# Signal detection based on real-time channel and phase tracking

Xin Meng, Qichao Zhang, Jianfu Teng

***Abstract*—**In order to solve the problem of fast time-varying channel in spaceborne AIS systems, a signal detection algorithm based on joint channel and phase real time tracking is proposed. The algorithm combines real-time tracking of the channel and phase to realize the joint estimation of parameters and symbol sequences. So, it avoids the serious distortion and crosstalk of the signal when the channel changes quickly, which can be better applied to the spaceborne AIS system to ensure the stability. Simulation results show that the algorithm has a better performance than differential detection, Viterbi decoding and per survivor processing (PSP) signal detection algorithm, and has strong ability of anti frequency offset.

***Keywords*—**Automatic Identification System, PSP Algorithm, Channel Tracking, Phase Tracking

## I. INTRODUCTION

IN recent years, with the rapid development of the world economy, the industries relying on ship transportation are also rapidly increasing. As a result, the number of ships in the sea area has increased dramatically, the density of marine traffic has been strengthened, and the encounter rate has augmented as well, which lead to the navigation environment of coastal waters has been changed a lot. At the same time, drawbacks of the radar communication are becoming more and more obvious, leading to frequent accidents on ships. This not only prevents the personal safety from being secured, but also easily causes ship oil spill accidents and severely pollutes the marine environment[1]. This means that it is very important to fortify the identification and supervision on the practical situation of maritime traffic. This will not only help the vessels to conduct their work in an orderly manner, but also be able to accurately receive the information sent by the ship in real time, so that the related departments could positioning and take actions the first time when ships are in danger[2, 3].

At the beginning of 1990s, in order to further enhance the safety of navigation of ships, the International Association of Lighthouse Authorities (IALA) in Marine Equipment Association first proposed the development of general ship recognition system proposal. After that, the International Maritime Organization (IMO), the International Telecommunication Union (ITU), the International Electrotechnical Commission (IEC) have given great concern and support, and finally adopts a new navigation system, Automatic Identification System (AIS)[4-7], which is used to automatically exchange messages between berths and shipboards. The message includes the ship identification, ship position, course and speed, besides, it receives the messages from other berth or base station and exchange information with the coast stations. The traditional AIS system based on very high frequency band achieves communication within the range of sight, and its coverage is limited. The spaceborne AIS system uses the low earth orbit satellite to receive the AIS signal, while the satellite height is 600-1000km, it can realize the global AIS coverage with a proper satellite constellation. More and more attention has been paid to the research in this field [8, 9]. However, in the satellite-borne AIS system, the signal collision is a key problem, while there are Doppler frequency offset and time delay. In the case, signal separation and detection are more difficulty. Blind source separation research is usually divided into two cases: single channel and multi-channel. On the aspect of separation for single channel signal, Zhao Zhiqiang[10] proposed the improvement of single channel blind source separation algorithm based on ICA, and Hong Danfeng, Ling Qing[11] proposed a ICA blind source separation algorithm based on wavelet transform. For the blind source separation of multi-channel AIS signals, Niknazar M[12] becker H proposed under-determined blind source separation algorithm. For signal detection, many algorithms have been developed for non-coherent detection of AIS signals. Chuo Gang, Wang Wenbo, Chang Yongyu[13] proposed the traditional differential detection algorithm, which, divides the received signal into two paths. And one way signal is multiplied by another with 1bit delay and phase shift. The sequence of source signals can be obtained by the filting and judgment. J.L.Buetefuer[14] and AM Rabiei[15] proposed double differential demodulation method, the detection performance of this algorithm is not affected by the frequency offset, but the algorithm changes the modulation of the transmitted signal, it is not suitable for satellite-based AIS system. Dimitrios Makakis and

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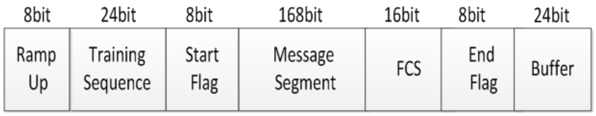
Kamilo[16] proposed a multi symbol differential detection algorithm based on Viterbi decoding, which combined differential detection and Viterbi decoding to achieve a low complexity signal detection. Fang Ting and Ma Shexiang[17] introduced the incoherent detection based on Viterbi algorithm. Compared with traditional signal detection method, Viterbi algorithm gets rid of the effect of Doppler frequency offset on the performance of the algorithm, and the bit error rate of the signal detection is also greatly reduced. In view of the superior performance of Viterbi algorithm, a large number of scholars have studied and improved it. Zhang Hao, Yang Yuhong[18] used the PSP algorithm to achieve signal separation and detection together. Bi Yan, Qian Liang[19] used the combination of PSP and Kalman filtering to achieve signal separation. PSP algorithm not only keeps the superior performance of Viterbi algorithm, but also greatly reduces the complexity [20].

