Analysis on the Impact of Phase Offset on Massive Antenna Array

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Abstract

Massive antenna array has been recognized as an important technology for the next generation mobile system. Although there are many researches on the theory of massive antenna array system, there are limited studies on the realization aspects about the massive antenna system. This paper investigates the non-ideal factors in the massive antenna system, especially the phase offset. Our analysis and simulation results demonstrate that massive antenna array system have a better performance than the small-scale antenna array system to the phase shift.

1. Introduction

Massive MIMO has become a focus of research since the publication of the paper from Marzetta [1]. The premise of massive MIMO is that the number of base station antennas is much larger than the number of single-antenna terminals. According to random matrix theory, the cross correlation of different terminals will decrease with an increased dimension of channel matrix, thus leading to an decrease of the inter-user interferences. As the dimension tends to be infinite, the noise and interferences vanish. In addition, the transmit power per terminal can be scaled down as the reciprocal of the number of base station antennas without performance loss and linear precoding schemes can also attain the optimality, for instance, MRT (maximum ratio transmission), pre-ZF (pre-zero forcing) and pre-MMSE (pre-minimum mean square error) [2]. It is widely recognized as a key technology of 5G system [6].

The above conclusions hold with perfect CSI at the base station and under favorable propagation characteristics. In a FDD system, the pilot overhead is proportional to the number of antennas and the downlink training, feedback as well as uplink training is necessary. In a TDD system, only the uplink training is needed [3]. But TDD relies on reciprocity of the downlink and uplink channels. On one hand, the reciprocity holds without doubt for the physical propagation channel, but it does not without calibration for the transceiver RF chains. On the other hand, the beam formed by a large number of antennas is very narrow. So, the non-ideal factors may have a significant influence on the performance of massive MIMO system. Only when non-ideal factors can be fully compensated, we can obtain good performance. In the below, firstly the system model is presented. Secondly, the model of non-ideal factors is proposed. Thirdly, the effect of non-ideal factors is analyzed. Finally, the conclusions are verified by simulation results.

2. System Model

Suppose that the base station configures a two-dimension planar antenna array with the horizontal size of N_H and vertical size of N_v. Assume that the horizontal spacing among antenna elements is d_H , the vertical spacing among antenna elements is d_V . Each analog channel consists of a RF chain and an antenna. Each RF link includes five components, such as DAC, radio frequency mixer, filter, power amplifier and circulator. The system model used in our study is depicted as Fig.1.

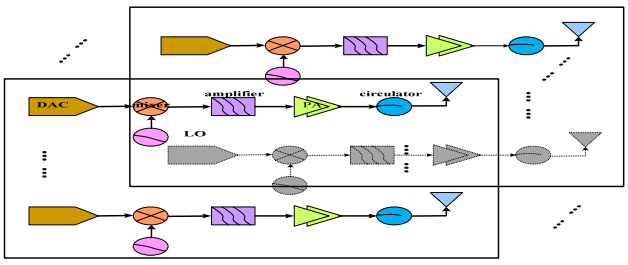

Fig.1. System Model

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3. Signal Model Including Non-Ideal Factors

According to Fig.1, the original signals pass through the DAC, radio frequency mixer, filter, power amplifier and circulator in the RF link to the calibration port. We focus on the analysis of the amplitude error and time delay in this section. The amplitude error is mainly caused by the non-linearity of the active RF components; While the time delay is caused by every component in this link. The total non-ideal RF link output signal is:

$$\begin{aligned} s_i^e &= s_i^{e,o} \cdot s_i^{e,LO} = \mathrm{A}_i^{e,o} \mathrm{A}_i^{e,LO} \mathrm{e}^{\mathrm{j}[(\omega_0+\omega_c)t+(\omega_0+\omega_c)\tau_i^0+\omega_c\tau_i^{LO}+\phi_i+\phi_i^{LO}]} \\ &= \mathrm{A}_i^{e,o} \mathrm{A}_i^{e,LO} \mathrm{e}^{\mathrm{j}[(\omega_0+\omega_c)t+\Delta\phi_i+\Delta\phi_i^{LO}]} \end{aligned} \tag{1}$$

Where $s_i^{e,o}$ and $s_i^{e,LO}$ are the original signal and the local oscillator signal with non-ideal factors respectively. A_i represents the amplitude, ω_0 is the original signal frequency and ω_c is the carrier frequency. $\Delta\phi_i = (\omega_0 + \omega_c)\tau_i^0$ and $\Delta\phi_i^{LO} = \phi_i^{LO} + \omega_c \tau_i^{LO}$.

