Coordinated Precoding Based on Distributed CSI for Multi-station and Multi-satellite MIMO Uplink System

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Abstract. Satellite communication has now become a necessary way for global communication. However, with the development of communication technology and wireless communication 5G technology and future 6G technical requirements, the current single measurement and control station corresponding to a single satellite injection system has shown many unavoidable problems. The communication rate and channel capacity can no longer meet the current communication needs and need to be greatly improved. Therefore, multiple-input multiple-output (MIMO, multiple-input multiple-output) technology has gradually become the research trend of satellite high-speed communication. This article proposes one This kind of multi-measurement and control station corresponds to the multi-satellite signal injection MIMO precoding algorithm, which converts multipath interference into the diversity gain of the system, increases the signal injection time and transmission rate in the cycle, and greatly improves the communication performance of the system. Exchange limited channel information between stations and iteratively update the transmitted covariance matrix information to obtain channel state information (CSI), and use the measurement and control station to transmit pilots and minimize the weighted mean square error (WMMSE, weighted minimum mean square error) algorithm continuous training Update the precoding matrix, and consider the worst case of the estimator, improve the WMMSE algorithm to make it have a certain anti-interference performance. In the Saleh-Valenzuela analog channel environment, using the RB-WMMSE precoding algorithm, the system has a good bit error rate and communication rate.

Keywords: MIMO · Low orbit satellite · Distributed CSI · Coordinated precoding algorithm

1 Introduction

The LEO satellite system can provide seamless wireless coverage to supplement and expand terrestrial wireless networks. After a series of standardization work, it will be merged into future wireless networks, especially 5G and the upcoming 6G integrated world-earth collaborative coverage network. The general trend [1]. However, the low-orbit satellite injection system has the lowest acquisition, tracking, release elevation

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and multipath effects caused by ionospheric or cloud reflections [2], resulting in low transmission rate and high bit error rate, which cannot meet the existing communication needs. Today's single-station and single-satellite injection system not only has a slow injection rate, but also fails to complete an effective ephemeris injection during most of the low-orbit satellite operating cycle. The multi-station and multi-satellite signal injection system is similar to the terrestrial multi-cell multi-user cellular network. Each receiver may suffer from intra-cell and inter-cell interference. Many terrestrial communication documents have analyzed this type of problem. An effective solution was proposed [3–12]. Liu Kang, Li Yun and others from Chongqing University of Posts and Telecommunications conducted an in-depth study on the interference alignment algorithm (IA) proposed by Syed Jafar [3]through joint precoding of multiple transmitters Designed to limit the interference from other transmitters to part of the receiver's space (interference subspace). Through the zero-forcing receiving matrix at the receiving end, all interference can be eliminated and useful signals can be obtained, but the interference alignment algorithm usually requires a perfect channel State information and its closed solution are difficult to obtain [4]. Pramono from Trinity University in Indonesia has conducted in-depth research on block diagonal linear precoding. This method can offset inter-user interference in MU-MIMO scenarios [5] and decompose multi-user scenarios in multiple parallel single-user scenarios. Crasmariu of NXP Semiconductors has made improvements to the block diagonal linear precoding algorithm [6]. This method can be applied to base stations (BS) in downlink multi-user scenarios, by reducing the low-level operations involved in QR decomposition. The complexity can be reduced without any impact on the overall system performance, but it only considers a part of the calculation of the block diagonalization (BD) precoding algorithm, and does not have scalability. Rasmus of KTH Royal Institute of Technology has studied the local CSI capture at the transmitter by using the reciprocity of the channel when using Time Division Duplex (TDD) [7]. In this mode of operation, each node in the network can perform an optimization iteration based on its current understanding of the local effective channel, which enables the iterative coordinated precoding algorithm to be implemented in a completely distributed manner [8]. Mingguang Xu of Northwestern University in the United States proposed a joint optimization of nonlinear precoder and receiving filter for the uplink and downlink in terrestrial cellular systems [9], but the uplink and downlink optimization cannot achieve simultaneous convergence and no Support multiple data streams. Haqiqatnejad of the University of Luxembourg proposed to use an iterative coordinate ascending algorithm to solve this total rate optimization problem [10] to obtain a robust precoding generator, which is between the best precoding signal and the worst-case additive distortion vector Iterative, but the computational complexity is high, and it is not suitable for use in the multi-station and multi-satellite injection system [11]. The MIMO precoding algorithm proposed in this paper for the signal injection of multiple satellites corresponding to the multiple satellites converts multipath interference into the diversity gain of the system, increases the signal injection time and transmission rate in the cycle, and considers the worst of the satellite and the measurement and control station In this case, the total rate optimization problem is solved, and a robust precoding generator is obtained, which greatly increases the reliability of the system.