In this paper, a signal detection algorithm based on real-time tracking of channel and phase is proposed. The algorithm can track the change of channel and phase, so as to avoid the serious distortion and crosstalk, and ensure the stability of the system when the channel changes too fast. The simulation results show that this algorithm has a better performance than differential detection, Viterbi decoding and per survivor processing (PSP) signal detection algorithm.

## II. SIGNAL MODEL

According to AIS protocol, the AIS message format is shown in Figure 1[21].



| 8bit | 24bit | 8bit | 168bit | 16bit | 8bit | 24bit |
|---|---|---|---|---|---|---|
| Ramp Up | Training Sequence | Start Flag | Message Segment | FCS | End Flag | Buffer |

Fig 1. The format of an AIS message

It consists of a ramp-up field, a training sequence, a start flag, a message segment, a Frame Check Sequence (FCS), an end flag and a buffer sequence. The ramp-up field coincides with the powering up of the transmitter of the AIS of a given ship. The training sequence field and the start flag field are predetermined AIS code sequences that are described herein to detect AIS message signal in the overlapped data. The message segment field contains information relating to the ship from which the AIS signal was transmitted. The FCS field is used for error detection. The end flag field is another predetermined AIS code sequences that may be employed during decoding. The buffer code is generally 24bit and is reserved as a signal delay. The AIS signal is a GMSK modulation signal with a bit rate of 9.6kbps. 161.945MHZ and 162.025MHZ are the working bands.

Assume that the received AIS baseband signal can be represented as:

$$y(t)=\sum_{i=1}^{M}h_i(t)e^{j(2\pi\Delta f_i t+\theta_i)}x_i(t)+v(t) \tag{1}$$

Where, $h_i(t)$ is the instantaneous amplitude of the *i-th* AIS signal, $\Delta f_i$ is the residual carrier, $\theta_i$ is the initial phase, $M$ represents the number of AIS signals, $v(t)$ is the Gaussian white noise. $x_i(t)$ is the baseband form of the *i-th* AIS signal, which can be expressed as

$$x_i(t)=\sum_{n=0}^{N}a_{i,n}g_i(t-nT+\tau_i(t)) \tag{2}$$

In above formula, $a_{i,n}$ represents the *n-th* symbol of *i-th* signal, $N$ represents the length of the symbol sequence, $g_i(t)$ is the channel filter, $T$ is the symbol period, $\tau_i(t)$ is the transmission delay of the *i-th* signal.

The received signal is sampled by the rate of symbol to obtain the following formula:

$$y_k=\sum_{i=1}^{M}h_{i,k}e^{j(2\pi\Delta f_i kT+\theta_i)}x_{i,k}+v_k \tag{3}$$

where,

$$x_{i,k}=\sum_{n=0}^{N}a_{i,n}g_i(kT-nT+\tau_{i,k}) \tag{4}$$

and, $\tau_{i,k}$ represents the time delay. The duration of $g_i(t)$ is from $(1-L_1)T$ to $L_2T$. Denote $L=L_1+L_2$, and define $L\times 1$ dimensional vectors as following

$$\bar{g}_{i,k}=h_{i,k}e^{j(2\pi\Delta f_i kT+\theta_i)}\left[g_i((L_1-1)T+\tau_{i,k}),g_i((L_1-2)T+\tau_{i,k}),\cdots g_i(-L_2T+\tau_{i,k})\right]^T \tag{5}$$

Then the received signal can be expressed as a simple form:

$$y_k=\sum_{i=1}^{M}\tilde{g}_{i,k}^{T}b_{i,k}+v_k \tag{6}$$

where $b_{i,k}=\left[a_{i,k-L_1+1},a_{i,k-L_1+2},\cdots a_{i,k+L_2}\right]^T$ (7)

