Linear Massive MIMO Precoding Based on Nonlinear High-Power Amplifier

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Abstract. Large-scale multiple-input multiple-output (MIMO) system has the advantages of high energy efficiency and spectrum utilization. But using some cheap hardware may cause some problems, such as nonlinearity of the high power amplifier (HPA). When HPA works in the nonlinear region, it will affect the received signal and greatly reduce the performance of the system. In this paper, we first study the impact caused by nonlinear HPA, and then we optimize the traditional precoding algorithm to design an improved precoding algorithm which can reduce the impact. The simulation results show that the proposed algorithms perform better in bit error ratio and system capacity compared to the block of diagonalization (BD) precoding algorithm and forced zero (ZF) precoding algorithm, especially in the condition of high signal to noise ratio (SNR). So we can draw the conclusion that the algorithms proposed in this paper are able to reduce the impact caused by nonlinear HPA to the system.

Keywords: Massive MIMO · High-power amplifier (HPA)
Precoding algorithm · Bit error ratio

1 Introduction

HPA plays an important role in wireless communication system. In general, in order to simplify the performance analysis and system design, we usually assume that HPA works in the linear region. However, in fact, this case is not always founded. HPA will also work in the nonlinear region in some cases. When it works in the nonlinear region, nonlinear distortion will be introduced to the received signal including amplitude distortion and phase distortion.

There are two kinds of nonlinear HPA model: memoryless models and memory models [1]. Between them, depending on their type, memoryless HPA have their own amplitude-to-amplitude (AM/AM) and amplitude-to-phase (AM/PM) conversion

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formulas. [2] mainly introduces three memoryless models: the TWTA model [3], SSPA model [4] and SEL model [5]. The memory HPA models include Volterra, Wiener, Hammerstein and memory polynomial models.

In recent years, [5] have studied the impact to the symbol error probability (SEP) caused by nonlinear HPA. [6] study the influence of nonlinear HPA on the system capacity and the average SEP of MIMO system, in which the signal is encoded by STBC. To deal with the problem caused by nonlinear HPA, the receiver or transmitter will be demanded to compensate to eliminate or reduce the impact of the nonlinear HPA. In terms of compensation scheme, they can be divided into two kinds: compensate in the transmitter or receiver respectively. Power back-off, peak to average power ratio (PAPR) reduction techniques methods [1–10] belong to the processing at the transmitter. The other kind contains the methods of post-distortion and iterative detection [1].

To resolve the problem, we first analyze the impact caused by nonlinear HPA on the transmission signal in the base station. Then we improve the traditional precoding algorithms, such as BD, ZF [11, 12], to present the improved precoding algorithms which can reduce the impact according to the impact caused by the nonlinear HPA. The simulation results show that the improved algorithms make up for the impact caused by nonlinear HPA. When HPA works in the linear region, the performance of traditional algorithms and improved algorithms are similiar. When HPA works in the nonlinear region, the performance of it is better than that of the traditional algorithms.

The structure of this paper is discribed below: the system model is introduced in the second section, which includes the impact of nonlinear HPA on the signal. The third section mainly analyzes the impact of the nonlinear HPA in details and puts forward the improvement scheme. The fourth section shows the numerical simulation results. When the HPA works in the nonlinear region, we compare the proposed precoding algorithm with BD and ZF precoding algorithms in term of bit error ratio and system capacity. The fifth section is the summary of the full paper.

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

This paper mainly studies on the single cell scenario, where the central base station services k users and the k-th user has M_k antennas. Therefore, the antennas of all users are $M = \sum_{k=1}^{K} M_k$. The base station has $N(N \geq 100)$ antennas. Under the Assumption that channel state information (CSI) is known to the base station and the power allocation of all the users are the same, the system model is shown in Fig. 1.

In Fig. 1, $W \in \mathbb{C}^{N \times M}$ is the precoding matrix of all users. $\boldsymbol{H}_k \in \mathbb{C}^{M_k \times N}$ is the channel matrix of k-th user, each element of which is a Gauss random variable whose mean is zero and variance is one. $s_k \in \mathbb{C}^{M_k}$ is the k-th user's original signal vector.

