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Analysis of MFSK/FH System Based on Adaptive Array Antenna with Beamforming Technique

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Abstract—**Anti-jamming/interference is the most important issue in the wireless communication. In this paper, based on the traditional *M*-array FSK modulation (MFSK/FH) system, an array antenna using the adaptive beamforming (BF) technique is adopted in the traditional MFSK/FH receiver (i.e., MFSK/FH-BF system), which improves the anti-jamming performance. Firstly, a modified FH-BF receiver using a uniform circle antenna (UCA), which is suitable for FH waveform, is proposed to reduce the effect of hopped frequency on the directions of the beam pattern. Then, the numerical relations among the FH parameters (e.g., the number of frequency slots), BF parameter (e.g., the number of snapshots), and system performance (bit-error rate and output signal-to-interference-plus-noise ratio) are systematically analyzed by theoretical analysis. Finally, the performance of the MFSK/FH-BF system is verified by simulation analysis. The theoretical and simulation results show that the direction of the beam pattern of the proposed BF-MFSK/FH system converges fast. On top of that, the proposed system is shown to be robust and capable of outperforming traditional systems with single frequency technique and single spatial technique (e.g., MFSK/FH system and MFSK-BF system) under complex jamming environments. It can be deployed in satellite systems, battlefield communication, and 5G cellular networks.**

Keywords—FH technique; beamforming technique; array signal processing; output SINR; Performance analysis

I. Introduction

With the rapid increase in the number of wireless communication users and the continuous improvement of the transmission rate, the frequency band resources in the wireless communication environment are increasingly crowded, and the interference becomes more and more serious. These interferences have a severe impact on the quality of wireless communication. How to suppress interference in a wireless environment has always been a hot issue in wireless communication academia and industry. At present, interference suppression technology mainly includes frequency domain anti-interference, time domain anti-interference, and spatial domain anti-interference. Frequency hopping (FH) technology is the preferred anti-jamming scheme in the frequency domain of wireless communication. Because of the random hopping of its working frequency points, the interfering party cannot accurately capture its changing law, thus achieving the purpose of interference suppression in the frequency domain. When the spectrum resources are limited, and there is tracking or broadband interference in the environment, interference suppression by frequency domain technology alone is not ideal [1-3]. Adaptive beamforming (BF) based on antenna arrays is a spatial interference suppression scheme. BF automatically adjusts the antenna beam pattern by an adaptive algorithm such as Minimum Mean Square (LMS), Sample Matrix Inversion (SMI), and Constant Modulus (CM). This ensures that the main lobe aligns with the desired signal direction and the zero trap aligns with the direction of arrival of the interference signal so as to improve the useful signal strength and achieve interference suppression [4,5]. However, adaptive beamforming techniques fail when the interfering signals are strongly correlated with the desired signals or when they are coming in close proximity to each other. Adaptive beamforming technology can be applied to satellite communication, military communication, and 5G cellular communication in complex wireless environments.

Considering the advantages and disadvantages of the above technologies, the hybrid system, which combines frequency-hopping technology with beamforming technology (FH-BF system), is a new communication scheme proposed from two dimensions of the spatial/frequency domain. There have been few studies on this hybrid communication system in recent years. According to the characteristics of different interference types in wireless environments, various beamforming algorithms suitable for the FH-BF system are proposed in reference [6-7], and the anti-interference performance is studied. The direction of arrival estimation of the expected signal of the FH-BF system is also another issue to be considered in the beamforming algorithm, which has been deeply studied in reference [8]. In the actual sonar system and weak signal satellite communication system (GPS/GNSS system), literature [9-11] uses FH-BF technology to suppress various interference and ensure communication links with high security and robustness. Especially in the uplink of 5G communication systems, [12,13] proposed a wave velocity forming scheme based on millimeter wave FH, which can further eliminate the multi-user interference in the base station sector and improve the transmission reliability of the system. In conclusion, the hybrid communication system based on FH technology and beamforming technology has broad application prospects in a variety of wireless communication scenarios.

