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Covariance-based Follower Jamming Blocking Algorithm for Slow FH-BFSK Systems

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***Abstract*—In this paper, a covariance-based algorithm with multiple antennas is proposed to eliminate the follower jamming for frequency hopping systems (FH) by finding the interference-blocking filter over quasi-static flat fading channels. The system uses the auto-covariance matrix of the received signal and M-array receive antennas. The simulation results show that the proposed approach can estimate the interference-blocking filter regardless of the jamming strength, which is especially available in the case that the follower jamming is much stronger than the FH signals.**

***Index Terms*—Frequency hopping(FH), follower jamming, antenna array, anti-interference filter, autocorrelation diversity, blind estimation**

I. Introduction

Frequency hopping (FH) is wildly used in civilian and military wireless communications due to its high data security. However, under the circumstances that the jammer with high transmitting power is closer to the receive antenna than FH signal transmitter, which means that the jamming power is comparable or much greater than the FH signal, the FH performance will deteriorate unacceptably. Particularly, follower jammers can efficiently cause interference to FH under some certain conditions. In follower jamming, the jammer intercepts the FH signal, modulates it by noise, amplifies and then transmits the jamming. Fast hopping may protect FH signal against such jamming by decreasing the allowable processing time of jammer. The jamming will arrive at receive antenna later than the FH signal because of the processing time of jammer. In order to avoid the follower jamming, the hopping rate should be enhanced to ensure that a frequency interval is shorter than jamming delay .

Unfortunately, FH system may have limitations for fast hopping[1]. In FH systems, the transmitters and receivers contain clocks for synchronization. The faster the hopping rate, the more accurate the clocks must be. And other limitations existing do not allow for enhancing the hopping rate greatly. Some maximum likelyhood (ML) based interference cancellation and detection schemes have been proposed by Ko, Le, and Huang in [1],[2]. These ML based schemes have high calculation complexity and they have to estimate the signal's channel before jamming arrives. Direction of arrival (DOA) estimation based smart antenna algorithms also have high calculation complexity, and their performances decline when the DOAs of desired signal and jamming are very similar or the power of jamming is much higher than the desired signal.

In this paper, a covariance-based anti-follower jamming scheme based on antenna array is proposed. This scheme is able to block follower jamming modulated by white noise without channel estimation. The proposed scheme makes use of the difference properties of the covariance of the FH signal and the follower jamming, and then find a interference-blocking filter by employing space diversity. The scheme is based on the autocorrelation matching algorithm proposed by Luo, Liu, Song, and Hu in[3]-[5]. Ying and Liu in [6],[7] extended the algorithm to the case when the signal was cyclostationary.

However, the follower jamming signal is not cyclostainary, although the FH signal is. In this paper, linear independent autocorrelation diversity vectors defined in [5] of FH signal and follower jamming are constructed to eliminate the jamming without channel estimation. The computational complexity of the algorithm is calculated comparing with [1]. Since the scheme is insensitive to jamming power, the scheme performs well under strong interference. The simulation study shows that the jamming can be eliminated completely when signal-to-noise ratio (SNR) varies from 0 dB to 16 dB. Also, it has strong robustness when the power of jamming is much higher than the FH signal.

II. SYSTEM MODEL DESCRIPTION

Consider a BFSK modulated slow FH system . To eliminate the follower jamming, the scheme explores the use of a simple M-element receive array antennas, where the FH signals and the follower jamming arrive with different fading channels [6]. The model is given below,

$$\mathbf{y}(t) = \mathbf{H}s(t) + \mathbf{F}j(t) + \mathbf{n}(t) \tag{1}$$

where

$\mathbf{y}(t)$: M-vector of the received signals
$s(t)$: The FH signal to be transmitted
$j(t)$: The follower jamming
$\mathbf{n}(t)$: M-vector of AWGN with the power of σ_n^2
$\mathbf{H}$: M-element flat fading channel of FH signal
$\mathbf{F}$: M-element flat fading channel of follower jamming