## III. SIGNAL DETECTION ALGORITHM BASED ON REAL-TIME CHANNEL AND PHASE TRACKING

### A. *Per survivor processing algorithm*

The basic idea of the PSP algorithm is to embed the real-time channel estimation technique into the Viterbi algorithm[22] to realize the joint estimation of parameters and sequences. In the algorithm, the training sequence is used to estimate the initial channel and the Viterbi decoding is performed after the channel estimation is completed. Calculate the branch metrics using the estimated channel parameters. In the process of grid search, for every surviving path, a set of estimated value of channel parameters should be reserved, according to the branch metric, the survive path to each state should be extend to next level. Based on the channel parameters at the last time, we can realize the adaptive tracking of the channel parameters without delay [23-25].

Because of the channel response is unknown, it is necessary to combine the sequence and channel response for the realization of the maximum likelihood estimation:

$$\hat{\Phi} = \underset{\Phi,G}{\arg\max}\{p(Y/\Phi,G)\} \tag{8}$$

Where, $\Phi$ represents the source signal sequence, $Y$ represents the received signal sequence, $G$ represents the channel response.

By the time of $K$ , the likelihood probability can be written:

$$p(Y/\Phi,G) = p\left(y_{0:K}\left|b_{1,0:K+L_2},\cdots,b_{M,0:K+L_2},\tilde{g}_{1,0:K},\cdots,\tilde{g}_{M,0:K}\right.\right) \tag{9}$$

Assuming that the components of the signal are independent of each other, the upper form can be expressed as:

$$p(Y/\Phi,G) = \prod_{k=0}^{K} p\left(y_k\left|b_{1,k},b_{2,k},\cdots,b_{M,k},\tilde{g}_{1,k},\tilde{g}_{2,k},\cdots,\tilde{g}_{M,k}\right.\right) \tag{10}$$

Expand the equation (10), then we have the following form:

$$p(Y/\Phi,G) = \left(\frac{1}{\sqrt{2\pi\sigma^2}}\right)^{K+1}\exp\left(-\frac{1}{2\sigma^2}\left|y_k-\tilde{g}_{1,k}^T b_{1,k}-\tilde{g}_{2,k}^T b_{2,k}-\cdots-\tilde{g}_{M,k}^T b_{M,k}\right|^2\right) \tag{11}$$

Therefore, the branch path metric of the *k* moments can be defined as:

$$\lambda(s_{k-1}\to s_k) = \left|e(s_{k-1}\to s_k)\right|^2 \tag{12}$$

Where,

$$e\left(s_{k-1}\to s_k\right) = y_k - \sum_{i=1}^{M}\tilde{g}_{i,k}^T b_{i,k}\left(s_{k-1}\to s_k\right) \tag{13}$$

and, $b_{i,k}\left(s_{k-1}\to s_k\right)$ is the symbol vector corresponding to the state transition $s_{k-1}\to s_k$. Minimize every state of $s_k$ to obtain the cumulative path metric. The minimal path in the cumulative path metric is retained as the surviving path of the state, and the cumulative path metric is shown as follows:

$$\Gamma(s_k) = \min\left\{\Gamma(s_{k-1})+\lambda(s_{k-1}\to s_k)\right\} \tag{14}$$

The channel response of each state is updated by LMS, and the update process is as follows:

$$\tilde{g}_{i,k+1} = \tilde{g}_{i,k}+\gamma b_{i,k+1}^{*}\left(s_k\to s_{k+1}\right)e\left(s_k\to s_{k+1}\right)^T \tag{15}$$

Where, $\gamma$ is the update step, * represents the conjugate operation.

### B. *Signal detection based on channel and phase tracking*

The traditional PSP[26,27] algorithm requires the estimation of the source signal to be performed in the joint space consisting of the symbol sequence and the channel response. According to equation (5) , it shows that the change of $\tilde{g}_{i,k}$ are mainly caused by $h_{i,k}$ $\tau_{i,k}$ and $\Delta f_i$ ,among them, $h_{i,k}$ and $\tau_{i,k}$ are not changed in a certain period of time, so the existence of $\Delta f_i$ , it makes $\tilde{g}_{i,k}$ change with time. When the change of $\Delta f_i$ goes beyond the PSP algorithm tracking capability, the algorithm is not applicable. In order to solve the problem of fast time-varying channel in satellite-based AIS system, a signal detection algorithm based on the joint real-time tracking of channel and phase is proposed.

