# A Simple Scheme for 2FSK Signal Extraction Based on Independent Component Analysis with Cosine Pulse Reference Signal


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***Abstract*—In this paper, we propose a simple scheme for 2FSK signal extraction based on independent component analysis with reference (ICA-R) in noisy and disturbed channel condition, and only one of the two carrier frequencies of the source 2FSK signal is required as the a priori information to generate a cosine pulse signal as the reference signal at receiver. Simulations under various channel conditions, such as different jamming signal type, Signal-to-Jamming Ratio (SJR) and Signal-to-Noise Ratio (SNR), are carried out to investigate the effectiveness and extraction performance of the proposed method. The simulation results show that the proposed method takes a good extraction effect when the carrier frequency of the reference signal equals to either one of the two carrier frequencies of the source 2FSK signal, and the anti-noise performance under strong interference condition is almost the same with the theoretical result in AWGN channel. Moreover, the anti-jamming performance keeps well even when the SJR is as low as -50 dB. Besides, we find that the wrong convergence phenomenon results from the inherent threshold parameter problem in ICA-R is solved in our proposed scheme.**



***Keywords—Blind Sources Separation, Signal Extraction, Independent Component Analysis (ICA), ICA with Reference (ICA-R)***


## I. INTRODUCTION

Binary frequency shift keying (2FSK) is widely used in wireless communication because of its strong anti-fading ability. However, the signal is difficult to be recovered in serious noisy and strong interference channel condition. Independent component analysis (ICA) can be used to separate the independent components (ICs) from the linear mixture of statistically independent sources by optimizing different criteria [1-2]. However, due to the inherent limitations of ICA, the order of the separated signals is arbitrary, and a manual selection of the separated ICs is required which could be complicated, time-consuming and unreliable [3]. While in wireless cooperation communications, there are some useful information available at the transmitter and receiver. Therefore, a practical alternative is to incorporate a priori knowledge as additional constrains into classical ICA algorithms, then only a subset, even only one, of the interested source signals can be extracted from the mixed observed signals.

The ICA with reference (ICA-R) proposed by Lu and Rajapakse [4] could be used to solve this problem. When a set of reference signals which carry some priori information of the desired ICs are available, ICA-R can exactly extract the desired ICs and discard the rest of components as irrelevant signals. As a result, the manual selection of the separated ICs in ICA can be omitted consequently. The ICA-R algorithm has been applied in many applications, such as speech analysis [5-6], identification of satellite micro-vibration system [7], reader collision recovery in RFID Systems [8], MIMO communications systems [9-10]. The key to extract the source of interested from the mixed signals based on the ICA-R algorithm is the generation of the reference signal. Various a priori information were used to generate the reference signal, such as the pitch frequency of the speech signal [5], sign function of the source signal [7], target signal's statistical characteristics [8], training sequences [9-10], azimuth information [11] and signal frequency [12], etc. However, in these studies, rectangular pulse signals with the same frequency as the target source are used as the reference signal, which need to be additional generated at receiver. Besides, noise free model were considered in most of these papers, and the inherent drawback of threshold parameter problem [13-15] exist.

In this paper, we consider the 2FSK signal extraction problem in disturbed and noisy environment. We propose a simple scheme to extract the source 2FSK signal based on ICA-R algorithm, where only one of the two carrier frequencies of the source 2FSK signal is required as the a priori information to generate a cosine reference signal at receiver. For the purpose of verifying the effectiveness of the proposed method, and studying the anti-noise and anti-jamming performance of the corresponding wireless communication system, several simulations under different conditions are carried out. The conditions contain various parameters such as jamming signal type, Signal-to-Jamming Ratio (SJR) and Signal-to-Noise Ratio (SNR). Results show that the proposed method performs good extraction ability by the proposed method, the anti-noise and anti-jamming performance of the system also perform well in strong interference and low SJR situation. Besides, it can 100 percent successfully extracted the source 2FSK signal in 5000 times Monte Carlo simulations, which means the inherent drawback of ICA-R is solved in this paper.

The rest of this paper is organized as follows. We briefly review the ICA-R algorithm in section II. And in section III, system model constructed to verify the proposed method, together with the simulation parameters and performance index used in the simulations are introduced. In section IV, simulations are carried out to investigate the effectiveness and extraction performances of the proposed method. The anti-noise and anti-jamming performance, together with the stability of the proposed method are also studied in this part. Finally, conclusions are drawn in section V.