2 Cooperative Precoding Algorithm for Multi-station and Multi-satellite

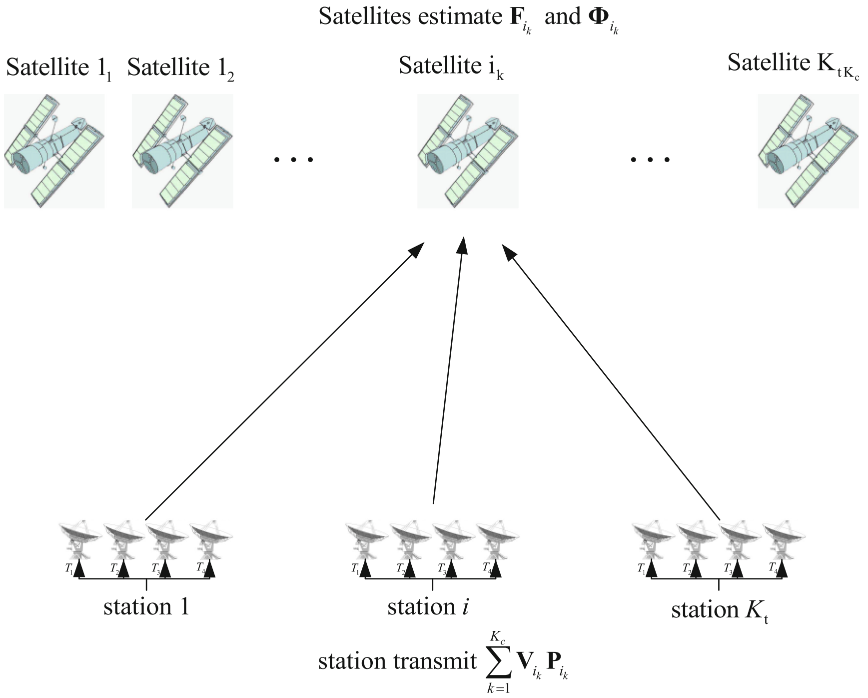

Fig. 1. Multi-station and multi-satellite injection system uplink

2.1 Optimization of the Total Rate of Signals from Multi-station and Multi-satellite

The multi-station and multi-satellite injection system model in this paper is shown in Fig. 1 and Fig. 2. There are a total of K_t stations, each of which serving K_c low-orbit satellite, for a total of $K_r = K_t K_c$ satellite, has M_t antennas. Each low-orbit satellite are equipped with M_r antennas and is only served data from one station. The signals from the other stations constitute intercell interference. The kth satellite served by station i will be often written as $\mathrm{i_k}$, $i \in \{1, \cdots, k_t\}$. Denote a MIMO broadcast channel between station j and satellite i_k as $\mathbf{H}_{i_k j}$. We let the signal $\mathbf{x}_{i_k}$, $\mathrm{x}_{i_k} \sim \mathcal{CN}\left(\mathbf{0}, \mathbf{I}_{N_d}\right)$, precoded by the linear precoding matrix $\mathbf{V}_{i_k} \in \mathbb{C}^{M_t \times N_d}$. $\mathbf{z}_{i_k}$ is a white Gaussian noise term, $\mathbf{z}_{i_k} \sim \mathcal{CN}\left(\mathbf{0}, \sigma_r^2 \mathbf{I}_{M_r}\right)$.

