Performance Analysis of Signal Detection Algorithm in Data Link System

Jiang Xiaolin[1,2], Qu Susu[1(✉)], and Tang Zhengyu[1]

[1] Heilongjiang University of Science and Technology, Harbin 150000, China
3216739483@qq.com
[2] Harbin Institute of Technology, Harbin 150000, China

Abstract. Data link is a defined message format and communication protocol. It is a real-time transmission system between sensors, control systems and weapon platforms. Data links connect geographically dispersed forces, sensors, and weapon systems to create seamless connectivity, information sharing, and increased command speed and coordination.In this paper, MIMO technology is applied to data link system to improve the information rate. The performance of data link system is closely related to MIMO technology. The comparative analysis of the (Zero Forcing)ZF, (Minimum Mean-Squared Error)MMSE, (Zero Forcing-Ordered successive interference cancellation)ZF-OSIC and (Minimum Mean-Squared Error-Ordered successive interference cancellation)MMSE-OSIC algorithms in MIMO technology was carried out. The results are as follows: MMSE-OSIC algorithm is the best among the four algorithms, MMSE, ZF algorithm is the worst, and ZF-OSIC is between them.

Keywords: Data link system · MIMO. MMSE - OSIC · MMSE. ZF - OSIC · ZF

1 Introduction

Data link communication system, full name controller pilot data link communications (CPDLC), mainly uses data instead of voice to provide traffic management for controllers and pilots. Data link communication system can provide communication services in air traffic service facilities, including release, application, report and so on in standard format [1, 2]. Meanwhile, it can also compensate channel congestion, signal mishearing and signal distortion in voice communication. The data link communication system provides the pilot with control information in text form. With the development of international SATCOM technology, CPDLC has been widely used by international airlines and traffic control systems as a means of communication through data link.In a single antenna system, there are two ways to improve the communication rate, which are to increase the transmission power and bandwidth. MIMO technology is introduced into data link system to further improve its performance [3].

MIMO technology transceiver antenna number is more than one, by a plurality of components. The signal from the sending end goes through multiple paths to the receiving

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end, maximizing the utilization of spectrum and increasing the capacity [4, 5]. In the same channel, space diversity technology is used to transmit multiple antennas. Compared with other technologies, MIMO technology has obvious advantages in increasing system capacity.

2 Data Link System MIMO System

2.1 V - BLAST Design

Beli-laboratories Layered spacetime (BLAST) was originally proposed by Foschini. Because of its simple structure, BLAST is of great significance to the improvement of frequency band utilization. BLAST simply means sending data in parallel using multiple transmitting antennas, and then data on each receiving antenna are separated [6]. It can be seen from its structure that the spectrum utilization of the system can be very high, As the number of antennas changes, so does the volume.

2.2 MIMO Model of Data Link System

Multiple antennas are installed on the data link end machine, and a MIMO system is formed between the two data link end machines. In this system, each antenna at the transmitting end sends signals at the same time, and the signals received at the receiving end are the superposition of signals sent by the transmitting end [7, 8]. The model is shown in Fig. 1:

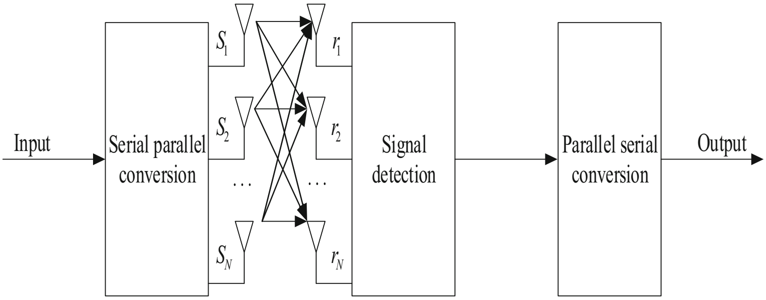

Fig. 1. MIMO signal model of data link system

Suppose at a certain time, the signal vector sent by the sender is $x = [x_1\ x_2 \ldots x_N]^{\mathrm{T}}$, the signal vector received by the receiver is $r = [r_1\ r_2 \ldots r_M]^{\mathrm{T}}$, and the additive noise of the signal is $z = [z_1\ z_2 \ldots z_M]^{\mathrm{T}}$.Assuming that the transmission channel of the signal is A flat channel, that is, the channel H remains unchanged during transmission time of one frame of data, then the relationship between the signal received by the receiving end and the input end is:

$$r = Hx + z \tag{1}$$

In the type, H represents the transmission matrix of $N \times M$, as follows:

$$H = \left\{ \begin{matrix} h_{11} & h_{12} & \ldots & h_{1N} \\ h_{21} & h_{22} & \ldots & h_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ h_{M1} & h_{M2} & \ldots & h_{MN} \end{matrix} \right\} \tag{2}$$

Where, h_{MN} is the transmission channel coefficient,N is the N antenna at the transmitting end, and M is the M antenna at the receiving end.