The above research on the FH-BF system has the following main characteristics: Firstly, the focus of theoretical research is on the signal processing of array antenna, without considering the synthesized effects of FH parameters and antenna array parameters on the convergence and performance of FH-BF system, and the theoretical research and conclusions are not comprehensive enough. Secondly, most of the interference suppression methods are proposed under the known interference mode (blocking/wideband interference is earlier than the desired signal, tracking interference is later than the desired signal). The antenna array adopts a uniform linear array (only forming a two-dimensional pattern), so the above research is not practical in the actual interference environment. Thirdly, most studies assume that beam shaping is done within a frequency point interval, which ignores the directional error of beam shaping due to FH. Therefore, the above research results have limitations, which limit the practical application of the FH-BF system.

This paper proposes a solution to the above problems by focusing on the MFSK/FH-BF system and conducting in-depth research on the receiver's structure design, the beamforming convergence, and the anti-interference performance in the space/frequency domain. The antenna array at the receiver of the MFSK/FH-BF system adopts a uniform circular array (compared with a uniform linear array, the pattern of the circular array has a three-dimensional orientation) and SMI based on the minimum mean square error (MMSE) criterion is adopted for adaptive beamforming because the algorithm has good convergence [5]. Based on the characteristics of MFSK/FH signals, an adaptive beamforming receiver with a phase compensation module is adopted. The effects of multiple parameters (FH parameters (number of frequency points), beamforming parameters (number of fast beats), and system parameters (modulation order, signal-to-noise ratio, and signal-to-dry ratio, etc.)) on the performance of MFSK/FH-BF system are discussed from the point of view of signal analysis. The system structure and anti-interference analysis proposed in this paper does not need to be based on a specific type of interference. The research results are more general and provide valuable theoretical guidance for implementing the FH-BF system.

II. SYSTEM MODEL AND SIGNAL ANALYSIS

A. Sender Signal Analysis

The transmitter of the communication system adopts the FH mode based on MFSK modulation and sends an MFSK symbol within one hop interval. Assuming that the symbol interval of MFSK is T. In order to ensure the orthogonality of adjacent MFSK signals and FH signals, the minimum frequency interval of MFSK signals is $\Delta f_s = 1/T$, and the minimum frequency interval of FH points is $\Delta f_h = M\Delta f_s$, and M is the modulation order of MFSK[14]. Then the signal sent by the FH user is shown in Equation 1.

$$S^{(k)}(t) = \sqrt{2S_k} \cdot \exp\left[j\left(2\pi f_n^{(k)} \cdot \frac{M}{T}t + 2\pi \cdot \frac{d^{(k)}}{T}t \right) \right] \quad (1)$$
$$nT \le t \le (n+1)T$$

where $S^{(k)}$ represents the signal power of the k-th user. $d^{(k)}$ represents the MFSK signal sent by user k at time T. For different k and different n, the FH point $f_n^{(k)}$ meets the independent uniform distribution on [1, 2,…q] (i.e., random FH, q is the number of FH points). Similarly, different k means $d^{(k)}$ conforms to independent uniform distributions on [1,2,…M]. For analysis purposes, assume k=0 is the desired user transmitter. The jamming user k (k=1, 2, K) also sends MFSK-modulated random FH jamming signals. The difference here is that there may be multiple frequency points, Signal to Interference Ratio (SIR $=S_0/S_k$), thus, becomes important. When the interference can affect multiple q_j frequency points simultaneously, the probability that the user is expected to be affected by at least one interference source is $n_h = 1-(1-q_j/q)^K$.

B. MFSK/FH-BF System Receiver Model

The receiver of the MFSK/FH-BF system uses a uniform circular array with N_a=4 elements (Radius is r), and the layout pattern of antenna elements is shown in Figure 1.

