*Journal of Computing and Electronic Information Management*

ISSN: 2413-1660

# Interference Alignment Algorithm under Non-ideal Beam Space Channel in Massive MIMO System

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**Abstract:** To reduce the outage probability in communication, firstly, this paper studies the interference alignment algorithm under non-ideal channel based on the linear interference alignment algorithm and the minimum interference leakage (Min-Leakage) algorithm. Then the lens antenna array is introduced to convert physical channel into beam space channel and the interference alignment algorithm is studied under non-ideal beam space channel in massive Multi-input-Multi-output (MIMO) system. The simulation results show that the improved algorithm proposed in this paper can significantly reduce the outage probability and improve the communication performance of the system.

**Keywords:** Interference alignment, non-ideal channel, lens antenna arrays, outage probability.

## 1. Introduction

With the advancement of science and technology, wireless communication technology has made great strides, and its role in our lives is becoming more and more vital. In modern wireless communication technology development, MIMO technology plays a key role [1]. Multiple input multiple output, as the name implies, is to configure multiple transceiver antennas at the sending end and the receiving end. Signals are transmitted through the configured antennas. Under the premise of not consuming additional transmit power and spectrum resources, different signals using the same spectrum resource will be transmitted through different antennas [2-3], which considerably upgrades the utilization of the signal space dimension. Therefore, the system capacity is enhanced.

Today, massive MIMO technology is recognized as one of the key technologies of 5G. In a massive MIMO system, the number of antennas configured at the base station significantly exceeds that at the client. Nevertheless, the increase in the number of antennas means that the interference problem will become more severe, and the main method used to resolve this problem is the interference alignment technique [4].

The prototype of the interference alignment concept was used by Birk et al. as early as 1998 in the computer index coding problem [5]. It was not until 2008 that the term interference alignment was first proposed by Cadambe et al. [6-7], and it was verified that the combination of interference alignment technology and MIMO technology played a great role in enhancing the system capacity and user's freedom. The core idea of interference alignment is to design a reasonable precoding matrix $V_k$ at the transmitting end to compress the interference signal into a space with a smaller dimension, and then design a corresponding interference suppression matrix $U_k$ at the receiving end to eliminate the interference signal [8-9].

Since interference alignment requires the transmitter to obtain global channel state information [10], most of the research is based on the ideal channel. However, in practice, the channel state information will be affected by factors such as channel estimation error and feedback delay [11], resulting in errors between the channel state information obtained by the transmitter and the actual information. As a result, the interference alignment effect deteriorates and the system performance degrades.

Because of these problems, this paper mainly studies the interference alignment technology based on non-ideal channel state information in massive MIMO system, gives the outage probability expression, and introduces the lens antenna array to convert physical channel into beam space channel model [12]. Then the beam space channel is estimated and the outage probability is simulated and analyzed. The results show that the improved algorithm in this paper greatly reduces the outage probability and significantly improves the system performance of the communication system.

## 2. Interference Alignment Channel Model

Considering the Multi-cell-Multi-user massive MIMO system model shown in Fig. 1, assuming that the system has $K$ cells, each cell has $L$ single-antenna users and one base station, and the transmitter is configured with $M$ antennas ($M \gg L$). When analyzing interference, each cell analyzes one user, and the interference alignment channel model shown in Fig. 2 can be obtained. The signal is transmitted from the transmitter to the receiver after precoding, and then becomes the final received signal after interference cancellation. $X_i$ is the transmitted signal of transmitter $i$, $V_i$ is the precoding matrix of transmitter $i$, and $H_{ki}$ is the transmission channel matrix between transmitter $i$ and receiver $k$. When $i = k$, $H_{ki}$ is the transmission channel matrix of the desired signal, when $i \neq k$, $H_{ki}$ is the interference channel matrix. $U_k$ is the interference suppression matrix of receiver $k$, $Y_k$ is the received signal of receiver $k$, and $n_k$ is the Gaussian white noise at receiver $k$. $Y_k$ can be represented by (1) as:

$$Y_k = U_k^H H_{kk} V_k X_k + U_k^H \Big( \sum_{i=1, i \neq k}^{K} H_{ki} V_i X_i + n_k \Big), \qquad (1)$$

where $U_k^H H_{kk} V_k X_k$ is the desired signal, and $U_k^H \Big( \sum_{i=1, i \neq k}^{K} H_{ki} V_i X_i + n_k \Big)$ is the interference signal from other transmitters and the noise.