Let $\hat{\varphi}_{i,k} = 2\pi\Delta f_i kT+\theta_i$ , then equation (6) can be represented as:

$$y_k = \sum_{i=1}^{M} e^{j\hat{\varphi}_{i,k}}\hat{g}_{i,k}^T b_{i,k}+v_k \tag{16}$$

where, $\hat{g}_{i,k}$ is defined as:

$$\hat{g}_{i,k} = h_{i,k}\left[\tilde{g}_i\left(\left(L_1-1\right)T+\tau_{i,k}\right),\tilde{g}_i\left(\left(L_1-2\right)T+\tau_{i,k}\right),\cdots,\tilde{g}_i\left(-L_2T+\tau_{i,k}\right)\right]^T \tag{17}$$

Assuming that the state is transferred from $s_{k-1}$ to $s_k$ , the output is $y_k$ ,the state transition can be denoted as $s_{k-1}\to s_k$ and the entering symbol at time *k* is （$b_{1,k+L},b_{2,k+L},...,b_{M,k+L}$）. Then the equation (13) can be expressed as:

$$e(s_{k-1}\to s_k) = y_k - \sum_{i=1}^{M} e^{j\hat{\varphi}_{i,k}}\hat{g}_{i,k}^T b_{i,k}\left(s_{k-1}\to s_k\right) \tag{18}$$

Similarly, performing a minimization operation for each state $s_k$ , and by equation (14), the cumulative minimize path can be obtained. If $k\ge\delta$ , output the current symbol pair, in which $\delta$ is the decision delay.

LMS algorithm is used to update $\hat{g}_{i,k}$ and the update process is as follows:

$$\hat{g}_{i,k+1} = \hat{g}_{i,k} + \gamma e^{-j\hat{\varphi}_{i,k}} b_{i,k+1}^{*}(s_k \to s_{k+1}) e(s_k \to s_{k+1})^{T} \tag{19}$$

Unlike the traditional PSP algorithm, in addition update $\hat{g}_{i,k}$ and $\hat{\varphi}_{i,k}$ are also needed to be updated. Assuming that the length of symbol sequence corresponding to the survival path at time $k$ is $N_t + L - 1$, and the phase $\hat{\varphi}_{i,k+1}$ at the next moment can be estimated as follows:

$$\begin{aligned}\hat{\varphi}_{i,k+1} &= \arctan\left(\sum_{l=k-N_t+1}^{k}\left[y_l - \hat{y}_{1,l} - \cdots - \hat{y}_{i-1,l}\right]y_{i,l}^{*}\right)\\ &= \arctan\left(\sum_{l=k-N_t+1}^{k}\left[\left[y_l - e^{j\hat{\varphi}_{1,k}}\hat{g}_{1,k}^{T}(s_k)b_{1,l}(s_k) - \cdots - e^{j\hat{\varphi}_{i-1,k}}\hat{g}_{i-1,k}^{T}b_{i-1,l}(s_k)\right]\left[g_{i,k}^{T}(s_k)b_{i,l}(s_k)\right]^{*}\right]\right)\end{aligned} \tag{20}$$

Where, $y_{i,l}$ is the baseband form of the *i-th* AIS signal, which can be represented as:

$$y_{i,l} = \hat{g}_{i,k}^{T}(s_k) b_{i,l}(s_k) \tag{21}$$

$\hat{y}_{i,l}$ is the modulated signal, which can be expressed as:

$$\hat{y}_{i,l} = e^{j\hat{\varphi}_{i,k}} \hat{g}_{i,k}^{T}(s_k) b_{i,l}(s_k) \tag{22}$$

Where, $\hat{g}_{i,k}^{T}(s_k)$ is the channel response corresponding to the survival path of the state $s_k$ , $b_{i,l}(s_k)$ is the symbol sequence corresponding to the state $s_k$ .

The algorithm can be implemented as follows steps.