The received signal at satellite i_k is

$$\mathbf{y}_{i_k} = \mathbf{H}_{i_k i}\mathbf{V}_{i_k}\mathbf{x}_{i_k} + \sum_{(j,l)\neq(i,k)} \mathbf{H}_{i_k j}\mathbf{V}_{j_l}\mathbf{x}_{j_l} + \mathbf{z}_{i_k} \tag{1}$$

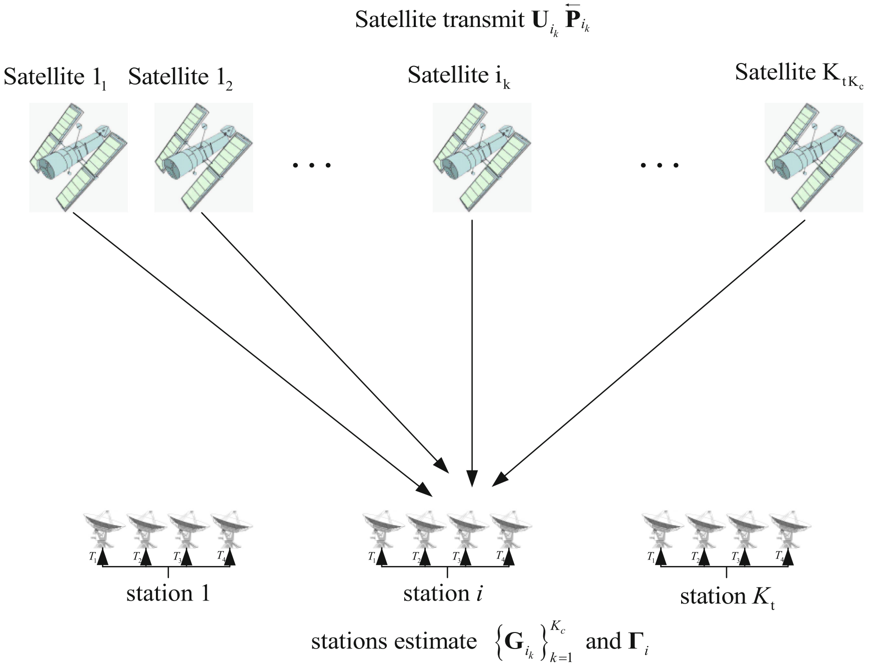

Fig. 2. Multi-station and multi-satellite injection system downlink

It can only find a local optimal solution. Introducing optimization variables $\left\{\mathbf{W}_{\mathbf{i_k}}\right\}$ (the weight matrix of the MSE algorithm), the above optimization problem is transformed into the same global optimization problem. Excellent solution of WMMSE optimization problem:

$$\begin{aligned} &\underset{\substack{\{\mathbf{A}_{i_k}\},\{\mathbf{V}_{i_k}\} \\ \{\mathbf{W}_{i_k}\succ 0\}}}{\text{minimize}} \sum_{(i,k)} \alpha_{i_k}\left(\mathrm{Tr}\left(\mathbf{W}_{i_k}\mathbf{E}_{i_k}\right) - \log\det\left(\mathbf{W}_{i_k}\right)\right) \\ &\text{subject to} \sum_{k=1}^{K_c} \mathrm{Tr}\left(\mathbf{V}_{i_k}\mathbf{V}_{i_k}^{\mathbf{H}}\right) \le P_i,\, i = 1, \ldots, K_t \end{aligned} \tag{2}$$

2.2 RB-WMMSE Algorithm Based on Distributed CSI

The uncertainty expressed in Eq. (3) cannot be achieved using the above definition, for example, part of the objective function of the optimization problem in Eq. (3) cannot be expressed by $\mathbf{G}_{i_k}$ and $\mathbf{F}_{i_k}$ at the same time. Therefore, the uncertainty of CSI needs to be used to solve the characteristic variables when alternately minimized. When solving the precoder, consider the measurement and control station When solving the receiving filter and MSE weight matrix, the CSI uncertainty from the satellite is considered. The following will introduce the alternate minimization process of the three variables in detail.