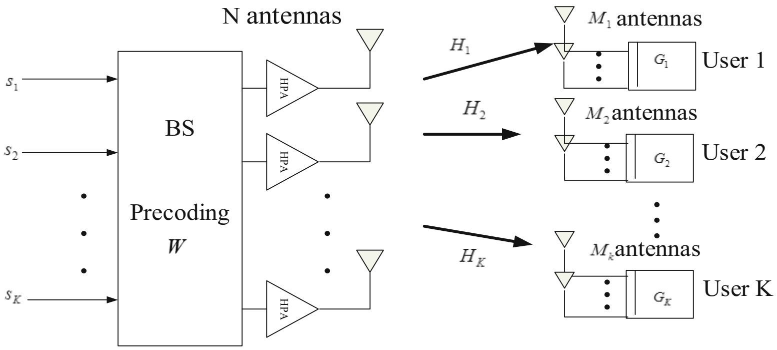

Fig. 1. System model

Thus, when the HPA is working in the linear region, we can obtain that the received signal of all users $\boldsymbol{y} = [y_1, y_2, \cdots, y_k]^T$ is given by

$$\boldsymbol{y} = \boldsymbol{HWs} + \boldsymbol{n} = \boldsymbol{HX} + \boldsymbol{n} \tag{1}$$

where $\boldsymbol{H} = [H_1^T, H_2^H, \cdots, H_k^T]^T$ is the channel matrix of all users. And $\boldsymbol{X} \in \mathbb{C}^N$ is the signal matrix after precoding. $\boldsymbol{n} \in \mathbb{C}^M$ is the user's noise vector, each element of which is a Gauss random variable whose mean is zero and variance is σ^2.

When HPA works in the nonlinear region, in order to simplify the expression, modulated signal can be rewritten into polar form

$$s_{in} = re^{j\theta} \tag{2}$$

Passing through nonlinear HPA, the signal can be expressed as:

$$s_{out} = f_A(r)e^{jf_P(r)}e^{j\theta} \tag{3}$$

where $f_A(\cdot)$ and $f_P(\cdot)$ are AM/AM and AM/PM conversion formulas. Next, we will list some types of memoryless HPA model. And we mainly analyze the first one.

The first is SSPA, whose conversion formulas are

$$f_A(r) = \frac{r}{\left[1 + (\frac{r}{A_{os}})^{2\beta}\right]^{1/2\beta}},\ f_P(r) = 0 \tag{4}$$

where A_{os} is the output voltage, and β is the conversion factor.

The second is TWTA, whose conversion formulas are

$$f_A(r) = A_{is}^2 \frac{r}{r^2 + A_{is}^2},\ f_P(r) = \frac{\pi}{3}\frac{r^2}{r^2 + A_{is}^2} \tag{5}$$

where A_{is} is the input voltage.

The third is SEL, whose conversion formulas are

$$f_A(r) = \begin{cases} r & r \le A_{is} \\ A_{is} & r > A_{is} \end{cases}, \quad f_P(r) = 0 \tag{6}$$

When the HPA is operating in the nonlinear region, passing through the channel, we can get the received signal $\boldsymbol{y} = [y_1, y_2, \cdots, y_k]^T$

$$\boldsymbol{y} = \boldsymbol{Hu} + n \tag{7}$$

where $\boldsymbol{u} \in \mathbb{C}^N$ is the output signal which has been effected by nonlinear HPA. According to (3), we can get $u_i (i = 1, 2, \cdots, N)$

$$u_i = f_A(|x_i|)\exp[j(\theta_i + f_P(|x_i|))] \tag{8}$$

It can be seen from (8) that the nonlinear HPA has some impact on the transmitted signal. In the next section, we will analyze the impact of nonlinear HPA and according to the impact, we can propose an improved precoding algorithms.

3 Precoding Design

By (8), we can rewrite the received signal as a product of transmitting signal and the factor

$$u_{ij} = f_A(|x_{ij}|)\exp[j(\theta_{ij} + f_P(|x_{ij}|))] = \frac{f_A(|x_{ij}|)}{|x_{ij}|} x_{ij} \tag{9}$$

As can be seen from the above that, passing through the nonlinear HPA, the emission signal will multiply a factor $d_{ij} = \frac{f_A(|x_{ij}|)}{|x_{ij}|}$, which represents the level of the impact. And we can see from the factor that the level of the impact only relies on the signal’ s amplitude.