Step 1

Establish symbol transfer status. Enter the initial symbol state at time k, a state shift from $s_{k-1}$ to $s_k$ while outputting $y_k$ .This shift can be written as

$$s_{k-1} \xrightarrow{(b_{i,k},y_k)} s_k . \tag{23}$$

By the time of $K$ , the likelihood probability can be written as shown in formula (10).

Step 2

Path metrics and channel initialization. Set k=0,for each state $s_0$ ,initialize $g_{i,0}$ with some certain value,save survivor path $p_0 = (s_0)$ and its relative metric $\Gamma(s_0)$=0.

Step 3

Outputs symbol. Assuming δ is the decision delay, when k≥δ, output symbols $b_{i,k-\delta}$ at time (k-δ) according to the optimal retention path.

Step 4

Path metrics to expand and filter. The branch path metric at time k can be defined as shown in formula (18). The cumulative path metric is shown as a formula (14).

Step 5

Parameter estimation (LMS): for the transitions $\mu_k \to \mu_{k+1}$ that extend the survivors, the CIR vectors are updated according to formula (19). In addition, according to formula (20), the phase information at the next time is updated.

Step 6

Return to step 3 after the parameters are updated.

The algorithm flow is shown in Figure 2.

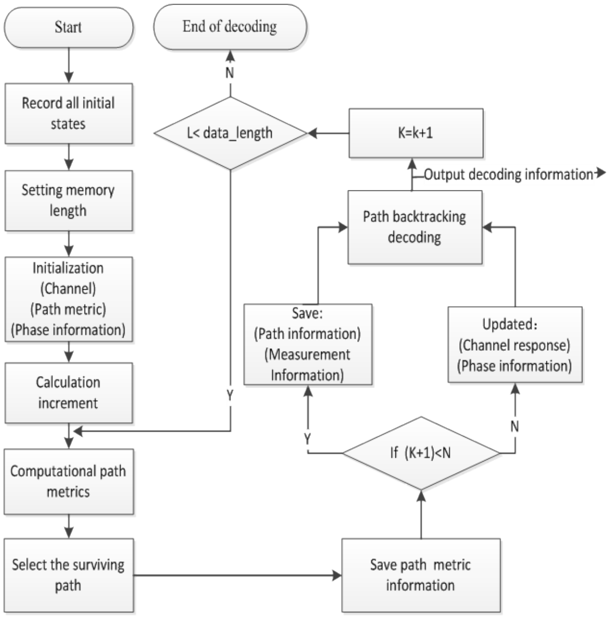


Fig. 2 Algorithm block diagram

## IV. SIMULATION RESULTS

In the simulations, the AIS signal is modulated by GMSK, which the modulation index is 0.5, and the symbol rate is 9600bit/s. Meanwhile, the length of the symbol sequence is 10000bits. According to the problems of the satellite-based AIS system, the simulation experiments are carried out from the aspects of existence frequency offset, time delay, the length of symbol interference and the number of interference signals, respectively.

(1) Simulation experiment one, Assuming the length of the symbol crosstalk is $L = 5$ , step length $\gamma = 0.05$ , add Gaussian white noise into the single signal, and the performance of algorithm is evaluated by bit error rate. From Fig.3, it can be seen that the bit error rate performance of this algorithm is better than one bit difference detection, two bit difference detection, Viterbi decoding and traditional PSP algorithm.