The data link terminal converts the high-speed data stream through a series and forms a low-speed parallel data stream, which is simultaneously transmitted through N antennas on the same frequency band.In nature, there is a multipath effect in the channel, and the signal reaches the receiving end through various fading, and the receiving end recovers the original data stream from the obtained signals. Under the condition of constant signal bandwidth and transmitting power, the system capacity is significantly improved [9, 10].

3 Signal Detection Algorithm

In the data link system, a reasonable signal detection algorithm can be designed and the spatial separation gain can be used to eliminate the interference and noise between the sending end and the receiving end, so as to maximize the transmission rate and increase the capacity of the system.

3.1 ZF Detection Algorithm

ZF algorithm is the simplest detection, and it is effective. Its idea is to use the breaking matrix to enhance the received signal vector linearly, and finally detect the received signal to obtain the sent signal vector [11]. Then the receiving vector is:

$$r = Hx + z \tag{3}$$

ZF technology uses a weighted matrix to eliminate interference:

$$H^{+} = (H^{\mathrm{H}}H)^{-1}H^{H} \tag{4}$$

Where $(\bullet)^{\mathrm{H}}$ is emmett transpose.

$$\tilde{x}_{\mathrm{ZF}} = H^{+}r = x + (H^{\mathrm{H}}H)^{-1}H^{\mathrm{H}}z = x + \tilde{x}_{\mathrm{ZF}} \tag{5}$$

Among them, $\tilde{x}_{\mathrm{ZF}} = H^{+}z = (H^{\mathrm{H}}H)^{-1}H^{\mathrm{H}}z$. The resulting

$$r^{\cdot} = x + H^{-1}z \tag{6}$$

It can be seen that the ZF detection algorithm is simple in implementation and low in computational complexity. The multi-stream interference between signals is eliminated, but the noise is amplified.

3.2 MMSE Detection Algorithm

ZF amplifies the noise during detection, MMSE takes advantage of the statistical characteristics of noise to optimize the ZF algorithm, that is, to minimize the minimum mean square error.

$$\begin{aligned} \mathrm{W}_{MMSE} &= \arg\min_{w} E\left[\left\| x - \mathrm{W}^{\mathrm{H}} r \right\|^{2}\right] \\ &= \left(E\left(rr^{\mathrm{H}}\right)\right)^{-1} E\left(rx^{\mathrm{H}}\right) \\ &= \left(\mathrm{H}^{\mathrm{H}}\mathrm{H} + \sigma_{Z}^{2}\mathrm{I}\right)^{-1}\mathrm{H}^{\mathrm{H}} \end{aligned} \tag{7}$$

In formula (7), σ_Z^2 is the variance of noise, It can be seen that MMSE detection algorithm needs statistical information σ_Z^2 of noise. From the weighted matrix W_{MMSE} of MMSE, the estimated value of the transmitter can be expressed as:

$$\tilde{x}_{\mathrm{MMSE}} = W_{\mathrm{MMSE}} r = \left(\mathrm{H}^{\mathrm{H}}\mathrm{H} + \sigma_{Z}^{2}\mathrm{I}\right)^{-1}\mathrm{H}^{\mathrm{H}} r \tag{8}$$

Thus, the corresponding mean square error can be obtained as follows:

$$\begin{aligned} \mathrm{MMSE} &= \mathrm{E}\left[(x - \mathrm{W}_{MMSE} r)(x - \mathrm{W}_{MMSE} r)^{\mathrm{H}}\right] \\ &= \mathrm{I} - \mathrm{H}\left(\mathrm{H}\mathrm{H}^{\mathrm{H}} + \sigma_{Z}^{2}\mathrm{I}\right)^{-1}\mathrm{H} \\ &= \left(I + \sigma_{Z}^{2}\mathrm{H}^{\mathrm{H}}\mathrm{H}\right)^{-1} \end{aligned} \tag{9}$$