The transmitted FH signal $s(t)$ is given by

$$s(t) = s_{BFSK}(t) \cdot s_{HOP}(t) \tag{2}$$

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where:

$$\begin{aligned} s_{BFSK}(t) &= [\sum_n a_n g(t-nT_0)]\cos(2\pi f_1 t+\phi_1) \\ &+[\sum_n \bar{a}_n g(t-nT_0)]\cos(2\pi f_2 t+\phi_2) \end{aligned} \tag{3}$$

where $\bar{a}_n$ is diminished radix complement of a_n , a_n equals to 1 and 0 with the same probability of $\frac{1}{2}$, T_0 denotes the interval for transmitting a bit. $g(t)$ is rectangle window, i.e. $g(t) = 1$ for $0 \leq t < T_0$, and $g(t) = 0$ otherwise. The mixing frequency signal is described as follows,

$$\begin{aligned} s_{HOP}(t) = \sum_{m=1}^{N}\sum_{n=1}^{N} a_{n,m} g(t-nT_0)\cos(2\pi f_n t+\theta_n) \\ \cdot \sum_{k=-\infty}^{\infty}\delta(t-kNT_0) \end{aligned} \tag{4}$$

where

$$a_{n,m} = \begin{cases} 1 \ , n=m \\ 0 \ , n\neq m \end{cases} \tag{5}$$

where N is the number of hopping frequencies, f_n the hopping frequency, T_0 the hopping frequency interval equaling that of transmitting a bit, NT_0 the hopping period.

The follower jammer first intercepts the FH signal. Without the perfect knowledge of the desired signal such as the hopping frequency of the desired signal, the jammer modulates the signal received on noise, then amplifies the modulated signal and transmits it. A follower jamming signal can thus be represented as

$$j(t) = n_j(t)\cdot s(t-T_c) \tag{6}$$

where T_c is the delay of the jamming arriving at receive antenna with respect to FH signal, the statistic properties of $n_j(t)$ is assumed to be similar with white noise. The amplitude of $n_j(t)$ is considered as constant in an interval of T_j $(T_j \leq T_0)$, then the autocorrelation function of $n_j(t)$ equals 0 when $\tau \geq T_j$.

Through out the paper we assume that:

A1 $s(t)$, $j(t)$ and $\mathbf{n}(t)$ are statistically independent to each other.

A2 In $s(t)$, both $s_{BFSK}(t)$ and $s_{HOP}(t)$ have continuous phases of ϕ_1 , ϕ_2 and θ_k .

A3 $[\mathbf{H}\ \ \mathbf{F}]$ is full column rank.

In this paper, a interference-blocking filter $\mathbf{w}$ is supposed to be found. In theory, the jamming is fully eliminated and the desired signal is retained only when

$$\begin{cases} \mathbf{w}^\dagger \mathbf{H} \neq 0 \\ \mathbf{w}^\dagger \mathbf{F} = 0 \end{cases} \tag{7}$$

where the superscript † means conjugate transpose. ***A3*** ensures that the filter exists. When the number of receive antenna arrays is large enough, the probability that $[\mathbf{H}\ \mathbf{F}]$ is full column rank approximately equals 1. If the desired signal's channel and jamming's channel are known, finding such a filter should be easy. Because the follower jamming arrives at the receive antenna later than FH signal, it is reasonable to assume that the desired signal's channel could gain by channel estimation. However, channel detection means more spending of system, and the noncooperative follower jamming's channel is not able to be detected by most simple methods. To avoid the channel detection, a blind estimation algorithm based on the *autocorrelation matching principle* is proposed in [5], and it formulates that different signals even overlopping in both time and frequency domain can be separated by this principle when their *autocorrelation diversity vectors* are linear independent.

The *autocorrelation diversity vector* is defined as

$$\mathbf{v}_n = [r_n(\tau_1), r_n(\tau_2), ..., r_n(\tau_L)] \tag{8}$$

where $r_n(\tau)$ is the n th signal's autocorrelation function with a lag τ .In this definition, $0 < \tau_1 < \tau_2 < ... < \tau_L$.

III. PROPERTIES OF COVARIANCE OF THE FH SIGNAL

Some important properties of the covariance of the FH signal and the follower jamming are discussed in this section. The properties of them are exploited to construct two linear independent *autocorrelation diversity vectors*, then the algorithm based on [8] will be used to find the interference-blocking filter in the next section. As shown in (2), the FH signal is described as two parts. The autocorrelation function of $s_{BFSK}(t)$ is represented as following,

$$\begin{aligned} & r_{S_{BFSK}}(t,\tau) = E\{s_{FSK}(t+\tau/2)s^*_{FSK}(t-\tau/2)\} \\ & = \tfrac{1}{L_n}\{\tfrac{1}{2}\sum_n |a_n|^2 g(t-nT_0)[\cos(4\pi f_1 t+2\phi_1)+\cos(2\pi f_1\tau)]+ \\ & \tfrac{1}{2}\sum_n |\bar{a}_n|^2 g(t-nT_0)[\cos(4\pi f_2 t+2\phi_2)+\cos(2\pi f_2\tau)]\} \end{aligned} \tag{9}$$

where $E\{\cdot\}$ means mathematical expectation, the superscript * means conjugation, and L_n is the data length of a_n .