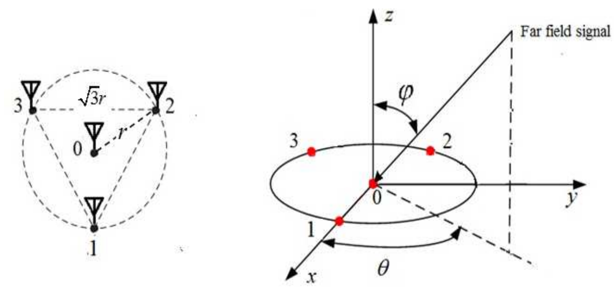


Figure 1 Array form of four uniform circular antennas

Circular arrays can suppress interference signals from three dimensions compared to linear arrays. In the case of the FH waveform, in order to avoid the phase ambiguity between the elements with maximum spacing in the circular array, the radius of the circular array is set as $r \le \lambda_{\min}/2\sqrt{3}$, where λ_{min} represents the wavelength corresponding to the highest frequency of f_{max}, then $\lambda_{\min} = T/(qM)$. Assume that the user expects the signal to arrive in the wave (φ_0, θ_0) , where φ_0 represents the angle between the arrival of the signal and the normal vector on the X-Y plane, $\theta_0 \in [0, 2\pi)$. θ_0 represents the angle between the projection of the arrival of the signal on the X-Y plane and the positive half axis of X, $\theta_0 \in [0, 2\pi)$; In addition, the direction of arrival of the interference signal can be expressed as (φ_k, θ_k), k=1,2,...,K . With array element 0 as the benchmark, the guiding vectors of the four array elements can be described by Equation 2.

$$\begin{aligned} \mathbf{a}_n^{(k)} = \Big[& 1,\ \exp\left(-j \cdot \alpha_n^{(k)} \pi \sin(\varphi_k)\cos(\theta_k)\right), \\ & \exp\left(-j \cdot \alpha_n^{(k)} \pi \sin(\varphi_k)\cos(\theta_k - \tfrac{2\pi}{3})\right), \\ & \exp\left(-j \cdot \alpha_n^{(k)} \pi \sin(\varphi_k)\cos(\theta_k - \tfrac{4\pi}{3})\right) \Big]^{\mathrm{T}} \end{aligned} \quad (2)$$

where $\alpha_n^{(k)} = f_n^{(k)}/f_{\max}$, $f_n^{(k)}$ represents the frequency point of the k-th user on the n-th FH interval $\alpha_n^{(k)}$, reflects the influence of FH on the guiding vector of an antenna array, which makes the system have a pointing error. $[x]^{\mathrm{T}}$ is the transpose of the vector x. In this paper, the wireless communication channel is considered an Additive White Gaussian Noise (AWGN) and K strong interference source. In the n-th FH code chip interval, the signals received by N_a array elements can be expressed by Equation 3.

$$\mathbf{r}_n(t)=\mathbf{A}_n\mathbf{S}(t)P\left(t-nT\right)+\mathbf{n}(t) \tag{3}$$

where $\mathbf{A}_n=\left[\mathbf{a}_n^{(0)},\mathbf{a}_n^{(1)},\ldots,\mathbf{a}_n^{(K)}\right]$, sending signal matrix is denoted as $\mathbf{S}(t)=\left[S^{(0)}(t),S^{(1)}(t),\cdots,S^{(K)}(t)\right]^{\mathrm{T}}$. $S^{(0)}(t)$ and $S^{(1)}(t)$, $\cdots$, $S^{(K)}(t)$ represent the complex envelope of the desired signal and K interference signals, $\mathbf{n}(t)$ represents the Gaussian additive white noise vector with power spectral density $N_{0/2}$ of the two-sided band, and P(t-nT) represents the rectangular unit impulse function with width [nt, $(n+1)T$).

C. Receiver Model and FH Interference Suppression

In general, assume that the user k=0 is the expected user and realize the synchronization between FH and receiving (that is, the expected user knows the FH code $\{f_n^{(0)}\mid n=1,2,\ldots\}$) at both the receiver and the transmitter. According to the receiver model, signals on N_a branches are de-hopping respectively, and the signal shown in Equation 4 is obtained.

$$\mathbf{X}(t)=\mathbf{r}(t)C(t) \tag{4}$$

where $C(t)=\exp\left(-j2\pi t\, f_n^{(0)}M/T\right)$ is the complex envelope of the local FH carrier of the desired receiver.