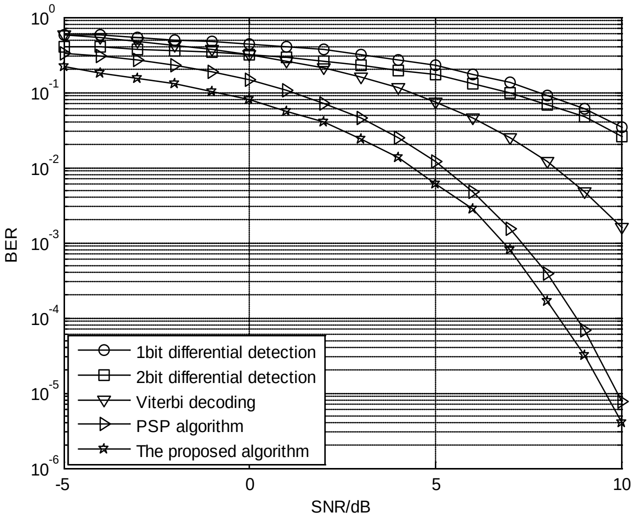


Fig. 3 Error rate curve under different algorithms with L=5

(2) Simulation experiment two, in the time-varying channel conditions, which the channel parameters are different. The following are the simulation results of the Rayleigh channel. Set the normalized frequency offset are 0.2 and 0.3, respectively (in Fig.4, normalized frequency offset is denoted as f), and the error rate curve is shown in Fig.4. It can be seen that the bit error rate performance of the algorithm is superior to the PSP signal detection algorithm.

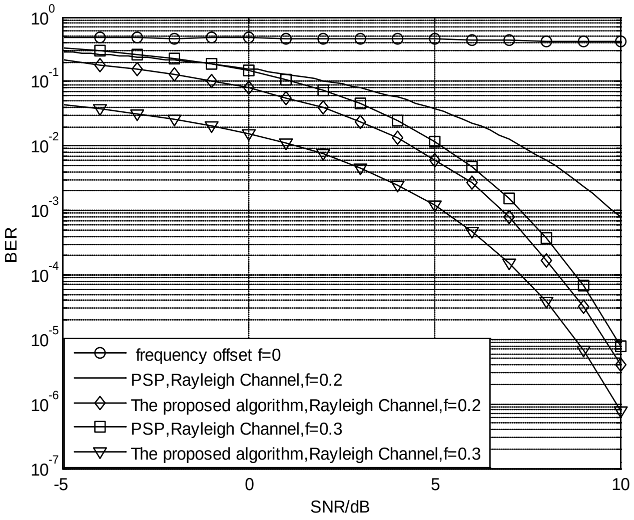


Fig. 4 Error rate curve of the proposed algorithm under different frequency offset

(3) Simulation experiment three, In the simulation, set the length of intersymbol interference as $L=3$, $L=5$ and $L=7$, respectively, and the simulations are shown in Fig.5. From the figure, it can be seen that the bit error rate performance of signal detection algorithm based on channel and phase real-time tracking is superior to that of traditional PSP signal detection algorithm.

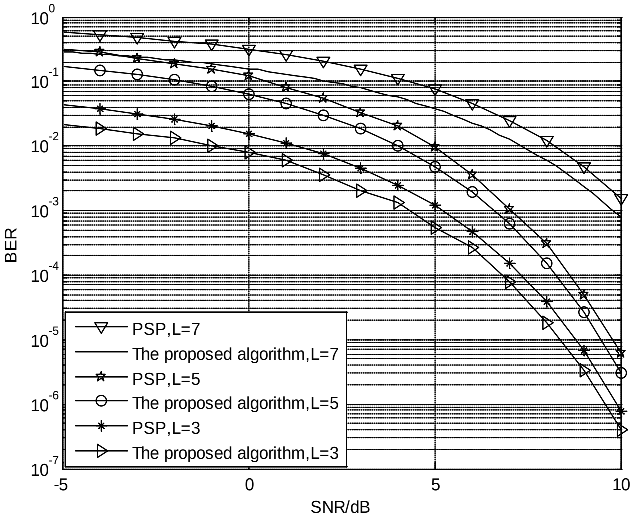


Fig. 5 Error rate curve of the proposed algorithm under different intersymbol interference

(4) Simulation experiment four, in the aspect of anti delay, Fig.6 shows the detection performance when the time delay value is 0, $\frac{1}{8}T_b$, $\frac{2}{8}T_b$ and $\frac{3}{8}T_b$, respectively, from which we can see that the error rate is still low when time delay is $\frac{2}{8}T_b$, and it can meet the requirements of satellite-based AIS system.