According to (4), we have

$$\begin{aligned} & r_{S_{HOP}}(t,\tau) = E\{s_{HOP}(t+\tau/2)s^*_{HOP}(t-\tau/2)\} \\ & = \tfrac{1}{2N}\sum_{m=1}^{N}\sum_{n=1}^{N} |a_{n,m}|^2 [\cos(4\pi f_n t+\theta_n)+\cos(2\pi f_n\tau)] \\ & \cdot g(t-nT_0)\sum_{k=-\infty}^{\infty}\delta(t-kNT_0) \end{aligned} \tag{10}$$

The signals $s_{BFSK}(t)$ and $s_{HOP}(t)$ are considered to be statistic independent, so the autocorrelation of FH signal is given below,

$$r_s(t,\tau) = r_{s_{BFSK}}(t,\tau)\cdot r_{s_{HOP}}(t,\tau) \tag{11}$$

If the frequency of the BFSK and mixing frequency signal is selected elaborately so that the fundamental waves of two signals have a mutual period NT_0 , the influence of t could be eliminated by synchronization in the recerver.

As described in (6), the follower jamming is modulated by a white noise-like signal $n_j(t)$. The autocorrelation of $n_j(t)$ equals 0 when $\tau \geq T_j$. $n_j(t)$ is considered to be independent to $s(t)$, so the autocorrelation function of $j(t)$ is formulated as follows,

$$r_j(t,\tau) = r_{n_j}(\tau)\cdot r_s(t-T_c,\tau) \tag{12}$$

where:

$$r_{n_j}(\tau) = \begin{cases} \frac{T_j - \tau}{T_j}, \ \tau \leq T_j \\ 0, \ otherwise \end{cases} \tag{13}$$

After eliminating the influence of t by synchronization, we take a small value for τ , for example, a snapshot interval $T_{snapshot}$ of the signal. The autocorrelation function of $s(t)$ approximates $\frac{1}{2}$ when $\tau = T_{snapshot}$. As shown in (13), $r_{n_j}(\tau)$ approximates 1 when $\tau = T_{snapshot}$. Meanwhile, the probability that $r_s(t - T_c, T_{snapshot}) = 0$ approximately equals 0, which can be analyzed from (12).

Hence, we can construct two linear independent *autocorrelation diversity vectors* making use of these properties. The *autocorrelation diversity vector* is defined in (8). Then the two vectors representing the FH signal and the follower jamming separately are given below,

$$\begin{array}{c} \mathbf{v}_s = [r_s(t, T_{snapshot}), \ r_s(t, NT_0)] \\ \mathbf{v}_j = [r_j(t, T_{snapshot}), \ r_s(t, NT_0)] \end{array} \tag{14}$$

In (14), $r_s(t, T_{snapshot})$ approximates $\frac{1}{2}$ and $r_s(t, NT_0)$ equals $\frac{1}{2}$ after eliminating the influence of t , as described in (11). Whenas, $r_j(t, T_{snapshot})$ is not equal to 0 with probability 1 and $r_s(t, NT_0) = 0$ as formulated in (12) and (13). In view of these, $\mathbf{v}_s$ and $\mathbf{v}_j$ are linear independent obviously.

IV. SEARCHING FOR THE INTERFERENCE-BLOCKING FILTER

We first study the vector of signal $\mathbf{y}(t)$. In view of ***A1***, the covariance matrix of $\mathbf{y}(t)$ is given by,

$$\begin{array}{l} \mathbf{R}_y(t, \tau) = E\{\mathbf{y}(t + \frac{\tau}{2})\mathbf{y}^\dagger(t - \frac{\tau}{2})\} \\ = \mathbf{H} r_s(t, \tau)\mathbf{H}^\dagger + \mathbf{F} r_j(t, \tau)\mathbf{F}^\dagger + \sigma_n^2 \delta(\tau)\mathbf{I} \end{array} \tag{15}$$

In order to estimate the interference-blocking filer, the autocorrelation function of FH signal $s(t)$ has to be known by receiver. So both t and τ should be known by the receiver. An interval of one block of FH signal should be integral multiple of NT_0 so as to eliminate the influence of t . It is not necessary to know the autocorrelation function of $j(t)$ for this algorithm. We want to design the interference-blocking filter $\mathbf{w}$ defined in (7), which can be accomplished by decomposing (15). According to [8], a closed solution of the filter by matrix decomposition is given as follows.