From Equation 2, the hopping of expected user frequency $f_n^{(0)}$ will change the direction vector $\mathbf{a}_n^{(0)}$ on the antenna array element, resulting in the pointing error of the system. To reduce the impact of pointing errors on the system, a phase compensation module is added to the receiver to compensate for the pointing error caused by the expected user frequency hop. The system structure is shown in Figure 2.

Since the user is expected to know the FH code $\{f_n^{(0)}\mid n=1,2,\ldots\}$ at the receiving and sending terminals, it is easy to obtain its phase compensation quantity $f_{\max}/f_n^{(0)}$.

Therefore, the compensated guidance vector can be written as Equation 5.

$$\begin{cases}\mathbf{A}_n^*=\left[\mathbf{a}*_n^{(0)},\ \mathbf{a}*_n^{(1)},\ \ldots,\mathbf{a}*_n^{(K)}\right]\\ \mathbf{a}*_n^{(k)}=\left[1,\ \exp\left(-j\cdot\dfrac{f_n^{(k)}}{f_n^{(0)}}\pi\sin(\varphi_k)\cos(\theta_k)\right),\right.\\ \qquad \exp\left(-j\cdot\dfrac{f_n^{(k)}}{f_n^{(0)}}\pi\sin(\varphi_k)\cos(\theta_k-\dfrac{2\pi}{3})\right),\\ \qquad \left.\exp\left(-j\cdot\dfrac{f_n^{(k)}}{f_n^{(0)}}\pi\sin(\varphi_k)\cos(\theta_k-\dfrac{4\pi}{3})\right)\right]^{\mathrm{T}}\end{cases} \tag{5}$$

$$\begin{aligned}\mathbf{X}(t)&=\mathbf{a}_n^{*(0)}\sqrt{2S_0}\exp\left(j2\pi\frac{d^{(0)}}{T}t\right)+\\&\quad\sum_{k=1}^{K}\delta\left(f_0^{(k)},f_0^{(0)}\right)\cdot\mathbf{a}_n^{*(k)}\sqrt{2S_k}\exp\left(j2\pi\frac{d^{(k)}}{T}t\right)+\mathbf{n}'(t)\\&=\mathbf{a}_n^{*(0)}D\left(t\right)+\sum_{k=1}^{K}\mathbf{a}_n^{*(k)}I^{(k)}(t)+\mathbf{n}'(t)\qquad 0\le t\le T\end{aligned} \tag{6}$$

Replace the guidance vector $\mathbf{A}_n$ in Equation 3 $\mathbf{A}_n^*$, and the signal can be expressed in Equation 6 at the bottom of this page.

The first item on the right side of Equation 6 is the desired user signal part; The second item is K jamming user signal parts; The third item $\mathbf{n}'(t)$ represents $N_a\times 1$. When $f_0^{(k)}\neq f_0^{(0)}$, there is $\delta\left(f_0^{(k)},f_0^{(0)}\right)=0$ an interference signal $I(t)\equiv 0$, that is, the system realizes interference cancellation in the frequency domain; When $f_0^{(k)}=f_0^{(0)}$, there is $\delta\left(f_0^{(k)},f_0^{(0)}\right)\neq 0$ and $I(t)\neq 0$, indicating that there is FH interference. When the interfering party adopts broadband interference and multi-tone interference, the probability $\delta\left(f_0^{(k)},f_0^{(0)}\right)\neq 0$ is greatly increased. At this time, the effect of only using FH technology to improve the anti-interference performance of the system is limited. Equation 6 explains the principle of interference suppression in the frequency domain by FH technology.

D. Adaptive beamforming spatial interference suppression based on MMSE-SMI algorithm

Since wideband interference and multi-tone interference cannot be effectively suppressed when only the frequency domain interference suppression method is used, MFSK/FH-BF system adopts an adaptive beamforming method to suppress interference from airspace. Therefore, the classical digital adaptive beamforming algorithm -- SMI algorithm based on MMSE is adopted in this paper. Through the MMSE-SMI algorithm, the beamforming module can obtain the Na×1 dimensional weight vector , and then adjust the phase and amplitude of the branch signals of each array element to eliminate the interference signals. Under the minimum mean square error criterion, the adaptive SMI algorithm solves the optimal weight through the sampling signal points of the received signal , and the optimal weight is given by the optimal Wiener solution, as shown in Equation 7.