$$\begin{aligned} & \underset{\substack{\{\mathbf{A}_{i_k}\},\{\mathbf{V}_{i_k}\} \\ \{\mathbf{W}_{i_k} \succ 0\}}}{\text{minimize}} \; \underset{\{\text{uncertainty}\}}{\max} \sum_{(i,k)} \alpha_{i_k} \left(\operatorname{Tr}\left(\mathbf{W}_{i_k}\mathbf{E}_{i_k}\right) - \log\det\left(\mathbf{W}_{i_k}\right)\right) \\ & \text{subject to} \sum_{k=1}^{K_c} \operatorname{Tr}\left(\mathbf{V}_{i_k}\mathbf{V}_{i_k}^{\mathbf{H}}\right) \le P_i, i = 1, \ldots, K_t \end{aligned} \tag{3}$$

First fix $\left\{\mathbf{A}_{\mathbf{i_k}}, \mathbf{W}_{\mathbf{i_k}}\right\}$ to solve the optimization problem (3) for the precoding matrix $\mathbf{V}_{\mathbf{i_k}}$. It can be assumed that the CSI uncertainty in the problem (3) comes from the downlink channel estimation stage of the satellite and the measurement and control station, and the problem is transformed into the system For the local optimization problem at each measurement and control station, the estimation error at the measurement and control station is defined as $\tilde{\Gamma}_i = \mathbf{\Gamma}_i - \widehat{\mathbf{\Gamma}}_i^{\mathrm{s+i}}$ and $\tilde{\mathbf{G}}_{i_k} = \mathbf{G}_{i_k} - \widehat{\mathbf{G}}_{i_k}$, and the assumption is that the error is bounded denoted as $\left\|\widetilde{\mathbf{\Gamma}}_i\right\|_{\mathrm{F}} \le \varepsilon_i^{(\mathrm{BS})}$ and $\left\|\tilde{\mathbf{G}}_{i_k}\mathbf{W}_{i_k}^{1/2}\right\|_{\mathrm{F}} \le \xi_{i_k}^{(\mathrm{BS})}$. Error is based on the fixed weight matrix $\mathbf{W}_{i_k}$. The optimization problem in the worst case is:

$$\begin{aligned} & \underset{\{\mathbf{V}_{\mathrm{i_k}}\}}{\text{minimize}} \; \underset{\substack{\|\widetilde{\mathbf{\Gamma}}_i\|_{\mathrm{F}} \le \varepsilon_i^{(\mathrm{BS})} \\ \left\|\tilde{\mathbf{G}}_{i_k}\mathbf{W}_{i_k}^{1/2}\right\|_{\mathrm{F}} \le \xi_{i_k}^{(\mathrm{BS})}}}{\max} \sum_{k=1}^{K_c} \operatorname{Tr}\left(\mathbf{V}_{i_k}^{\mathrm{H}}\left(\widehat{\mathbf{\Gamma}}_i^{\mathrm{s+i}} + \tilde{\Gamma}_i\right)\mathbf{V}_{i_k}\right) \\ & -2\sqrt{\alpha_{i_k}}\operatorname{Re}\left(\operatorname{Tr}\left(\mathbf{W}_{i_k}^{1/2}\left(\widehat{\mathbf{G}}_{i_k} + \tilde{\mathbf{G}}_{i_k}\right)^{\mathrm{H}}\mathbf{V}_{i_k}\right)\right) \\ & \text{subject to} \sum_{k=1}^{K_c} \operatorname{Tr}\left(\mathbf{V}_{i_k}\mathbf{V}_{i_k}^{\mathrm{H}}\right) \le P_i, i = 1, \ldots, K_t \end{aligned} \tag{4}$$

Similar to the analysis of the above-mentioned precoding matrix $\mathbf{V}_{i_k}^{\mathrm{rob}}$, due to the statistical nature of the $\varepsilon_i^{(SAT)}$ covariance matrix error, which is associated with the unknown precoding matrix, further analysis cannot be performed, and diagonal loading correction of the expression is required.