Step 1: Let $\tau_1 = T_{snapshot}, \ \tau_2 = NT_0$. Substituting (14) into (15), a new equation gains.

$$\begin{array}{l} [\mathbf{R}_y(t, \tau_1), \mathbf{R}_y(t, \tau_2)] = [\mathbf{H} r_s(t, \tau_1)\mathbf{H}^\dagger + \mathbf{F} r_j(t, \tau_1)\mathbf{F}^\dagger, \\ \mathbf{H} r_s(t, \tau_2)\mathbf{H}^\dagger + \mathbf{F} r_j(t, \tau_2)\mathbf{F}^\dagger] \end{array} \tag{16}$$

Note that the item $\sigma_n^2 \delta(\tau)\mathbf{I}$ is removed due to $\tau > 0$.

Before processing the matrix, we first transform (16) into another form, i.e.

$$\tilde{\mathbf{R}}_y = \tilde{\mathbf{H}}\mathbf{v}_s + \tilde{\mathbf{F}}\mathbf{v}_j \tag{17}$$

where:

$$\tilde{\mathbf{R}}_y = [vect(\mathbf{R}_y(t, \tau_1)), vect(\mathbf{R}_y(t, \tau_2))] \tag{18}$$

$$\tilde{\mathbf{H}} = [vect(\mathbf{H}\mathbf{H}^\dagger)], \ \tilde{\mathbf{F}} = [vect(\mathbf{F}\mathbf{F}^\dagger)] \tag{19}$$

where $vect(\cdot)$ means arranging elements of a matrix by column.

Step 2: For calculating the filter $\mathbf{w}$ that makes $\mathbf{w}^\dagger \mathbf{F} = 0$, we first eliminate the item $\tilde{\mathbf{H}}\mathbf{v}_s$ by multiplying (17) by orthogonal complement of $\mathbf{v}_s$ represented as $\mathbf{v}_s^\perp$. The orthogonal complement of $\mathbf{v}_s$ is defined as follows,

$$\begin{cases} \mathbf{v}_s^\dagger \mathbf{v}_s^\perp = 0 \\ (\mathbf{v}_s^\perp)^\dagger \mathbf{v}_s^\perp = \mathbf{I} \end{cases} \tag{20}$$

Where $\mathbf{v}_s^\perp$ can be obtained by Singular Value Decomposition (SVD) of $\mathbf{v}_s$. Substituting $\mathbf{v}_s^\perp$ into (17), the equation becomes

$$\tilde{\mathbf{R}}_y \mathbf{v}_s^\perp = \tilde{\mathbf{F}}\mathbf{v}_j \mathbf{v}_s^\perp \tag{21}$$

Then elements of $\tilde{\mathbf{R}}_y \mathbf{v}_s^\perp$ are arranged in a $M \times M$ matrix $\mathbf{R}$, the filter $\mathbf{w}$ that satisfies (7) can be obtained by SVD of $\mathbf{R}$, i.e.

$$\mathbf{R} = [\mathbf{U} \ \mathbf{U}^\perp] \begin{bmatrix} \mathbf{\Lambda} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} [\mathbf{V} \ \mathbf{V}^\perp] = \mathbf{U}\mathbf{\Lambda}\mathbf{V}^\dagger \tag{22}$$

where $\begin{bmatrix} \mathbf{\Lambda} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix}$ is the singular value matrix and $\mathbf{\Lambda}$ contains all non-zero singular values, and $\mathbf{V}^\perp$ corresponding to zero singular values. Therefore, the solution of $\mathbf{w}$ is in the rang space of $\mathbf{V}^\perp$, i.e. $\mathbf{w} = \mathbf{V}^\perp \mathbf{c}$ for any column vector $\mathbf{c}$.

Step 3: The optimal $\mathbf{w}$ that maximizing the SNR of filtered signal first proposed in[7], is given by calculating the column vector $\mathbf{c}$. Then let $\mathbf{w} = \mathbf{V}^\perp \mathbf{c}$ where $\mathbf{c}$ can maximize

$$\mathbf{c}^\dagger \mathbf{V}^{\perp\dagger} \mathbf{R}_y(t, 0) \mathbf{V}^\perp \mathbf{c} \tag{23}$$

The optimal $\mathbf{c}$ is the eigenvector corresponding to the largest eigenvalue of $\mathbf{V}^{\perp\dagger} \mathbf{R}_y(t, 0) \mathbf{V}^\perp$.