$$\mathbf{w}=\mathbf{R}_{xx}^{-1}\mathbf{r} \tag{7}$$

where

$$\mathbf{R}_{xx}=\frac{1}{N}\mathbf{X}_N\mathbf{X}_N^H \tag{8}$$

$$\mathbf{r}=\frac{1}{N}\mathbf{d}^*\mathbf{X}_N \tag{9}$$

$$\mathbf{d}=\left[D(1),D(2),\ldots,D(N)\right] \tag{10}$$

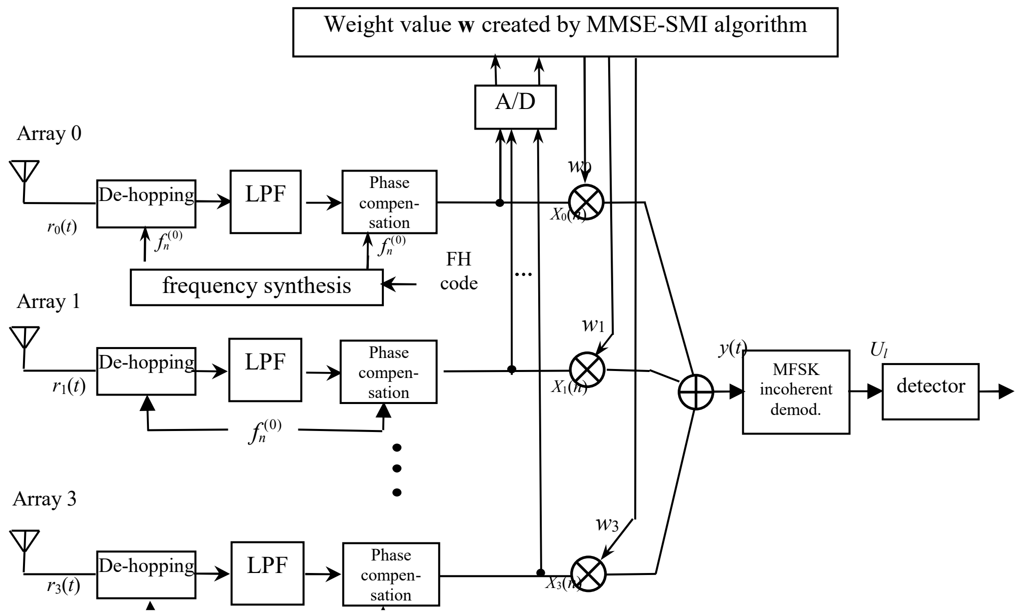


Figure 2 MFSK/FH-BF receiver system block diagram (expected user 0, N_a=4)

The MMSE-SMI algorithm estimates the correlation matrix $\mathbf{R}_{xx}$ and the correlation vector $\mathbf{r}$ by averaging the time of $\mathbf{X}(t)$ sampled signal. $\mathbf{X}_N$ represents the N blocks of sampled values $\mathbf{X}(t)$, and N is also called the number of fast beats and the block size. $\mathbf{d}$ indicates the sample value of reference data expected from the user. The value of N should be sufficiently large to meet the convergence of the adaptive beamforming MMSE-SMI algorithm; if the value of N is too large, the system complexity increases. Finally, the output signal based on the MMSE-SMI beamforming module can be expressed as shown in Equation 11.

$$y(t)=\mathbf{w}^H\mathbf{X}(t)=\mathbf{w}^H\mathbf{a}_n^{*(0)}D(t)+\sum_{k=1}^{K}\mathbf{w}^H\mathbf{a}_n^{*(k)}I^{(k)}(t)+\mathbf{w}^H\mathbf{n}'(t) \quad (11)$$

Through the operation of Equation 11, the interference term $I^{(k)}(t)$ left by FH can be further suppressed. This conclusion can be fully verified by subsequent simulation analysis.

