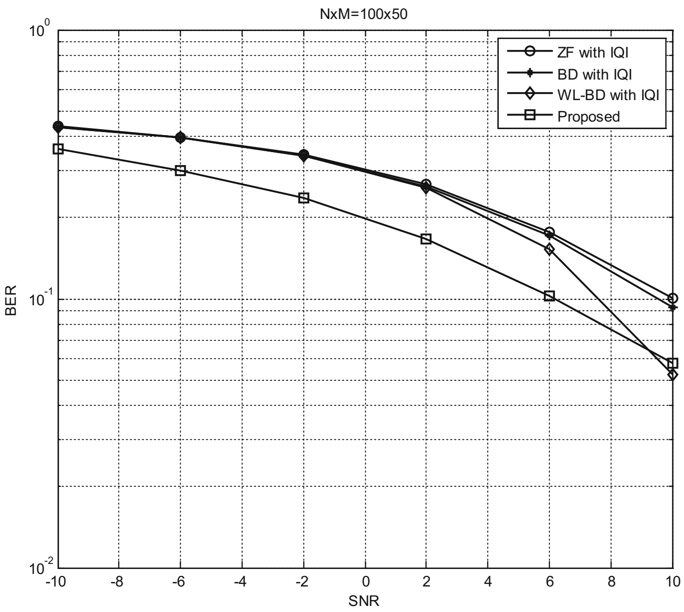

Fig. 2. Comparison of BER for different precoding algorithms on SNR

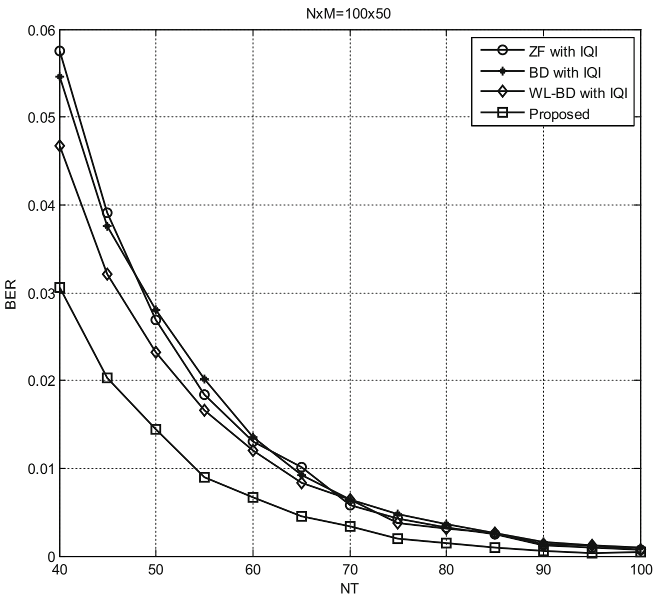

Fig. 3. Comparison of BER for different precoding algorithms on antennas of BS

Figure 3 shows the BER of the four precoding schemes when the number of the BS antennas is different. It is assumed that SNR is 2 dB, the number of users is 50, and every user has 2 antennas. Figure 3 clearly shows that the BER of the proposed precoding scheme and ZF, BD and WL-BD algorithms are decreasing when the number of antennas is increasing. The proposed algorithm has been superior to ZF, BD and WL-BD algorithms when the number of antennas at the BS increased from 40 to 100.

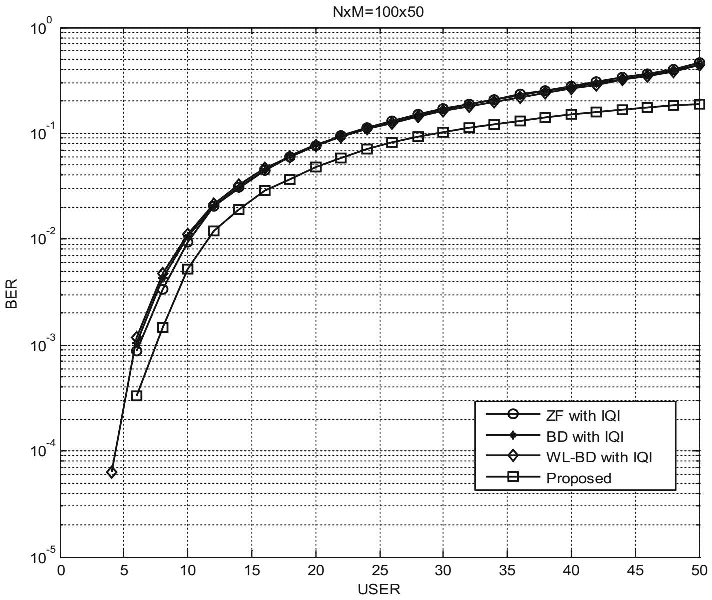

Fig. 4. Comparison of BER for different precoding algorithms on the numbers of users

Figure 4 shows the BER of the four precoding schemes for different the number of users, when the single-cell multi-user scenarios under the base station has IQ imbalance. Assuming that the value of SNR is 2 dB; the number of the BS antennas is 100. As can be seen from Fig. 4, with the number of users increasing, the BER of the four precoding scheme is increasing, the performance of system is declining, the emergence of this situation is reasonable. Though the number of users is increasing, the proposed algorithm has obvious advantages. The reason is the BER of other algorithms has been increasing, and the BER of this algorithm increased tend to be slow. This shows that this algorithm is suitable for application in massive MIMO scenarios.

5 Conclusions

Aiming at the problem of IQ imbalance in the large-scale MIMO system, this paper obtains a solution to the precoding matrix based on MMSE criterion to eliminate IQ imbalance. The numerical simulation results show that compared with ZF, BD and WL-BD precoding scheme, the BER of the proposed scheme has obvious advantages. In this paper, the algorithm offsets the effect of IQ imbalance on system performance, reduces the interference among users, and improves the overall performance of the system. However, there are still some deficiencies in this paper. For example, we do not consider the the scenario of total number of the BS receiving antennas is more than transmiting antennas and multi-cell scenarios, which will be the direction for further research in the future.

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