Using imperfect CSI on the satellite side, the optimization problem can be decomposed into the optimization problem of each satellite:

$$\begin{aligned} & \underset{\mathbf{A}_{i_k}, \mathbf{W}_{i_k} \succ 0}{\text{minimize}} \operatorname{Tr}\left(\mathbf{W}_{i_k}\left(\mathbf{I} + \mathbf{A}_{i_k}^{\mathrm{H}}\widehat{\mathbf{\Phi}}_{i_k}\mathbf{A}_{i_k}\right)\right) \\ & -2\operatorname{Re}\left(\mathbf{W}_{i_k}\widehat{\mathbf{F}}_{i_k}^{\mathrm{H}}\mathbf{A}_{i_k}\right) - \log\det\left(\mathbf{W}_{i_k}\right) \\ & \text{subject to} \left\|\mathbf{A}_{i_k}\mathbf{W}_{i_k}^{1/2}\right\|_{\mathrm{F}}^2 \le N_d/\sigma_r^2 \end{aligned} \tag{5}$$

The optimal receiving filter $\mathbf{A}_{i_k}^{\mathrm{rob}}$ and MSE weight matrix $\mathbf{W}_{i_k}^{\mathrm{rob}}$ can be solved:

$$\mathbf{A}_{i_k}^{\mathrm{opt}} = \left(\widehat{\mathbf{\Phi}}_{i_k} + \nu_{i_k}^{\mathrm{opt}}\mathbf{I}\right)^{-1}\widehat{\mathbf{F}}_{i_k} \tag{6}$$

$$\mathbf{W}_{i_k}^{\mathrm{opt}} = \left(\mathbf{I} - \widehat{\mathbf{F}}_{i_k}^{\mathrm{H}}\left(\widehat{\boldsymbol{\Phi}}_{i_k} + \nu_{i_k}^{\mathrm{opt}}\mathbf{I}\right)^{-1}\widehat{\mathbf{F}}_{i_k}\right)^{-1} \tag{7}$$

Combining the corresponding conclusions of the previous robust precoding matrix $\mathbf{V}_{i_k}^{\mathrm{rob}}$, the RB-WMMSE algorithm can be obtained. As shown in Table 1.