Hence, we can construct a function by (4) and (9)

$$\tilde{y} = \frac{f_A(\frac{1}{\tilde{x}})}{\frac{1}{\tilde{x}}} \exp(f_P(\frac{1}{\tilde{x}})) = \frac{1}{\left[1 + \left(\frac{1}{A_{os}\tilde{x}}\right)^{2\beta}\right]^{1/2\beta}} \tag{10}$$

where $\tilde{x} > 0$. For the convenience of analysis, we assume $t = 1/\tilde{x}$ and $A_{os} = 1$. $\beta \in [2, 3]$. So

$$\begin{aligned} \lim_{\tilde{x} -> \infty} 1/\tilde{x} &= \lim_{t -> 0} t = 0 \\ \lim_{\tilde{x} -> \infty} \tilde{y} &= \lim_{t -> 0} \frac{1}{(1 + t^{2\beta})^{1/2\beta}} \end{aligned} \tag{11}$$

Let $t^{2\beta} = m$, we can get

$$\lim_{\tilde{x}->\infty} \tilde{y} = \lim_{m->0} \left(\frac{1}{1+m}\right)^{1/2\beta} = 1 \tag{12}$$

Because $t > 0, 1 + t^{2\beta} > 1$, that is $\frac{1}{(1+t^{2\beta})^{1/2\beta}} < 1$, The simulation is shown in Fig. 2.

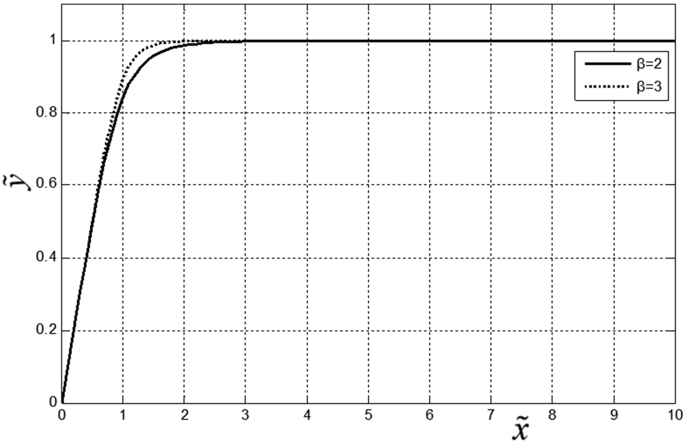

Fig. 2. The curve of relationship between A and B

We can see from Fig. 2 that $\tilde{y}$ increases with $\tilde{x}$ and gradually tends to be plat. When $\tilde{x} > 3$, $\tilde{y}$ gradually tends to be 1 and now the impact of nonlinear will be very small.

From the analysis above, we know that when $\tilde{x}$ is large enough, the impact of nonlinear will be very small. Hence, we can design a new precoding algorithm by dividing a factor α from the traditional precoding algorithm to eliminate the influence of nonlinear HPA. But if α is too large, it will reduce the power of emission signal, and if it is too small, we cannot eliminate the impact. So, in order to get proper α, we structure the following inequality

$$|1 - \tilde{y}| \leq 10^{\theta} \tag{13}$$

where $\theta < 0$ is the precision factor, $\tilde{y}$ is mentioned above. Take (10) into (13)

$$|1 - \tilde{y}| \leq 10^{\theta}$$

$$\left| 1 - \frac{1}{\left[1 + \left(\frac{1}{\tilde{x}A_{os}}\right)^{2\beta}\right]^{1/2\beta}} \right| \leq 10^{\theta}$$

$$\tilde{x} \geq \frac{1}{A_{os}\left[\left(\frac{1}{1-10^{\theta}}\right)^{2\beta} - 1\right]^{1/2\beta}} \tag{14}$$

From above, we can get that when $\alpha = \tilde{x} \geq \frac{1}{A_{os}\left[\left(\frac{1}{1-10^{\theta}}\right)^{2\beta} - 1\right]^{1/2\beta}}$, $\tilde{y}$ meet the need of the precision factor θ. The simulation is shown in Fig. 3

We can see clearly in Fig. 3 that factor α decreases with the increase of precision factor θ and the speed became faster and faster. But, we can see that when the precision is bigger enough and the precision reaches 10^{-4}, the factor α is still around 5. So it meets the need of α.