The covariance based interference-blocking algorithm can be summarized as follows,

A. To calculate the covariance matrix of received signal;

At the receives, the received signal is sampled N times per symbol. Using (1), the covariance of received signal is

$$\mathbf{R}_y(\tau) = \frac{1}{NL} \sum_{i=1}^{NL - \tau + 1} \mathbf{y}(i)\mathbf{y}(i + \tau - 1) \tag{24}$$

where L is the number of transmitted symbols.

B. To estimate the interference-blocking filter using the algorithm in **Step1**, **Step2**, and **Step3**.

The computational burden of the algorithm is mainly due to **A**, since **A** involves covariance matrix calculating based on large sample data. **B** is based on Singular Value Decomposition just in a $M \times M$ matrix, so the computation burden can be ignored comparing with **A**.

Equation (15) implies that the matrix $R_y(\tau)$ is a symmetric matrix. So $\frac{1}{2}M(M+1)NL$ times real addition and $\frac{1}{2}M(M+1)NL$ times real mutiplication are needed for calculating $R_y(\tau)$. In the proposed algorithm, $R_y(T_{snapshot})$ and $R_y(NT_0)$ are calculated. The number of real addition and real multiplication for this algorithm are given in Table I.

TABLE I
COMPUTATIONAL COMPLEXITY OF THE PROPOSED ALGORITHM

	Number of real addition	**Number of real multiplication**
2 antennas	6*NL*	6*NL*
M antennas	*M(M + 1)NL*	*M(M + 1)NL*

TABLE II
COMPUTATIONAL COMPLEXITY OF THE ALGORITHM PROPOSED IN [1]

	Number of real additon	**Number of real multiplication**
2 antennas	22*NL* - 2*L*	22*NL* + 3*L*

For comparing, the computational complexity of ML-based algorithm proposed in [1] is shown in Table II.

As shown in Table I, the computational complexity decreases greatly comparing with [1]. Note that the algorithm proposed in [1] is based on just two receive antennas, and the use of more than two receive antennas is not mentioned . In this paper, the algorithm can be easily extended to systems more than two receive antennas, and the computational complexity with *M* receive antennas is calculated.

V. SIMULATION

The simulation system contains one FH signal, one follower jamming, and four receiveing antennas. In this system, each hop has 1 BFSK symbols, the symbol rate is 10010 symbols per second. Both BSFK signal and mixing frequency signal have continuous phases, and they have a mutual period equals a hopping period. Each of plots is an average of 200 trails. In each trail, every coefficient of the desired signal channel $\mathbf{H}$ and jamming channel $\mathbf{F}$ is randomly generated. The followers jamming arrives at the receiving antennas later than FH signal with a lag time of half an interval of a hopping frequency. For each block of data, each information sequence consists of 10010 symbols, and we assume that the channeals is time-invariant over one block. The SNR is defiined as the average SNR over all receiving antennas, i.e.,

$$SNR = \frac{1}{4}\sum_{i=1}^{4}(SNR)_i \tag{25}$$

The SJR is defined as the ratio of total power of the FH signal to power of the follower jamming,

$$SJR = \frac{P_s}{P_J} \tag{26}$$

The Anti-Jamming Index (AJI) given in Fig.1 is used to scale the efficiency of the interference-blocing filter defined as followers,

$$AJI = \frac{\left|\mathbf{w}^{\dagger}\mathbf{H}\right|^2}{\left|\mathbf{w}^{\dagger}\mathbf{H}\right|^2 + \left|\mathbf{w}^{\dagger}\mathbf{F}\right|^2} \tag{27}$$

The AJI is 1 when the jamming is completely blocked. As shown in Fig.1, $0.98 \leq AJIs \leq 1$ for all SNR.Since the