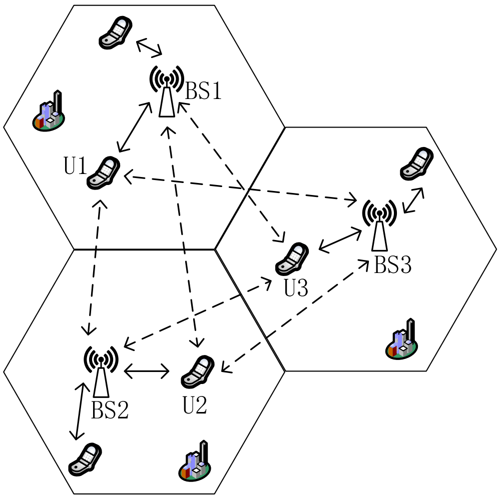


Fig. 1 Multi-cell-Multi-user massive MIMO system model

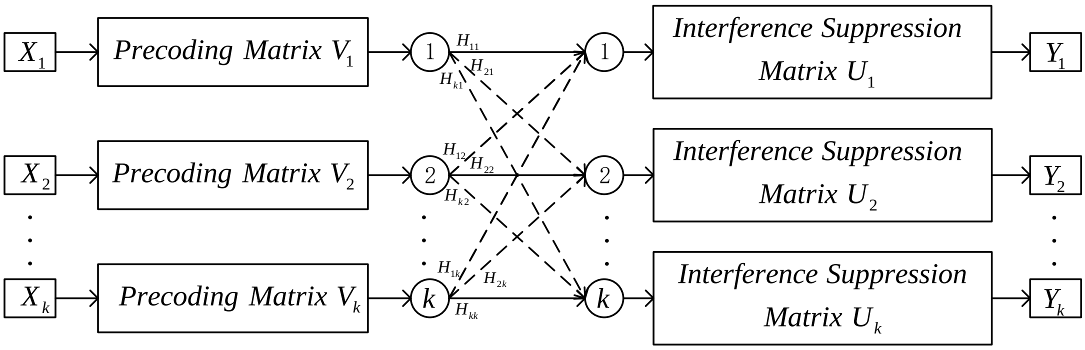


Fig. 2 Interference alignment channel model

To separate the desired signal and the interference signal, the design of the interference suppression matrix needs to satisfy the interference constraints and the signal space dimension constraints [13-14], namely:

$$U_k^H H_{ki} V_i = 0, \forall i \neq k, \qquad (2)$$

$$rank(U_k^H H_{kk} V_k) = d_k, \forall k, \qquad (3)$$

where $d_k$ is the degree of freedom of each user. If 3 users want to perform interference cancellation, the interference signals from transmitters 2 and 3 are aligned into a zero-signal space at receiver 1:

$$span(H_{12}V_2) = span(H_{13}V_3)\,. \tag{4}$$

In the same way, the interference signals are also aligned at receivers 2 and 3:

$$span(H_{21}V_1) = span(H_{23}V_3)\,, \tag{5}$$

$$span(H_{31}V_1) = span(H_{32}V_2)\,. \tag{6}$$

From (5) and (6), we can get:

$$V_3 = (H_{23})^{-1}H_{21}V_1\,, \tag{7}$$

$$V_2 = (H_{32})^{-1}H_{31}V_1\,. \tag{8}$$

Substitute (7) and (8) into (4) to get:

$$span(V_1) = span((H_{31})^{-1}H_{32}(H_{12})^{-1}H_{13}(H_{23})^{-1}H_{21}V_1)\,. \tag{9}$$

Then it can be deduced from (9) that $V_1$ is a matrix composed of the eigenvectors of $(H_{31})^{-1}H_{32}(H_{12})^{-1}H_{13}(H_{23})^{-1}H_{21}$, thus, $V_1$ can be expressed as:

$$V_1 = eig((H_{31})^{-1}H_{32}(H_{12})^{-1}H_{13}(H_{23})^{-1}H_{21})\,, \tag{10}$$