So, when we use the new precoding matrixes, the received signal can be expressed as

$$u_i = f_A([ws]_i)\exp[j(\theta_i + f_P([ws]_i))] = \frac{f_A([ws]_i)}{[ws]_i}\exp(f_P([ws]_i))[ws]_i = [ws]_i \tag{15}$$

Hence, we can deduce the improved precoding matrix $\boldsymbol{W}_{LNBD} = \boldsymbol{W}_{BD}/\alpha$, $\boldsymbol{W}_{LNZF} = \boldsymbol{W}_{ZF}/\alpha$ (LN represents linear normalization) which can remove the impact of nonlinearity from traditional precoding matrices.

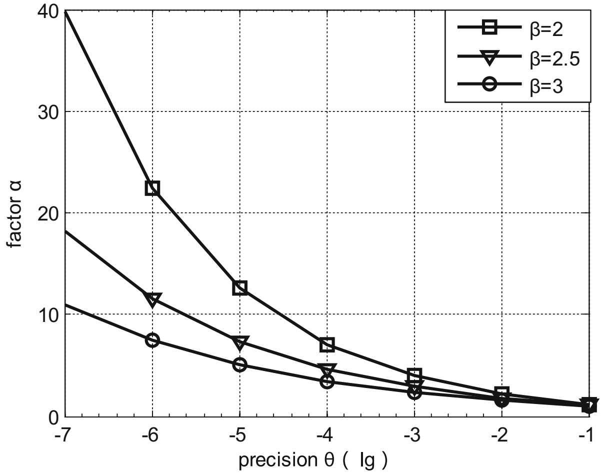

Fig. 3. The factor α under different θ

4 Numerical Results

In order to verify it's performance, we will compare the performance of improved algorithms with the BD and ZF precoding algorithms by simulation. The simulation parameters are as follows: the number of users per cell $k = 50$, the number of antennas