3.3 ZF-Based Sorting Serial Interference Elimination (ZF-OSIC) Detection Algorithm

ZFdetection algorithm is a one-time detection process by multiplying the inverse matrix of the channel matrix by the left, without considering the influence of the detection order of different layers on the detection [12].The sorted serial interference elimination (OSIC) method does not calculate all the solution vectors at one time, but achieves the solution of each layer by sorting and layer by layer detection. Theoretically, the best detection order is that the large signal-to-noise(SNR) ratio, the more sub vector is detected first. Therefore, the main idea of ZF-OSIC detection algorithm is to firstly detect the sub-vector in the maximum sub-layer of SNR, then detect the interference caused by this vector from the received signal, and then sort iteratively to complete the detection of the whole signal. The signal detection algorithm of each layer adopts ZF detection algorithm. The detailed steps of ZF-OSIC detection are shown below:

First, the initialization process, that is, when i = 1, let

$$\mathrm{G}_1 = \mathrm{H}^{+} \tag{10}$$

$$k_1 = \arg\min_{j} \left\| (G_1)_j \right\|^2 \tag{11}$$

And then recursion, every time $i = i+1$, until i is equal to the number of antennas, let

$$\mathrm{W}_{ki} = (G_1)_{ki} \tag{12}$$

$$y_{ki} = w_{ki}^T r_i \tag{13}$$

$$\hat{a}_{ki} = Q(y_{ki}) \tag{14}$$

$$r_{i+1} = r_i - \hat{a}_{ki}(\mathrm{H})_{ki} \tag{15}$$

$$G_{i+1} = \underset{ki}{\mathrm{H}_{-}^{+}} \tag{16}$$

$$k_{i+1} = \underset{j \notin \{k_1 \ldots k_i\}}{\arg\min} \left\| (G_{i+1})_j \right\|^2 \tag{17}$$

This algorithm uses the ZF algorithm, Where, $\underset{ki}{\mathrm{H}_{-}^{+}}$ represents the pseudo-inverse matrix of H after deleting column ki,$(G_1)_{ki}$ is the ki-th row vector of G_i,Q stands for quantitative decision function.In the whole calculation process, the SNR of each layer is not directly calculated, but the layer with the minimum SNR is indirectly found by finding the minimum row of G.This is because the average noise power of each layer is the same. When H of the layer is larger, G is smaller. That is, the larger the channel gain, the smaller the proportion of noise power in the receiving vector, and the higher the SNR.In addition, MMSE detection algorithm can also be used in the detection process of each layer, which is the only difference between MMSE-OSIC and ZF-OSIC algorithms [13–15].

4 Simulation of Detection Algorithm

This section simulates the MIMO detection algorithm of serial interference cancellation in multi-antenna data link system. The analog channel is Rayleigh channel, The noise on the receiving antenna is random and follows the independent distribution of zero mean.

As shown in Fig. 2 and Fig. 3, There are two antennas at the transmitter and two at the receiver, the modulation modes are QPSK and BPSK respectively, and the detection performance of the two modulation modes is very close. Compared with ZF detection algorithm, MMSE detection algorithm has better performance, According to theoretical analysis,ZF algorithm is offset by the interference between different antenna, separates the different algorithms of data flow, but has amplified noise, while MMSE algorithm considered the effect of noise and interference between antennas, makes the detection results of the receiver and transmitting between the minimum error in statistical sense. Therefore, the performance of MMSE detection is generally better than ZF detection on the whole, but the calculation of MMSE algorithm is large and the complexity is high. After sorting these two algorithms respectively, namely ZF-OSIC and MMSE-OSIC, it