$eig(x)$ in (10) represents the eigenvector of matrix $x$, and the schematic diagram of signal space alignment is shown in Fig. 3:

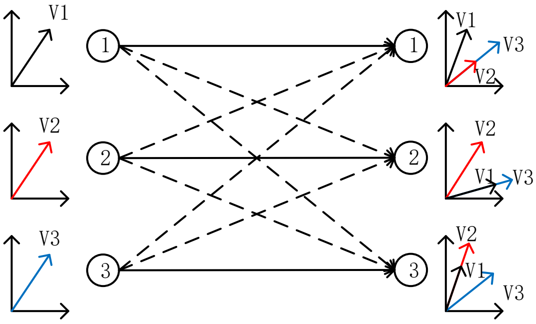


Fig. 3 Schematic diagram of signal space alignment

## 3. Interference Alignment Algorithm under Non-ideal Channel

### 3.1 LS Channel Estimation Algorithm

Least Squares (LS) channel estimation algorithm [15] is a linear channel estimation algorithm. Let $H_{ls}$ be the channel estimation matrix, and in the $Y_k = \sum_{i=1}^{K} H_{ki}X_i + N_k$ channel model, the cost function of the LS algorithm is:

$$\begin{aligned} J(H_{ls}) &= \left\| Y_k - X_k H_{ls} \right\|^2 \\ &= (Y_k - X_k H_{ls})^H (Y_k - X_k H_{ls}) \\ &= Y_k^H Y_k - Y_k^H X_k H_{ls} - H_{ls}^H X_k^H Y_k + H_{ls}^H X_k^H X_k H_{ls} \end{aligned}\,. \tag{11}$$

Find the first-order partial derivative of (11):

$$\begin{aligned}\frac{\partial J(H_{ls})}{\partial H_{ls}} &= -(Y_k^H X_k)^H - X_k^H Y_k + X_k^H X_k H_{ls} + (H_{ls}^H X_k^H X_k)^H \\ &= -2X_k^H Y_k + 2X_k^H X_k H_{ls} \\ &= 2X_k^H (X_k H_{ls} - Y_k)\end{aligned} . \tag{12}$$

Let $\frac{\partial J(H_{ls})}{\partial H_{ls}} = 0$, that is:

$$X_k H_{ls} - Y_k = 0 . \tag{13}$$

The channel estimation value of the LS algorithm is:

$$H_{ls} = X_k^{-1} Y_k , \tag{14}$$

and the normalized mean square error (NMSE) of the LS algorithm is:

$$NMSE = \frac{E\left\{\left\|H_{ki} - H_{ls}\right\|_F^2\right\}}{E\left\{\left\|H_{ls}\right\|_F^2\right\}} . \tag{15}$$

### 3.2 Linear Interference Alignment Algorithm under Non-ideal Channel

As is shown in interference alignment channel model, all channels are non-ideal channel estimated by the LS algorithm. The solution of $V_k (k = 1,2,3)$ has been given by (7) ~ (10). Then solve for $U_k$. Let:

$$H_k = \left[H_{kk}V_k ; H_{ki}V_i ; ...\right], i,k = 1,2,\cdots K, \forall i \neq k , \tag{16}$$

is the equivalent channel of receiver $k$, then:

$$U_k = (H_k)^{-1}(:,1:d_k) , \tag{17}$$

where $(H_k)^{-1}(:,1:d_k)$ means to take columns 1 to $d_k$ of $(H_k)^{-1}$ .The Signal to Interference plus Noise Ratio (SINR) of user $k$ obtained by this algorithm is:

$$\gamma_{k1} = \frac{U_k^H H_{kk} V_k}{U_k^H (\sum_{i=1, i\neq k}^{K} H_{ki} V_i + \sigma_k^2 I)} . \tag{18}$$

Let the threshold SINR is $\tau$ , then the outage probability [16] of user $k$ can be calculated as:

$$P_{out1}^k = P(\gamma_{k1} \leq \tau) = P(\frac{U_k^H H_{kk} V_k}{U_k^H (\sum_{i=1, i\neq k}^{K} H_{ki} V_i + \sigma_k^2 I)} \leq \tau) . \tag{19}$$

### 3.3 Min-Leakage Algorithm under Non-ideal Channel

The Min-Leakage algorithm under non-ideal channel mainly utilizes the reciprocity characteristics of the channel [17]. Then iterate repeatedly by flipping the communication link, and use the receiver's interference suppression matrix as the next transmitter's precoding matrix. Thus, the purpose of optimizing $V_k$ and $U_k$ is achieved. The schematic diagram of the optimization iteration is shown in Fig. 4, in which all channels are estimated by the LS algorithm.