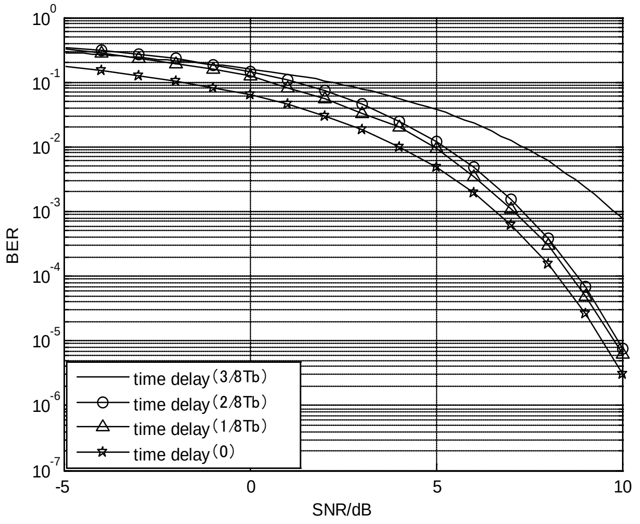


Fig. 6 Error rate curve of the proposed algorithm under different time delay

(5) Simulation experiment five, Fig.7 shows the detection error rate curve of the proposed algorithm when $S/I = 6\mathrm{d}B$. From the figure, it can be seen that in a certain signal to noise ratio, the error rate can reach to $10^{-5}$ when no interference exists. Assuming that there is an interference, and the value of SIR are 2dB, 4dB, 6dB, 8dB and 10dB, the bit error rate can only reach to $10^{-3}$, as can be seen from Fig.8 that under the

same SNR, the higher the SIR is, the better the detection performance can we get.

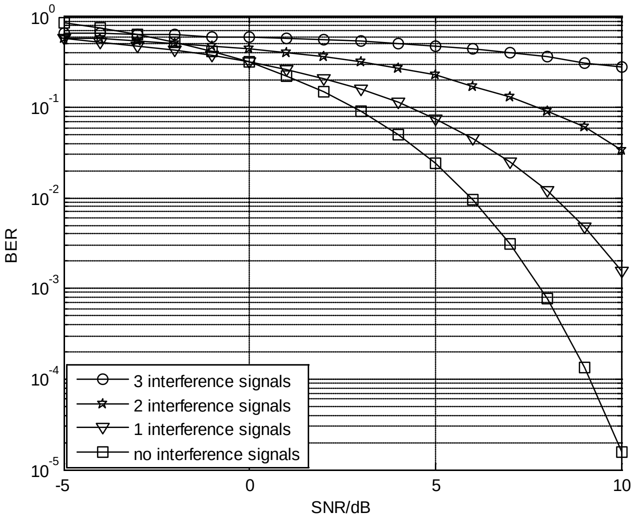


Fig. 7 Error rate curve of the proposed algorithm under different interference

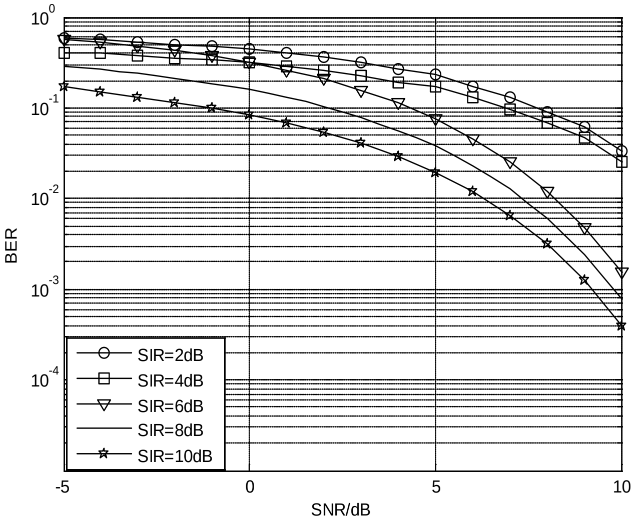


Fig. 8 Error rate curve of the proposed algorithm under different SIR

The detection algorithm is realized to detection of GMSK single signal under low SNR condition. However, with the increase of the mixed signal, the detection performance is decreased, therefore, further researches are needed to be proposed.

## V. CONCLUSION

The paper presents a signal detection method that combines the channel tracking and phase tracking together, this algorithm has strong tolerance ability about frequency offset errors, besides, it can overcome the problem of parameter estimation error which caused by the fast time-varying channel of spaceborne AIS system. However, with the increase of users, the mixed signal with the same frequency will be more and more, so the computation complexity of the algorithm will be increased exponentially with the increase of interference; In addition, with the increase of interference, the signal detection performance is getting more worse. Therefore, it is necessary for further research of this subject.

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