## II. ICA-R ALGORIGHM REVIEW

The one unit ICA-R can be described as a constrained optimization problem with inequality and equality constraints as in [16]:

$$\begin{cases} maximize & J(y) \\ subject\ to & g(\omega_p)\le 0 \ \ and\,/\,or \ \ h(\omega_p)=0 \end{cases} \tag{1}$$

where $y=\omega_p^T x$, $\omega_p$ and $x$ are the separation vector and observed signals respectively. The contrast function $J(y)$ can be approximated by $\rho\left[E\{f(y)\}-E\{f(v)\}\right]^2$, which can maximize the sum of marginal negentropies to find the ICs having mostly non-Gaussian distributions. The inequality constraint term $g(\omega_p)$ equals to $\varepsilon(y,r)-\xi$, which is exploited to incorporate the prior information of the desired signal into the ICA learning. $\varepsilon(y,r)$ is the closeness measurement function and $\xi$ is the closeness threshold. Whereas the equality constraint term $h(\omega_p)$ is used to bound the contrast function $J(y)$ and the separation vector $\omega_p$. Concretely, it can eliminate the correlation relationship between any of the two different output components and restrict each output to have a unit variance.

By introducing a slack variable $z$ and utilizing the Lagrange multipliers method [17], the corresponding augmented Lagrangian function of (1) can be derived as

$$\begin{aligned} L(\omega,\mu,\lambda)=J(y)-\frac{1}{2\gamma}\left[\max{}^2\{0,\mu+\gamma g(\omega_p)\}-\mu^2\right] \\ -\lambda h(\omega_p)-\frac{\gamma}{2}\left\|h(\omega_p)\right\|^2 \end{aligned} \tag{2}$$

where $\mu$ and $\lambda$ are Lagrange multipliers for the constrains $g(\omega_p)$ and $h(\omega_p)$, respectively. $\gamma$ is a scalar penalty parameter. Then, a Newton-like learning algorithm can be adopted to find the maximum of the augmented Lagrangian function in (2), and the derived update formula of the separation vector is

$$\omega_{p,k+1}=\omega_{p,k}-\eta R_{xx}^{-1}L'_{\omega_k}\big/L''_{\omega_k} \tag{3}$$

where $k$ denotes the iteration index, $\eta$ is the learning rate, $R_{xx}$ is the covariance matrix of the observed signals $x$, while $L'_{\omega_k}$ and $L''_{\omega_k}$ are the first and the second derivatives of $L$ with respect to $y$. The Lagrange multipliers $\mu$ and $\lambda$ are learned by the following gradient ascent methods:

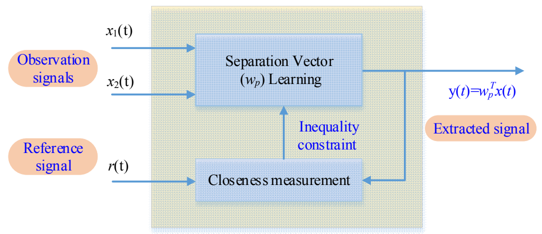


Fig.1 The schematic diagram of ICA-R algorithm.

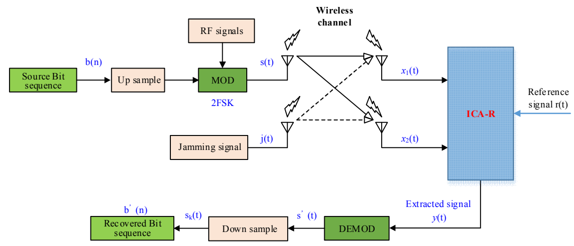


Fig. 2 The system model of the scheme we poposed, and of the simulation we carried out.

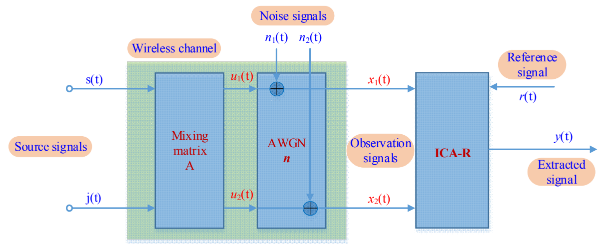


Fig. 3 The extracted parameter model of the simulation system.

$$\begin{cases} \mu_{k+1}=\max\{0,\mu_k+\gamma g(\omega_{p,k})\} \\ \lambda_{k+1}=\lambda_k+\gamma h(\omega_{p,k}) \end{cases} \tag{4}$$

Once the separation vector $\omega_p$ is converged, the desired IC can be calculated as:

$$y=\omega_p^T x \tag{5}$$

The schematic diagram of ICA-R algorithm can be described as Fig. 1.