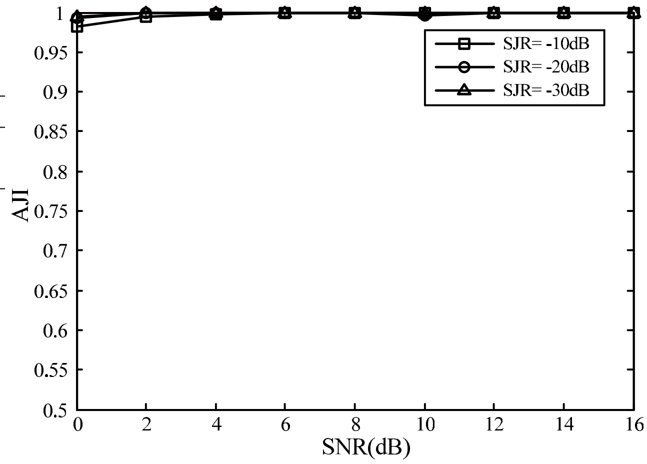

Fig. 1. Anti-Jamming Index

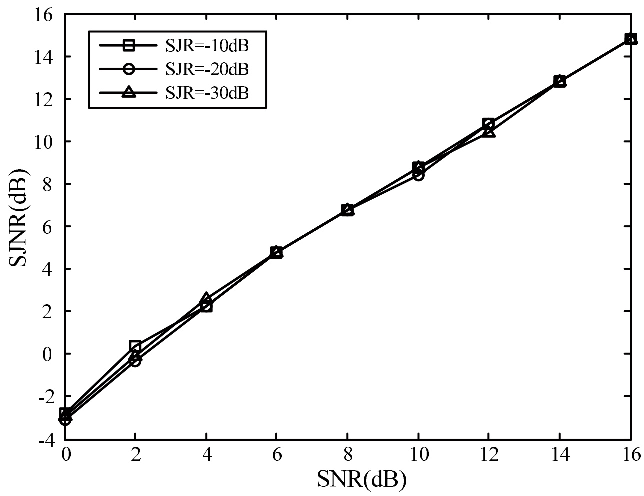

Fig. 2. Output SJNR

output power of the desired signal is not calculated by AJI, we also show the output SJNR plot in Fig.2. The SJNR is defined below,

$$SJNR = \frac{(\mathbf{w}^{\dagger}\mathbf{H})^2 P_s}{(\mathbf{w}^{\dagger}\mathbf{F})^2 P_J + \sigma_n^2} \tag{28}$$

When the jamming is completely blocked and $(\mathbf{w}^{\dagger}\mathbf{H})^2 \geq 0.25$, the $SJNR \geq inputSNR$, which is implied in (24). Fig.2 shows a huge improvement in SJR by the filter. Even when the jamming is 1000 times of the desired signa, the output $SJNR$ approximates the input SNR. The three curves are almost coincident implying that the anti-jamming algorithm is power of jamming insensitive.

The performance of the method is compared with a system with conventional beamformer [9] in Fig.3. As shown in Fig.3, the system with conventional beamformer can not work normally under the jamming with such a high power. Note that two points in the 1400 points of the 200 trails of the proposed algorithm are removed, because of their large devia-

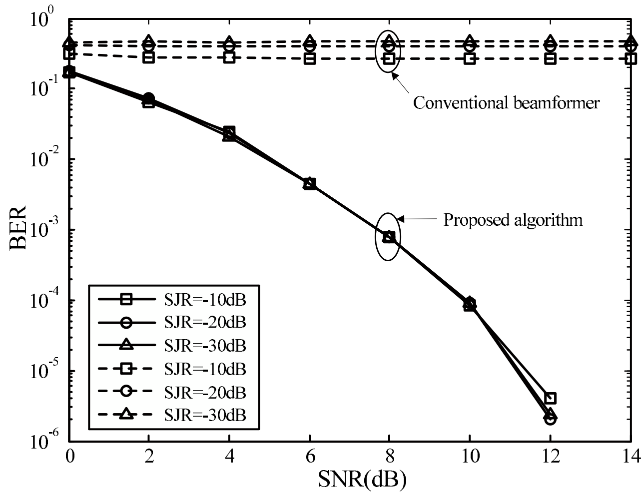

Fig. 3. BER of interference-blocking system and system with conventional beamformer

tion from the curves. The deviation is caused by similarity of desired signal's channel and jamming's channel, which happens with very low probability. The three BER curves of the proposed algorithm are almost coincident implying that the anti-jamming algorithm is power of jamming insensitive, which is also shown in Fig.2.

VI. Conclusion

In this paper, a covariance-based anti-follower jamming algorithm for slow FH system has been proposed. The algorithm is based on autocorrelation diversity and space diversity. Synchronization and choosing frequency of BFSK signal and mixing frequency signal are needed in this algorithm. The algorithm estimates the interference-blocking filter blindly and gives a closed solution of the filter avoiding iterative method, so the computational complexity decreased greatly than ML-based algorithm. The algorithm is insensitive to power of jamming. Simulations show that the algorithm almost blocks all of the jamming even when the input power is 1000 times that of the desired signal.

VII. Acknowledgement

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