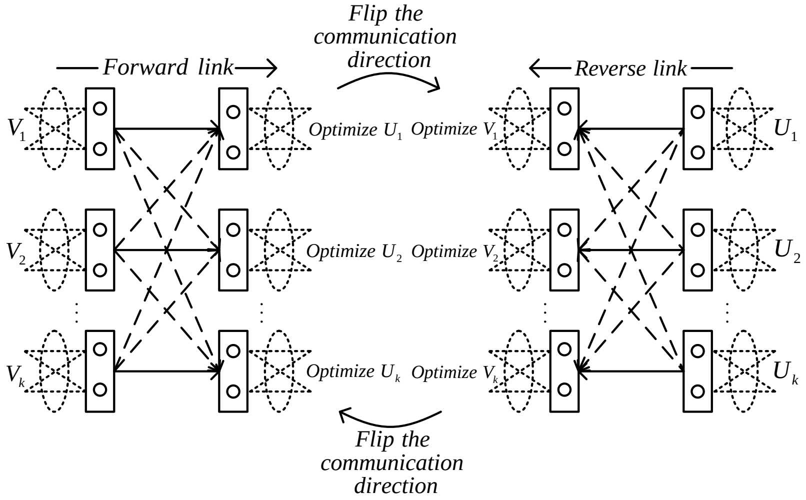


Fig. 4 Schematic diagram of optimization iteration

The total interference caused by other transmitters to receiver $k$ is:

$$I_k = Tr[U_k^H Q_k U_k]. \tag{20}$$

Where:

$$Q_k = \sum_{i=1, i \neq k}^{K} H_{ki} V_i V_i^H H_{ki}^H, \tag{21}$$

is the interference covariance matrix of the receiver $k$, $Tr[x]$ is the trace of matrix $x$. The $q$th column of $U_k$ satisfies:

$$[U_k]_q = eig[Q_k]_q, q = 1, 2, \cdots, d_k, \tag{22}$$

where $eig[Q_k]_q$ represents the eigenvector corresponding to the $q$ th smallest eigenvalue of the matrix $Q_k$.

In the iterative flipping process, let the transmit precoding matrix of the reverse channel be the interference suppression matrix of the original channel, that is, let $\overleftarrow{V}_k = U_k$. Similarly, let $\overleftarrow{U}_k = V_k$, and $\overleftarrow{H}_{ik}$ is the reverse channel. Therefore, for the $i$ th receiver in the reciprocal network, the total interference it receives is:

$$\overleftarrow{I}_i = Tr[\overleftarrow{U}_i^H \overleftarrow{Q}_i \overleftarrow{U}_i]. \tag{23}$$

The interference covariance matrix is:

$$\overleftarrow{Q}_i = \sum_{k=1, k \neq i}^{K} \overleftarrow{H}_{ik} \overleftarrow{V}_k \overleftarrow{V}_k^H \overleftarrow{H}_{ik}^H. \tag{24}$$

The $q$th column of $\overleftarrow{U}_i$ satisfies:

$$[\overleftarrow{U}_i]_q = eig[\overleftarrow{Q}_i]_q, q = 1, 2, \cdots, d_i. \tag{25}$$

Iterate until the algorithm converges, and each iteration will update $V_k$ and $U_k$. The SINR of user $k$ obtained by this algorithm is:

$$\gamma_{k2} = \frac{U_k^H H_{kk} V_k V_k^H H_{kk}^H U_k}{U_k^H \left( \sum\limits_{i=1, i\neq k}^{K} H_{ki} V_i V_i^H H_{ki}^H + \sigma_k^2 I \right) U_k}, \tag{26}$$

and the outage probability is:

$$P_{out2}^k = P(\gamma_{k2} \le \tau) = P\left( \frac{U_k^H H_{kk} V_k V_k^H H_{kk}^H U_k}{U_k^H \left( \sum\limits_{i=1, i\neq k}^{K} H_{ki} V_i V_i^H H_{ki}^H + \sigma_k^2 I \right) U_k} \le \tau \right). \tag{27}$$