Table 1. RB-WMMSE Algorithm

```
RB-WMMSE Algorithm（Estimated CSI）

satellite：
    1 Pilot transmission fromstations: estimate $\widehat{\boldsymbol{\Phi}}^{(\rho)}{}_{i_k}$, $\widehat{\mathrm{F}}^{(\rho)}{}_{i_k}$
    2 let $\widehat{\boldsymbol{\Phi}}_{i_k} = \rho\widehat{\boldsymbol{\Phi}}_{i_k}{}^{(\rho)}$, $\widehat{\mathrm{F}}_{i_k} = \sqrt{\rho}\widehat{\mathrm{F}}_{i_k}{}^{(\rho)}$
    3 find $v_{i_k}$ to satisy $\left\|\mathbf{A}_{i_k}\mathbf{W}_{i_k}^{1/2}\right\|_{\mathrm{F}}^{2} \le N_d/\sigma_r^2$
      $\mathbf{W}_{i_k} = \left(\mathbf{I} - \widehat{\mathbf{F}}_{i_k}^{\mathrm{H}}(\widehat{\Phi}_{i_k} + v_{i_k}\mathbf{I})^{-1}\widehat{\mathbf{F}}_{i_k}\right)^{-1}$
      $\mathbf{A}_{i_k} = (\widehat{\Phi}_{i_k} + v_{i_k}\mathbf{I})^{-1}\widehat{\mathbf{F}}_{i_k}, \mathbf{U}_{i_k} = \sqrt{\alpha_{i_k}}\mathbf{A}_{i_k}\mathbf{W}_{i_k}^{1/2}$
station：
    4 Pilot transmission from UEs: estimate $\widehat{\Gamma}_i^{s+i+n}$ and $\widehat{\mathbf{G}}_{i_k}$
    5 Obtain $\mathbf{W}_{i_k}^{1/2}$ through feedback
    6 find $\mu_i \ge -\min\left(\frac{\sigma_t^2}{\gamma^2}, \lambda_{M_t}(\widehat{\Gamma}_i^{s+i+n}) - \zeta\right)$
      to satisfy $\sum_{k=1}^{K_c}\mathrm{Tr}\left(\mathbf{V}_{i_k}^{(\rho)}\mathbf{V}_{i_k}^{(\rho),\mathrm{H}}\right) \le \rho P_i$
      $\mathbf{B}_{i_k}^{(\rho)} = (\widehat{\Gamma}_i^{\mathrm{s+i+n}} + \mu_i\mathbf{I})^{-1}\widehat{\mathrm{G}}_{i_k}, \mathrm{V}_{i_k}^{(\rho)} = \sqrt{\alpha_{i_k}}\mathbf{B}_{i_k}^{(\rho)}\mathbf{W}_{i_k}^{1/2}$
    7 $\mathbf{V}_{i_k} = \frac{1}{\sqrt{\rho}}\mathbf{V}_{i_k}^{(\rho)}$
8 repeat
9 until fixed number of iterations
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3 Simulation and Analysis

In order to verify the transmission rate and bit error rate of RB-MMSE precoding in a multi-measurement and control station multi-satellite MIMO up-and-coming system.

The MU-MIMO system model was built in Matlab2014. The model is divided into the signal uplink of the measurement and control station to the satellite and the feedback downlink of the satellite to the measurement and control station. The system uses QPSK modulation, the additive noise is Gaussian white noise, and it is assumed that the noise received by each satellite is independent and identically distributed. The total number of measurement and control stations is 3, each measurement and control station has 4 antennas, and each satellite has 2 antennas, each frame A maximum of 10 satellites are selected for transmission, and the third-order Saleh-Valenzuela channel is used for simulation in the simulation.

As shown in Fig. 2, the unoptimized WMMSE algorithm uses distributed CSI acquisition but cannot be combined well. The system spectrum efficiency curve drops significantly at 15 dB. Consider the worst-case RB-WMMSE algorithm compared with it, it has a certain degree of robustness, the curve is always in a stable state, and the performance is close to the WMMSE algorithm under perfect CSI estimation. The reliability of the RB-WMMSE algorithm when applied to a MIMO injection system with multiple measurement and control stations and multiple satellites Stronger.