The errors caused by amplitude and time delay can be easily corrected by the calibration circuit. In the following, we only focus on the analysis of the effects of the local oscillator phase error. Then, the signal transmitted from the ith antenna element can be rewritten as follows:

$$s_i^e = \mathrm{e}^{\mathrm{j}(\omega_c t+\Delta\phi_i+\Delta\phi_i^{LO})} \tag{2}$$

Assuming the azimuth angle of departure is φ and the elevation angle of departure is θ, then the total transmit signal of the planar antenna array can be formulated as [4]:

$$s^e = \sum_{m=1}^{N_H} \sum_{n=1}^{N_V} w_{m,n} v_{m,n} e^{j\Delta\phi_{m,n}^{LO}} e^{j\omega_c t} \tag{3}$$

Where the $v_{m,n}$ and $w_{m,n}$ can be respectively represented as:

$$\begin{aligned} v_{m,n} &= \exp\left(-i \cdot 2\pi\left((n-1)\cdot\frac{d_V}{\lambda}\cdot\cos(\theta)+(m-1)\cdot\frac{d_H}{\lambda}\cdot\sin(\theta)\cdot\sin(\varphi)\right)\right) \\ & m = 1,2,...N_H; n = 1,2,\ldots N_V; \end{aligned} \tag{4}$$

$$\begin{aligned} w_{m,n} &= \frac{1}{\sqrt{N_H N_V}} \exp\left(i \cdot 2\pi\left((n-1)\cdot\frac{d_V}{\lambda}\cdot\sin(\theta_{etilt})+(m-1)\cdot\frac{d_H}{\lambda}\cdot\cos(\theta_{etilt})\cdot\sin(\phi_{escan})\right)\right) \\ & m = 1,2,...N_H; n = 1,2,\ldots N_V; \end{aligned} \tag{5}$$

4. Analysis on the Impact of Phase Offset

According to formula (3)-(5), when we fix the m, the planar antenna array becomes a linear antenna array, which means $\theta = 90^0$. In this case, the signal can be represented as below:

$$s^e = \sum_{n=1}^{N_V} e^{j\left((n-1)\frac{\omega_c d}{c}(\sin\varphi-\sin\varphi^0)+\Delta\phi_n^{LO}\right)} e^{j\omega_c t} \tag{6}$$

Where φ^0 is the main orientation of the beam and $\Delta\phi_n^{LO}$ can be written as $\Delta\phi_n^{LO} = (1-n)\frac{\omega_c d}{c}\sin(\Delta\delta_n^{LO})$, so we have:

$$s^e = \sum_{n=1}^{N_V} e^{j\left((n-1)\frac{\omega_c d}{c}(\sin\varphi-\sin\varphi^0-\sin(\Delta\delta_n^{LO}))\right)} e^{j\omega_c t} \tag{7}$$

From formula (11), we can find that the main beam direction is changed because of the phase offset. But when $N_v \to \infty$, the average value $\Delta\overline{\phi}_n^{LO} \to E\{\Delta\phi_n^{LO}\} = 0$. In order to study the effects to the main beam width, formula (11) can be transformed to the below one.

$$s^e = e^{j(\omega_c t+\Delta\phi^{LO})} \cdot \sum_{n=1}^{N_V} e^{j((n-1)\beta)} \tag{12}$$

Where $\beta = \frac{\omega_c d(\sin\varphi - \sin\varphi^0)}{c}$ and the antenna pattern gain can be get as (13).

$$G_{\varphi^0} = \left| \frac{\sin(N_v \beta / 2)}{N_v \sin(\beta / 2)} \right| \tag{13}$$

From the formula (13), the main beam width is as below.

$$BW_{\varphi^0} = 2\arcsin(\lambda / N_v d) \tag{14}$$

when $N_v \to \infty$, the $BW_{\varphi^0} \to 0$, this means the beam width will be very narrow in the massive antenna array case.

5. Simulation Results

In our simulation, we assume the system frequency is 2GHz. The spacing between two antenna elements is $0.5 * \lambda$ and the antenna type is omni-antenna. The amplitude of each antenna element is one. In order to compare the differences when the number of antennas goes large, the number of antenna of the reference system is 4 or 8 and the number of antenna of the massive antenna array system is 16 or 1024. We use the Gaussian distribution $N(0, \sigma^2)$ to approximate the distribution of the phase offset. The main beam direction $\varphi^0 = 0$. In the simulation, three different σ^2 values are used. One correspond to the large phase offset case, one is the median phase offset case and the last one is small phase offset case. The values of σ^2 are 1, 0.5 and 0. 05 respectively.