## 4. Interference Alignment Algorithm under Non-ideal Beam Space Channel

Each antenna in MIMO system requires a dedicated Radio Frequency (RF) link [18]. In massive MIMO system, the number of RF links required is also very large because of the large number of antennas. To reduce the number of RF links, the lens antenna array [19-20] can be introduced into the interference alignment channel model in Fig. 2 to convert physical channel into beam space channel in angular domain, thereby improving the system performance. The system model is shown in Fig. 5:

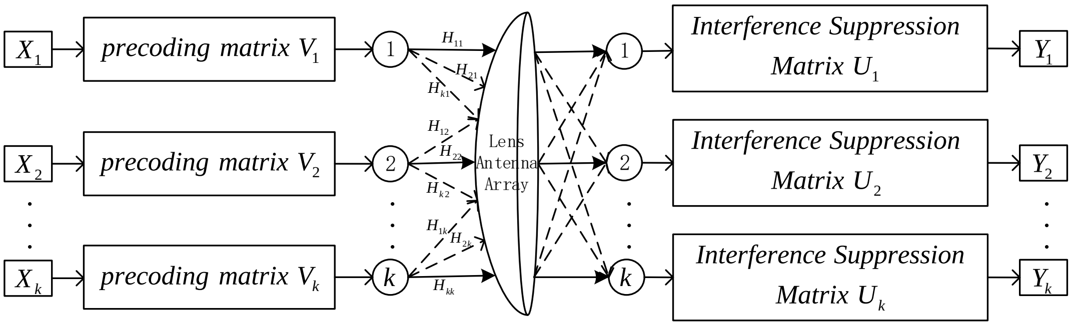


Fig. 5 Interference alignment beam space channel model

The channel in Fig. 5 adopts the Saleh-Valenzuela channel model [21], and the channel vector of the $k$th receiver is:

$$h_k = \sqrt{\frac{N}{L_k + 1}} \sum_{j=0}^{L_k} \beta_k^{(j)} a(\psi_k^{(j)}) = \sqrt{\frac{N}{L_k + 1}} \sum_{j=0}^{L_k} c_{k,j}, \tag{28}$$

where $\beta_k^{(j)}$ is the composite gain, $\psi_k^{(j)}$ is the spatial direction, $a(\psi_k^{(j)})$ is the antenna array response, $c_{k,j} = \beta_k^{(j)} a(\psi_k^{(j)})$ is the $j$th diffusion path in $h_k$, and $L_k$ is the number of diffusion paths. For a typical $N$ antenna uniform linear array there is:

$$a(\psi) = \frac{1}{\sqrt{N}} [e^{-j2\pi\psi m}], \tag{29}$$

where $m$ is an element belonging to a symmetric index set centered at 0, and the spatial direction is defined as $\psi \triangleq \frac{d}{\lambda} \sin\theta$. $\theta$ is the direction of arrival of the wave, $\lambda$ is the carrier wavelength, $d = \frac{\lambda}{2}$ is the distance between antennas.

The beam domain conversion is done by the unitary matrix $W$, which consists of $N$ steering vectors in orthogonal directions and covers the entire space:

$$W = [a(\psi_1), a(\psi_2), ..., a(\psi_N)]^H \text{ .} \tag{30}$$

The beam space channel is defined as:

$$H = WH = [Wh_1, Wh_2, \cdots, Wh_K] \text{,} \tag{31}$$

where $H = [h_1, h_2, \cdots, h_K]$ is the uplink channel matrix, and the signal $Y_k$ received by the receiver is:

$$\begin{aligned} Y_k &= U_k^H H_{kk}^H V_k X_k + \sum_{i=1, i\neq k}^{K} U_k^H H_{kk}^H V_i X_i + U_k^H n_k) \\ &= U_k^H (WH_{kk})^H V_k X_k + U_k^H (\sum_{i=1, i\neq k}^{K} (WH_{ki})^H V_i X_i + n_k) \text{.} \\ &= U_k^H H_{kk}^H W^H V_k X_k + U_k^H (\sum_{i=1, i\neq k}^{K} H_{ki}^H W^H V_i X_i + n_k) \end{aligned} \tag{32}$$