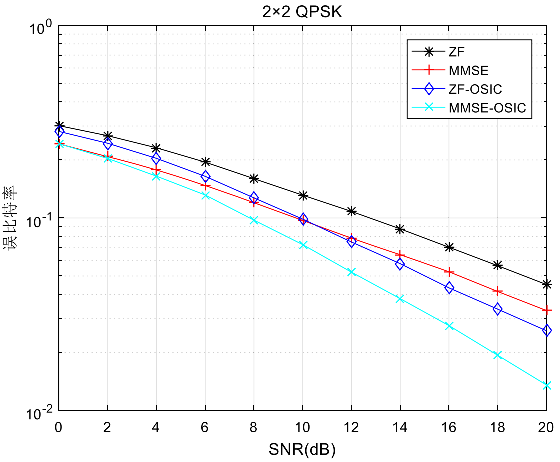

Fig. 2. Bit error rate performance of 2 × 2 QPSK different algorithms

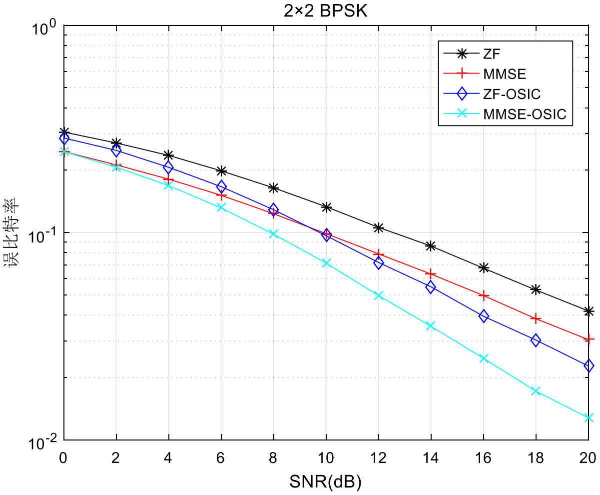

Fig. 3. Bit error rate performance of 2 × 2 BPSK different algorithms

can be seen that their detection performance is superior to ZF algorithm and MMSE algorithm, and MMSE-OSIC algorithm is the best.

According to the simulation comparison in Fig. 4 and Fig. 5, it is observed that when the number of transmitting and receiving antennas is 8 × 8 respectively and the modulation mode is QPSK and BPSK, the bit error rate in QPSK modulation mode is better than that in BPSK modulation mode. The bit error rate of ZF-OSIC and MMSE-OSIC is much better than that of algorithm ZF and MMSE respectively. When the SNR is greater than 10 dB, the effect of ZF-OSIC and MMSE-OSIC is more obvious. The higher the SNR is, the lower the bit error rate of the detection of both is, In a word, MMSE-OSIC has the best detection performance.

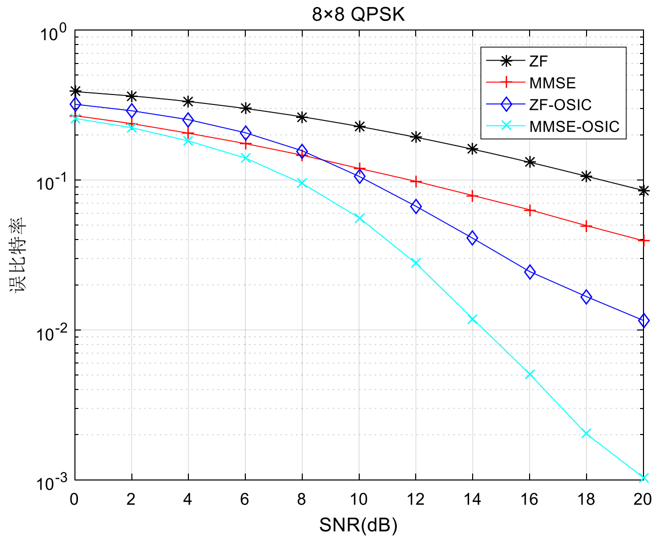

Fig. 4. Bit error rate performance of 8 × 8 QPSK different algorithms

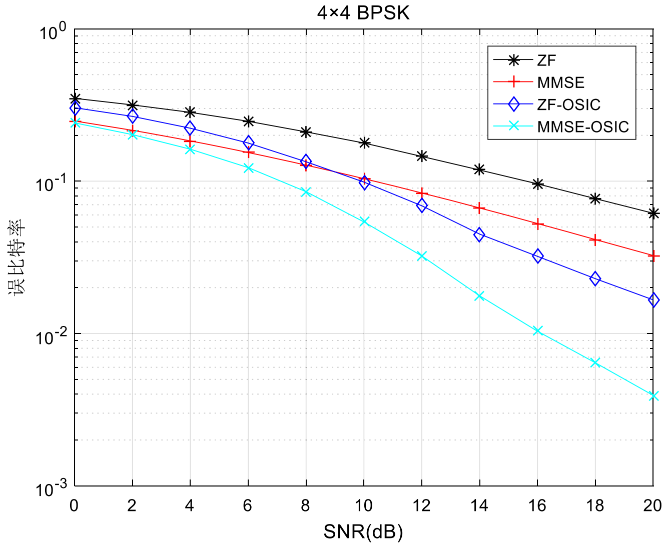

Fig. 5. Bit error rate performance of 8 × 8 BPSK different algorithms

5 Conclusion

In the design of data link end, MIMO technology is introduced into it, and the system model of multi-antenna data link is given. This model uses MIMO spatial multiplexing technology to send data stratified and sent out through different antennas. After independent subchannel fading, through theoretical analysis, the system capacity of the data link end is improved. The algorithm is verified by several simulations, it shows that MMSE-OSIC has the best performance, followed by ZF-OSIC, MMSE and ZF, which have the worst performance. When the number of transmitting antennas increases, the corresponding interference is bound to increase, so it is an inevitable trend to improve the detection of the system.

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