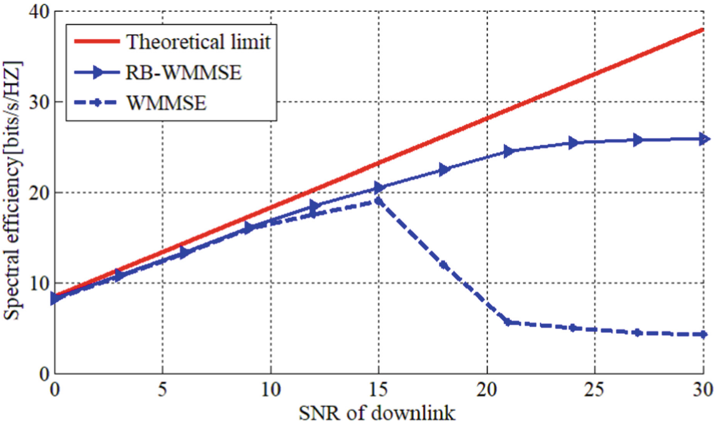

Fig. 3. RB-WMMSE robustness curve

Study the impact of the distributed CSI-based RB-WMMSE algorithm on the transmission rate of the satellite signal upload system when the downlink and uplink SNR changes. The uplink SNR affects the uplink data transmission and uplink estimation performance, and the downlink SNR only affects Downlink estimation performance, so in the simulation, the downlink SNR is fixed to 0 dB, and the uplink SNR is used as a variable to study. We will compare it with the maximum signal to interference and noise ratio precoding (MaxSINR), the WMMSE algorithm and RB under perfect CSI estimation - WMMSE algorithm compares the performance index of system spectrum efficiency. As shown in Fig. 3, the performance of the RB-WMMSE algorithm with fully distributed CSI is close to the WMMSE algorithm with perfect CSI estimation, and its spectral efficiency is always better than traditional MaxSINR precoding, especially under low signal-to-noise ratio It can also achieve a better rate increase, which can well meet the rate requirements of future low-orbit satellite signals (Fig. 4).

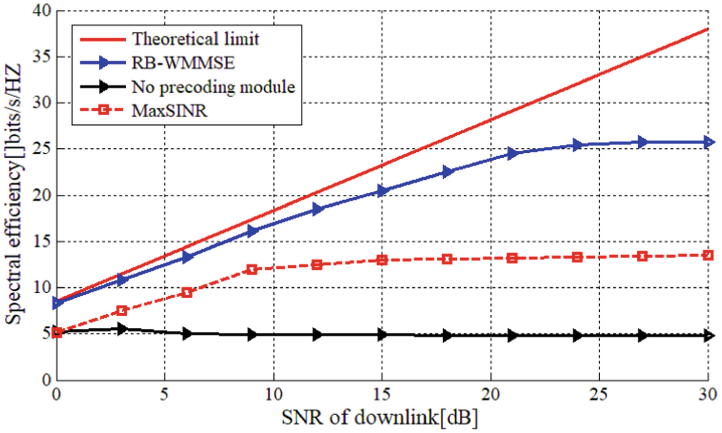

Fig. 4. RB-WMMSE precoding spectrum efficiency curve

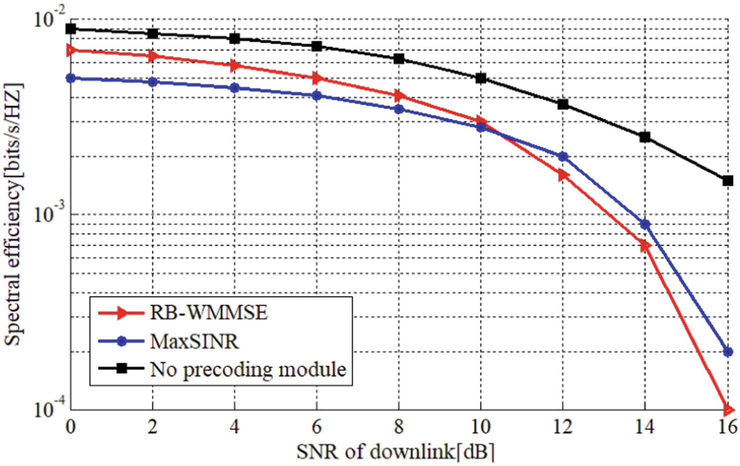

Fig. 5. RB-WMMSE bit error rate curve

The solution of the RB-WMMSE algorithm rationally corrects the overall optimization problem of the system to the worst-case optimization problem of each satellite, which greatly reduces the complexity of the algorithm and has a certain degree of interference alignment effect, as shown in Fig. 3. As shown, the bit error rate curve when the uplink SNR remains unchanged at 0 dB, as the downlink SNR increases, it quickly reaches the order of magnitude, which makes the measurement and control station maintain high-speed signal transmission while the low-orbit satellite signal is injected into the system It also has a good bit error rate and can ensure effective high-speed signal transmission (Fig. 5).

4 Conclusion

This paper studies the precoding algorithm applied to the multi-station and multi-satellite MIMO injection system. This paper proposes the RB-WMMSE precoding algorithm, which converts multipath interference into the diversity gain of the system, and increases the signal injection time and transmission rate in the cycle. And considering the worst case of the estimator, improve the WMMSE algorithm to make it have certain anti-jamming performance. In the Saleh-Valenzuela simulated channel environment, the RB-WMMSE precoding algorithm is used. Under the condition of ensuring a good bit error rate, the system spectral efficiency curve always remains stable and close to the ideal CSI estimation curve, which can meet the requirements of future low-orbit satellite signals. The high-speed demand for injection has certain practical value.

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