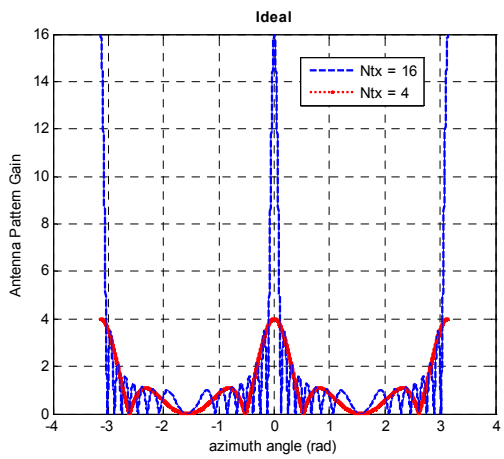

Fig.2. Ideal antenna pattern gain

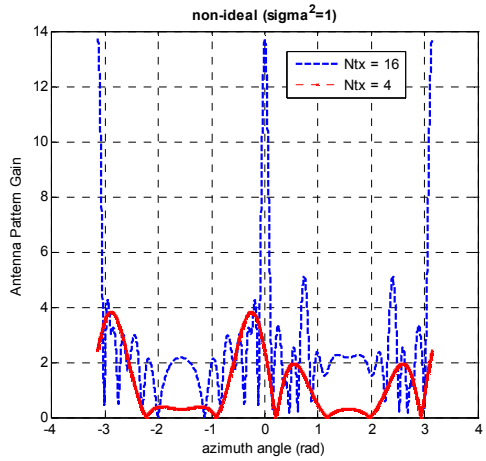

Fig.3. Large phase offset case

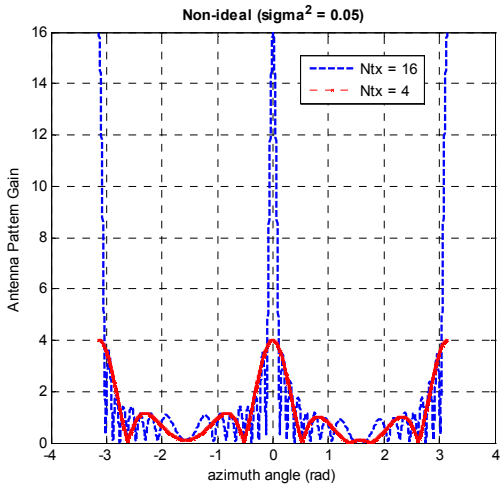

Fig.4. Small phase offset case

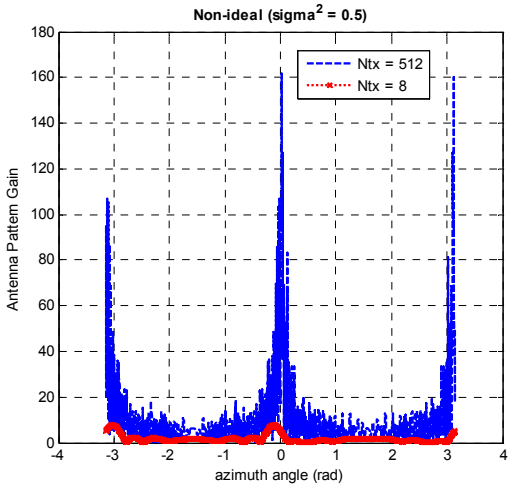

Fig.5. Median phase offset case

Figure 2 and figure 4 show that when the phase offset goes smaller, the main beam direction of the reference system and massive antenna array system have good performance, as depicted in Figure 4. Figure 3 and Figure 5 show the effects of the phase offset of different shift degree to the antenna pattern. Figure 3 shows that the impact of phase offset on the main beam direction becomes negligible with the increase of the antenna number. And when the antenna number gets larger, as shown in Figure 5, the beam width becomes narrower and the impact of the phase offset on the main beam direction becomes less significant.

6. Conclusion

In this paper, we have studied the phase offset influences on massive antenna array. Our analysis includes phase offset influences on the main beam direction and the beam width when the antenna number approaches to infinity. By means of analysis and simulation, we find that when then antenna number tends to be infinite the beam width approaches to be very narrow and the main beam direction of massive antenna array system is more robust.

7. Acknowledgments

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8. References

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