## III. SYSTEM MODEL AND PARAMETERS

### A. System Model

An end-to-end wireless communication link employing 2FSK modulation and transmitting in a slowly fading channel with additive white Gaussian noise (AWGN) is carried out to verify the extraction effectiveness and performance of the method we proposed. The system diagram is described in Fig. 2. At the transmitter, a source bit sequence $b(n)$ is up sampled first. Then, it is modulated by two radio frequency (RF) signals. The generated 2FSK signal $s(t)$ and a jamming signal $j(t)$ are transmitted to a slowly fading AWGN wireless communication channel respectively. At the receiver side, the observed signals are processed by the ICA-R algorithm, with the help of a reference signal $r(t)$. The extracted signal $y(t)$ is demodulated by noncoherent detection. The demodulated signal is down sampled to be the recovered bit sequence $b'(n)$, which is then compared with the source bit sequence $b(n)$ to analyze the bit error rate (BER) performance of the system.

The extracted parameter model of the simulation system is demonstrated in Fig. 3. Parameters are marked in the figure.

## *B. Simulation Parameters*

We assume that the source 2FSK signal and the jamming signal are linearly mixed by a mixing matrix, and then a random noise is added to the mixed signal according to the SNR. The mixing matrix is set to be A= [0.97289 0.13587; 0.59811 0.31953], which is full column rank. The reference signal is a single tone cosine RF signal, with the frequency equals to $f_r$. Let the reference signal be $r$, the closeness measurement function, equality constraint term, and the non-quadratic function of the contrast function are chosen equals to $\varepsilon(y,r)=E\left\{(y-r)^2\right\}$ , $h(\omega_p)=E\{y^2\}-1$ , and $f(y)=-\exp(-y^2/2)$ , respectively. Other parameters used in ICA-R algorithm are set to be $\lambda$=1, $\mu$=0.4, $\gamma$=1, $\eta$=0.5, $\xi$=1. Moreover, the received signal is pre-whitened to reduce the computational load, and the separation vector is initialized by w=(r*z) to speed up the algorithm convergence, where z is the whitened data.

## *C. Performance Index*

After ICA-R processing, we can obtain the extracted signals. To evaluate the extraction performance of the algorithm, cosine similarity (*CosSim*) and BER in variable SJR and SNR are measured in simulations. *CosSim* is defined as follows:

$$CosSim(x,y)=\frac{\sum_k x(k)y(k)}{\sqrt{\sum_k x^2(k)\sum_k y^2(k)}} \tag{6}$$

The larger the value *CosSim*(*x*,*y*), the better similarity between the source signal *x* and the extracted signal *y*, and stronger the extraction ability of the proposed method.

The SJR and SNR are expressed as follows:

$$SJR=10\log(P_S/P_J) \tag{7}$$

$$SNR=10\log(P_S/P_n) \tag{8}$$

where $P_S$, $P_J$ and $P_n$ denote the power of source 2FSK signal, jamming signal and noise signal, respectively.

# IV. SIMULATION RESULTS AND ANALYSIS

## *A. Effectiveness of The Proposed Method*

In the first experiment, we demonstrated the effectiveness of the proposed method by testing the extraction ability utilizing either one of the two carrier frequencies of the source 2FSK signal as the a priori information to generate the reference signal. A two-tone jamming signal with carrier frequencies of 2.1kHz and 7.9kHz is mixed with a source 2FSK signal, whose carrier frequencies are 2kHz and 8kHz. The sampling rate of the signals is set to be 20kHz. The generation rate of the source bit sequence is set to be 1kbps. Other simulation parameters are set to be SNR=10dB and SJR=-10dB. The time domain waveforms of the source 2FSK signal, reference signal and the extracted signal are demonstrated in Fig. 4. The bottom line of column (a) and (b) are the two extracted signals utilizing a reference signal with frequency of 2kHz and 8kHz respectively. We can see that both the extracted signals are quite similar to the source 2FSK signal on time domain waveform, which perfectively verifies the effectiveness of the proposed method.