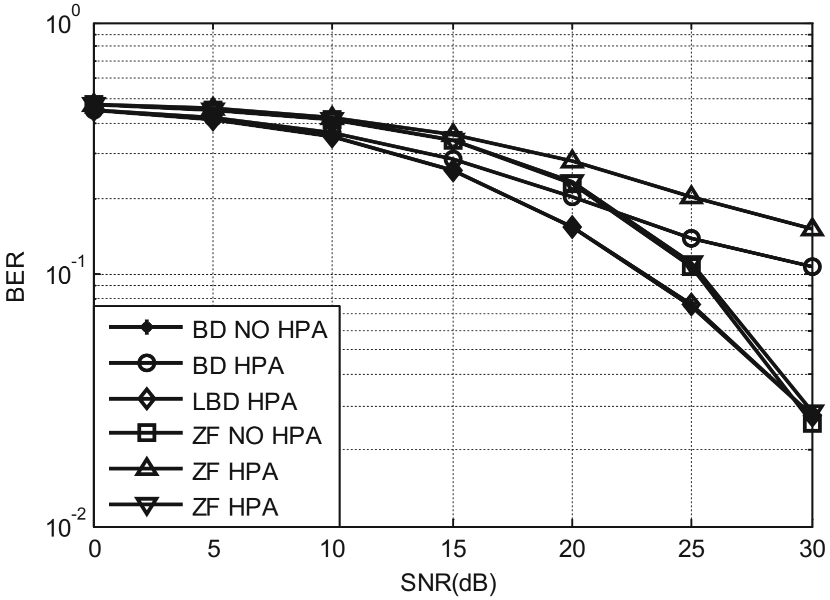

Fig. 4. BER comparison of different precoding algorithms under nonlinear HPA

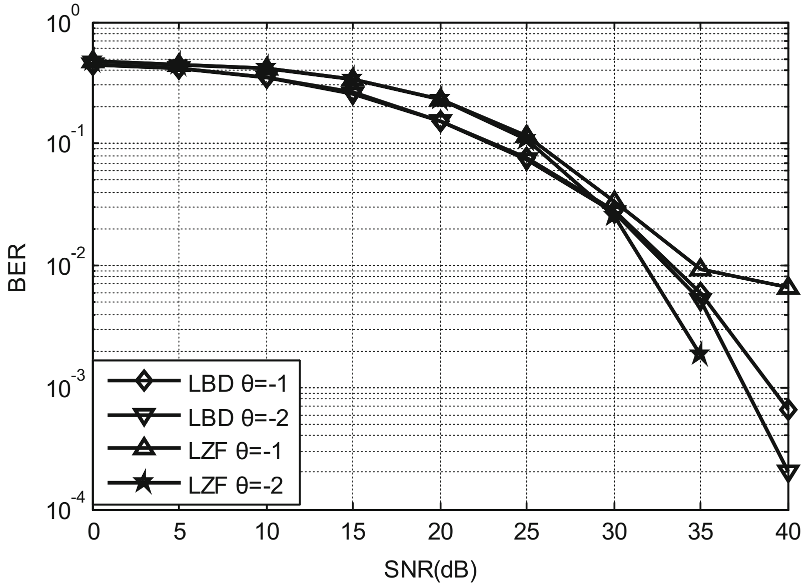

Fig. 5. The impact of different precision on BER

per user $M_k = 2$, noise variance $\sigma_n^2 = 1$. Signal-noise-ratio (SNR) is defined as $P_k / M_k \sigma_n^2$. Bit error ratio (BER) is calculated based on quadrate phase shift keying (QPSK) modulation.

Figure 4 shows the difference between traditional algorithms (BD, ZF) and the proposed algorithms on bit error ratio when HPA works in the nonlinear region and the precision is 0.1. In the low SNR region, these two kinds of algorithms make no difference. With the increase of SNR, the difference between them becomes larger and larger. BER of the proposed algorithms is clearly lower than BD and ZF precoding algorithms. We also can see from it that the BER of the proposed algorithms is similar to that of the condition where there is no influence of nonlinear HPA and it uses the traditional algorithm. So the proposed algorithms remedy the influence of nonlinear HPA on BER.

Figure 5 shows the impact of different precision on BER. As shown in the figure that in the low SNR region, it makes no difference. In high SNR region, the BER decreases as the precision increasing. Under the same θ, the performance of LBD is better than LZF, and as the SNR increases, the difference is getting greater and greater.

Figure 6 shows the difference between traditional algorithms (BD, ZF) and the proposed algorithms on system capacity when HPA works in the nonlinear region and the precision is 0.1. In the low SNR region, these two kinds of algorithms make no difference. With the increase of SNR, the difference between them becomes larger and larger. The capacity of the proposed algorithms is clearly larger than BD and ZF precoding algorithms. So the proposed algorithms remedy the influence of nonlinear HPA on capacity.

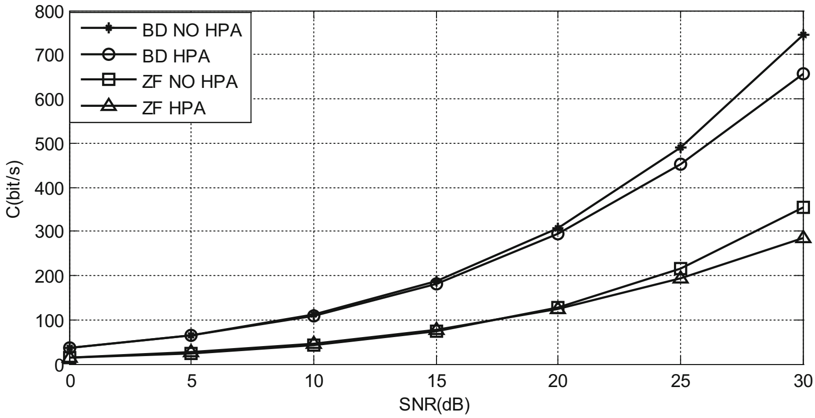

Fig. 6. Capacity comparison of different precoding algorithms under nonlinear HPA

5 Conclusion

Aiming at the problem of nonlinear HPA in large-scale MIMO system, this paper analyzes its impact on the system at first, and then we propose the improved precoding algorithms according to the impact. We can see clearly from the simulation results that the improved algorithms can effectively compensate for the influence of nonlinear HPA caused on the system. In addition to the research mentioned in this paper, it is necessary to further study the situations where there are some other hardware problems accompany with incomplete channel information.

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