Therefore, it can be deduced from (18) and (32) that the SINR of user $k$ obtained by using the linear interference alignment algorithm under non-ideal beam space channel is:

$$\gamma_{k3} = \frac{U_k^H H_{kk}^H W^H V_k}{U_k^H (\sum_{i=1, i\neq k}^{K} H_{ki}^H W^H V_i + \sigma_k^2 I)} \text{,} \tag{33}$$

and the outage probability is:

$$P_{out3}^k = P(\gamma_{k3} \le \tau) = P(\frac{U_k^H H_{kk}^H W^H V_k}{U_k^H (\sum_{i=1, i\neq k}^{K} H_{ki}^H W^H V_i + \sigma_k^2 I)} \le \tau) \text{.} \tag{34}$$

Then from (26) and (32), it can be deduced that the SINR of user $k$ obtained by using the Min-Leakage algorithm under non-ideal beam space channel is:

$$\begin{aligned} \gamma_{k4} &= \frac{U_k^H H_{kk}^H V_k V_k^H (H_{kk}^H)^H U_k}{\sum_{i=1, i\neq k}^{K} U_k^H H_{ki}^H V_i V_i^H (H_{ki}^H)^H U_k + U_k^H \sigma_k^2 I U_k} \\ &= \frac{U_k^H (WH_{kk})^H V_k V_k^H ((WH_{kk})^H)^H U_k}{U_k^H (\sum_{i=1, i\neq k}^{K} (WH_{ki})^H V_i V_i^H ((WH_{ki})^H)^H + \sigma_k^2 I) U_k} \text{,} \\ &= \frac{U_k^H H_{kk}^H W^H V_k V_k^H W H_{kk} U_k}{U_k^H (\sum_{i=1, i\neq k}^{K} H_{ki}^H W^H V_i V_i^H W H_{ki} + \sigma_k^2 I) U_k} \end{aligned} \tag{35}$$

and the outage probability is:

$$P_{out4}^{k} = P(\gamma_{k4} \le \tau) = P(\frac{U_k^H H_{kk}^H W^H V_k V_k^H W H_{kk} U_k}{U_k^H (\sum_{i=1, i\neq k}^{K} H_{ki}^H W^H V_i V_i^H W H_{ki} + \sigma_k^2 I) U_k} \le \tau) \quad . \tag{36}$$

The steps of Min-Leakage algorithm under non-ideal beam space channel are shown in table 1:

Table 1 Steps of improved Min-Leakage algorithm

| |
|---|
| 1. Construct unitary matrix $W$ from array response vector $a(\psi_n)$ |
| 2. Solve the beam space channel $H_{ki}$ and perform channel estimation on the beam space channel |
| 3. Initialize the precoding matrix: $V_i^H V_i = I_{di}$ |
| 4. Solve the interference covariance matrix: $Q_k = \sum_{i=1, i\neq k}^{K} H_{ki} V_i V_i^H H_{ki}^H$ |
| 5. Solve the interference suppression matrix: $[U_k]_q = eig[Q_k]_q, q = 1, 2, \cdots, d_k$ |
| 6. Take advantage of channel reciprocity, let: $\overleftarrow{V}_k = U_k$ |
| 7. Solve the reverse interference covariance matrix: $\overleftarrow{Q}_i = \sum_{k=1, k\neq i}^{K} \overleftarrow{H}_{ik} \overleftarrow{V}_k \overleftarrow{V}_k^H \overleftarrow{H}_{ik}^H$ |
| 8. Solve the reverse interference suppression matrix: $[\overleftarrow{U}_i]_q = eig[\overleftarrow{Q}_i]_q, q = 1, 2, \cdots, d_i$ |
| 9. Take advantage of channel reciprocity again, let: $\overleftarrow{U}_k = V_k$ |
| 10. Repeat steps 4 to 9 until the algorithm converges |

## 5. Simulation results

### 5.1 Simulation of Linear Interference Alignment Algorithm under Non-ideal Channel

As is shown in interference alignment channel model, let $K = 3$， $L = 8$ and $M = 200$， all channels are independent and identically distributed complex Gaussian channels, and the channels are estimated by LS algorithm. The Gaussian white noise varies with the SNR, and the estimation error is within 0.35. 100 Monte Carlo simulations are performed for each experiment, and the final result is the statistical average. The simulation results are shown in Fig. 6:

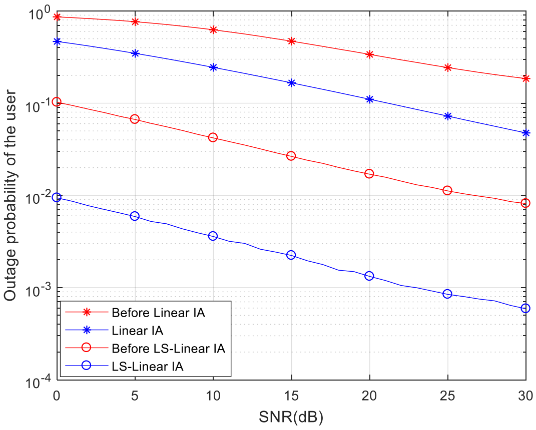
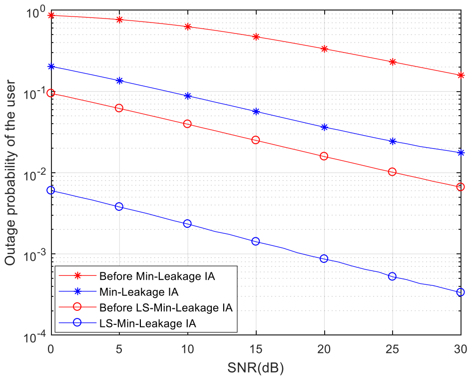


Fig. 6 Simulation of outage probability of linear interference alignment algorithm under non-ideal channel

Fig. 6 simulates outage probability based on the linear interference alignment algorithm (legend 2) and the linear interference alignment algorithm under non-ideal channel (legend 4) respectively. The results show that the outage probability is reduced after using both algorithms. The outage probability obtained by the interference alignment algorithm under non-ideal channel is the lowest, which is two orders of magnitude lower than that obtained by the traditional linear interference alignment algorithm.

### 5.2 Simulation of Min-Leakage Algorithm under Non-ideal Channel

On the basis of interference alignment channel model in Fig. 2, the communication link is repeatedly flipped and iterated by channel reciprocity. The number of iterations is limited to 100 times. 100 Monte Carlo simulations are performed for each experiment, and the final result is the statistical average. The simulation results are shown in Fig. 7 and Fig. 8:



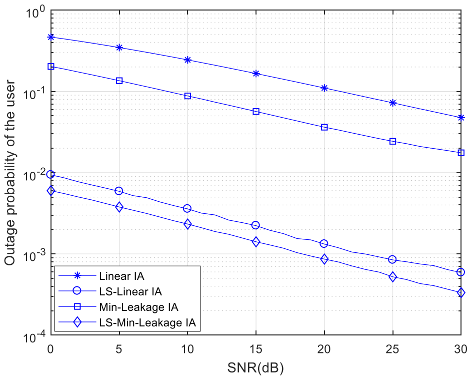


Fig. 7 Simulation of outage probability of Min-Leakage algorithm under non-ideal Channel

Fig. 8 Comparison of outage probability between linear and Min-Leakage algorithms

Fig. 7 simulates the outage probability based on the Min-Leakage algorithm (legend 2) and the Min-Leakage algorithm under non-ideal channel (legend 4). The Min-

Leakage algorithm under non-ideal channel obtains the lowest outage probability. Fig. 8 compares the outage probability between the linear (legend 2) and the Min-Leakage (legend 4) algorithms under non-ideal channel. The latter has a lower outage probability, indicating that the latter algorithm is more effective.