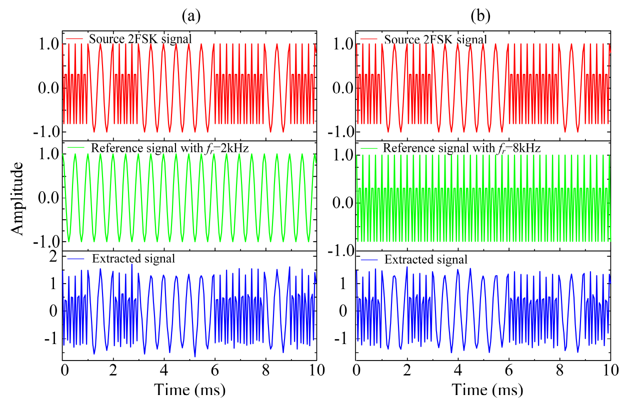


Fig. 4 Extracted signal utilizing different reference signal. (a) simulation result using the reference signal with $f_r$=2kHz. (b) simulation result using the reference signal with $f_r$=8kHz.

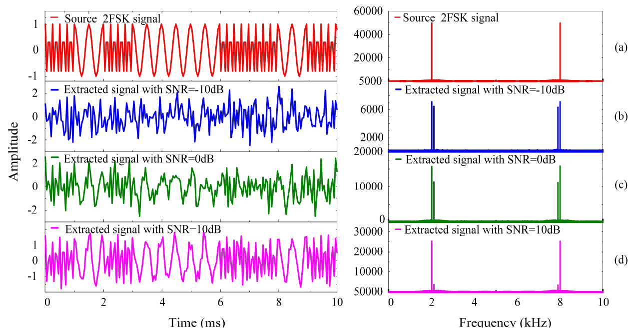


Fig. 5 Extracted signal in different *SNR* when *SJR* is fixed to -10dB. Row (a)~(d) are the time and frequency domain waveform of the source and extracted signals.

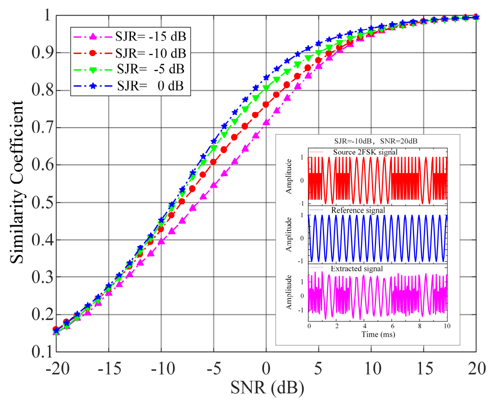


Fig. 6 Relationship between the *SimCoe* and *SNR* in different SJR.

## *B. Analysis of the Extraction Performance Under Different Conditions*

The extraction performance of the proposed method depends on the power of jamming and noise signal relative to the 2FSK signal, namely SJR and SNR. We study the relationships among them in this section.

First, we study the time and frequency domain characterize of the extracted signal in different SNR when SJR is fixed to -10 dB. A two-tone signal with carrier frequencies of 2.1 kHz and 7.9 kHz is chosen as the jamming signal, which is close to the source 2FSK signal with carrier frequencies of 2 kHz and 8 kHz. A cosine pulse signal with carrier frequency of 2 kHz is set to be the reference signal. The SNR is spread