### 5.3 Simulation of Improved Linear Interference Alignment Algorithm

As shown in interference alignment beam space channel model, let $K=3$, $L=8$ and $M=200$, all channels are beam space channels, and use the LS algorithm to estimate the beam space channels. The Gaussian white noise changes with the SNR, and the estimation error is within 0.35. 100 Monte Carlo simulations are performed for each experiment, and the final result is the statistical average. The simulation results are shown in Fig. 9:

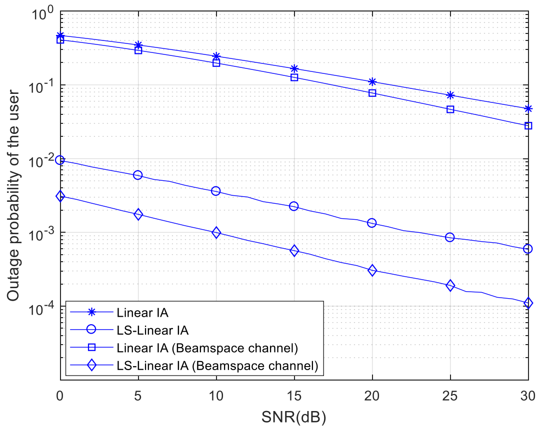


Fig. 9 Simulation of outage probability of improved linear interference alignment algorithm

Fig. 9 simulates the outage probability based on the linear interference alignment algorithm under beam space channel and non-ideal beam space channel (legend 3 and legend 4). The results show that the algorithm using the beam space channel is better than the algorithm without it. The algorithm with the lowest outage probability is the linear interference alignment algorithm under non-ideal beam space channel. In other words, the improved algorithm in this paper is better.

### 5.4 Simulation of Improved Min-Leakage Algorithm

On the basis of interference alignment beam space channel model, the communication link is repeatedly flipped and iterated by channel reciprocity. The number of iterations is limited to 100 times. 100 Monte Carlo simulations are performed for each experiment, and the final result is the statistical average. The simulation results are shown in Fig. 10 and Fig. 11:

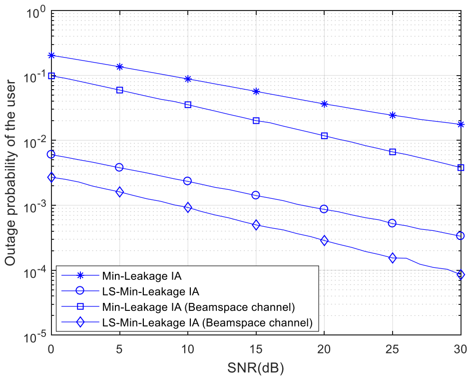


Fig. 10 Simulation of outage probability of improved Min-Leakage algorithm

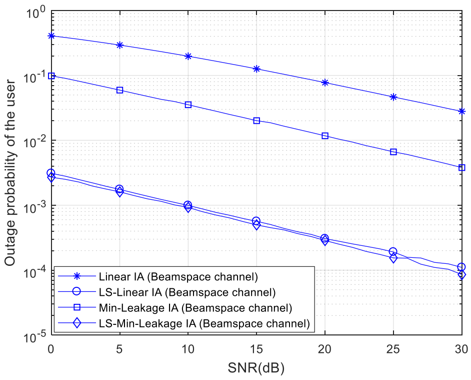


Fig. 11 Comparison of outage probability between improved linear and Min-Leakage algorithms

Fig. 10 simulates the outage probability between the Min-Leakage algorithm under beam space channel (legend 3) and non-ideal beam space channel (legend 4). The results show that the algorithm using the beam space channel is better than the algorithm without it. The algorithm with the lowest outage probability is the Min-Leakage algorithm under non-ideal beam space channel. Fig. 11 compares the linear interference alignment algorithm (legend 2) and the Min-Leakage algorithm (legend 4) under non-ideal beam space channel. It shows that the Min-Leakage algorithm under non-ideal beam space channel is slightly better than linear interference alignment algorithm under non-ideal beam space channel, but they are much better than the traditional algorithms. Both improved algorithms reduce the outage probability greatly and improve the performance of communication system immensely.

## 6. Conclusion

Based on the traditional interference alignment algorithm, this paper first studies the interference alignment algorithm under non-ideal channel. Then introduces the lens antenna array to convert physical channel into beam space channel and studies the linear interference alignment algorithm and the Min-Leakage algorithm under non-ideal beam space channel in massive MIMO system. By simulating the outage probability, it is verified that whether the improved algorithm is compared with the traditional interference alignment algorithm or the interference alignment algorithm under non-ideal channel, the outage probability is significantly reduced, and the performance of the communication system is improved.

## Acknowledgments

This work was supported in part by the Natural Science Foundation of Gansu Province (20JR5RA535).

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