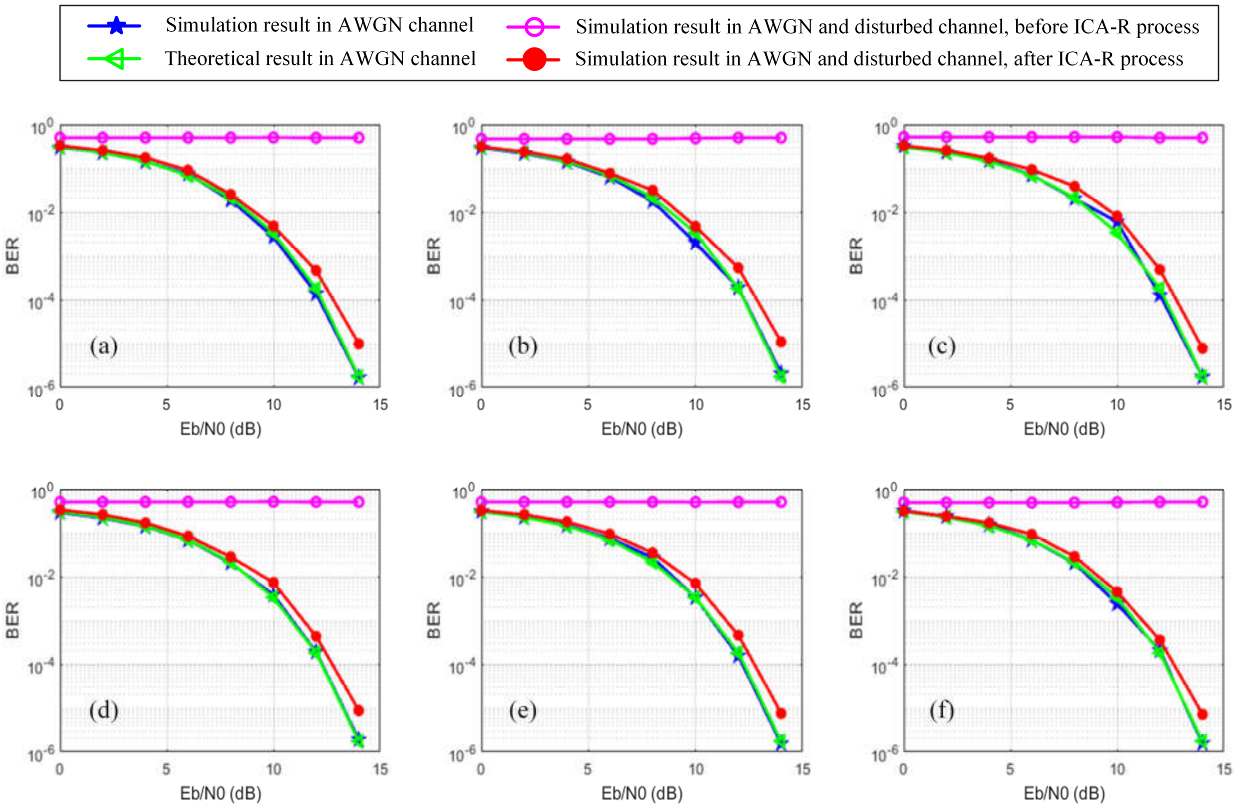


Fig. 7 Anti-noise performance in different disturbing condition. In (a)~(c), the jamming signals are wideband noise signal, three-tone signal and BPSK signal respectively, and the frequency of the reference signal is equal to the lower one of the source 2FSK signal. While in (a)~(c), the jamming signals are also the same wideband noise signal, three-tone signal and BPSK signal respectively, and the frequency of the reference signal is equal to the higher one of the source 2FSK signal.

from -10dB to 10dB with a step of 10dB. The results are shown in Fig. 5. It is obvious that the time domain waveform of the extracted signal is more and more similar to that of the source 2FSK signal, while the frequency amplitude of the jamming signal decreases and that of the source 2FSK signal increases, as the SNR increases. Therefore, high SNR would be helpful to improve the extraction ability of the method.

Second, we investigate the relationship between the similarity and SNR in different SJR. The SJR is spread from -15dB to 0dB with a step of 5dB and 500 times Monte Carlo simulations are carried out in each SJR. The results are demonstrated in Fig. 6. It is obvious that the similarity increases as the SNR increases when SJR is fixed to an invariable value, and the larger the SJR, the faster the similarity increases. Besides, the relationship curves are almost in *S*-style, in which the similarity starts at about 0.16 and ends at about 1. In other words, the mixed source signals can be exactly extracted if the SNR is large enough. The time domain waveforms of the source 2FSK signal, reference signal and extracted signal when SJR=-10dB and SNR=20dB are also demonstrated as inset in the figure. It can be seen that the extracted signal is almost the same as the source signal, corresponding to a *CosSim* of 0.99.

## C. Anti-noise Performance Analyzation

We measure the anti-noise performance of the proposed scheme by plotting BER (Bit error rate) curves based on $E_bN_0$ (Ratio of bit energy to noise power spectral density) in different disturbing condition when SJR is fixed at -30dB. The carrier frequencies of the source 2FSK signal are 16 kHz and 24 kHz, and the sampling rate of the signals is set to be 64 kHz. The generation rate of the source bit sequence is increased by 4kbps. The reference signals used in the simulations are cosine pulse signals with the carrier frequencies the same with one of the two carrier frequencies of the source 2FSK signal. To be general, three types of jamming signal including wideband noise, multi-tone pulse signal and modulated signal are employed to simulate the disturbing condition. The carrier frequencies are listed in Table I. The BER performance of the wireless communication system without ICA-R process is also measured in the simulations. The results are shown in Fig. 7. It is obvious that the signals without ICA-R process are disturbed seriously by jamming signal, whose BER keeping in around 0.5. However, the BER performance is greatly improved after ICA-R process. We can see that the BER decreases as $E_bN_0$ increases, and the anti-noise performance is almost the same with the theoretical results perform in AWGN channel, discarding the disturbing condition and the frequency of the reference signal. Besides, considering to achieve the BER on the level of $10^{-5}$, no more than 1 dB addition of $E_bN_0$ is required compared to the theoretical result in AWGN channel condition.

TABLE I. Carrier Frequencies of the Source Signals in BER Test (kHz)

| Source 2FSK signal | Reference signal | Wideband noise signal | Three-tone signal | BPSK signal |
|---|---|---|---|---|
| 16 and 24 | 16 or 24 | 16 | 15, 20 and 25 | 16 |

## D. Anti-jamming Performance Analyzation

To verify the anti-jamming performance of the proposed scheme, we plot BER curves based on SJR when $E_bN_0$ is fixed at 14 dB. The jamming signal is set to be a 2FSK signal with

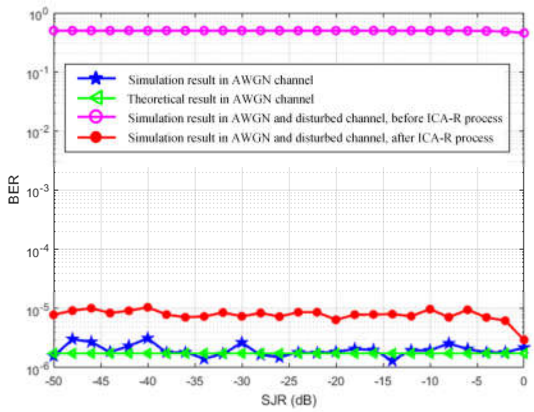


Fig. 8 Anti-jamming performance in different SJR.

carrier frequencies of 15.9 kHz and 24.1 kHz, which is close to the source 2FSK signal with carrier frequencies of 16 kHz and 24 kHz. The SJR is spread from -50 dB to 0 dB with a step of 2 dB. The results are shown in Fig. 8. It can be seen that the BER achieved by the proposed method (after ICA-R process) is keeping at the same $10^{-5}$ level of the theoretical result in AWGN channel, even when the SJR is as small as to -50 dB. In other words, the anti-jamming performance of the proposed scheme performs well in strong interference condition. It is a good character in real wireless communication system.

### *E. Robustness Analyzation*

It is reported in [13-15] that the ICA-R algorithm is not reliable, because it is strongly dependent on the threshold parameter such that it cannot always succeed to extract the desired source. However, we find that the method we proposed in this paper can avoid this problem. We carry out 5000 times Monte Carlo simulations in three disturbed conditions to verify it. The simulation parameters are same with them in aforementioned anti-noise performance analyzation. It is worthy to note that the threshold parameter $\xi$ is valued 1. The results are shown in Table II. It is obvious that none of them is wrongly converged, compare to below 65 "correct" extractions per 100 trials by the original ICA-R [4, 13], and about 90 by the new version of ICA-R in [14].

TABLE II. Wrong Convergence Times in 5000 Times Monte Carlo Test

| **Frequency of reference signal** | **Jamming signal type** | | |
|---|---|---|---|
| | ***wideband noise*** | ***three-tone*** | ***BPSK*** |
| $f_r$=16 kHz | 0 | 0 | 0 |
| $f_r$=24 kHz | 0 | 0 | 0 |

## V. CONCLUSION

In this paper, in order to solve the problem of exactly extract the source 2FSK signal in a disturbed and noisy condition, a simple signal extraction method based on ICA-R algorithm is proposed. The innovation of the method is that only one of the two carrier frequencies of the source 2FSK signal is required as the a priori knowledge to generate the reference signal at receiver, which is easy to be realized in real wireless communication system. We verify the effectiveness and investigate the performance of the proposed method via several numerical simulations, where a cosine pulse signal with carrier frequency same with either one of the two carrier frequencies of the source 2FSK signal are used as the reference signal, and different types of jamming signals such as wideband noise, multi-tone and modulated signals are also utilized to construct the disturbed environment. The results show that the source 2FSK signal can be exactly and stably extracted in all 5000 times Monte Carlo simulations, which means that the inherent threshold parameter problem in ICA-R is solved in this paper. Moreover, the anti-noise performance in strong interference situation with SJR=-30 dB is almost the same with the theoretical results perform in AWGN channel. Besides, the anti-jamming performance also performs well in wide range strong interference condition even when the SJR is as low as -50 dB.

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