E. System Output SINR and Signal Demodulation

For the output signal y(t) of the beamforming module, its average SINR can be obtained by the mean of SINR within N_h FH intervals, as shown in Equation 12.

$$SINR=\frac{1}{N_h}\sum_{n=1}^{N_h}\frac{S_0\left|\mathbf{w}^H\mathbf{a}_n^{*(0)}\right|^2}{\sum_k S_k\delta\left(f_0^{(k)},f_0^{(0)}\right)\left|\mathbf{w}^H\mathbf{a}_n^{*(k)}\right|^2+S_n\left\|\mathbf{w}^H\right\|^2} \quad (12)$$

where S_0, S_k, and S_n are the desired signal, the interference signal, and the noise signal power, respectively. As can be seen from Equation 12, when FH suppression takes effect ($\delta\left(f_0^{(k)},f_0^{(0)}\right)=0$), SINR increases accordingly. When FH fails, the array weight of BF plays a decisive role.

Then, the output signal y(t) of the bundle forming module is sent to the MFSK incoherent receiver, which has M branches. The output signal U_l of the l branch is described by the demodulator decision rule: the subscript l corresponding to the maximum U_l value is the estimated value of the sent MFSK symbol [15], as shown in Equation 13.

$$\hat{d}=\arg\left\{\max_l U_l\right\},\qquad l=0,1,\ldots,M-1 \quad (13)$$

where

$$U_l=\left|\frac{1}{T}\int_0^T y(t)\exp\left(-j\frac{2\pi lt}{T}\right)dt\right|^2=\left|\sqrt{2S_0}\mathbf{a}_n^{*(0)}+\sum_{k=1}^{K}\mathbf{a}_n^{*(k)}\sqrt{2S_k}\,\delta\left(f_0^{(k)},f_0^{(0)}\right)+\mathbf{n}'(t)\right|^2 \quad (14)$$

Based on the above analysis, we get the SINR theoretical expression of the output signal of the MFSK/FH-BF system and the expression of the system decision variable.

III. Simulation and Discussion

Based on the conclusion of the signal analysis in the previous section, the numerical relationships between the FH parameters (number of FH points q), adaptive wave velocity forming parameters (number of fast beats N), system parameters (Number of interference sources K, modulation order M, signal-to-noise ratio SNR and signal-to-dry ratio SIR, etc.) and the performance (bit error rate BER and output SINR) of MFSK/FH-BF system are discussed in this section. In order to fully verify the advantages of the proposed MFSK/FH-BF system, the anti-jamming capability of the single-antenna MFSK/FH system and the traditional MFSK-BF system are also presented in this section. In the following analysis, it is assumed that the DoA of the interfering user and the expected user are different, and the number of interference frequency points is q_i=5.

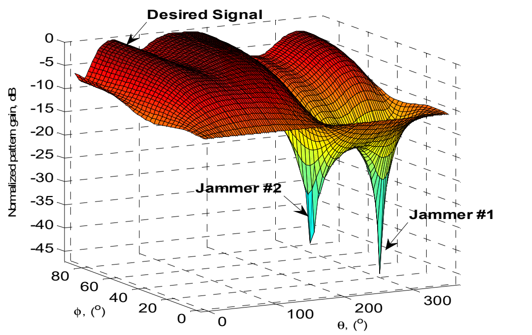
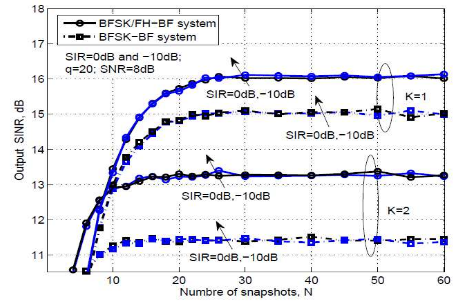


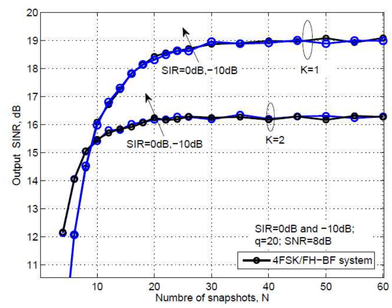
Figure 3 Three-dimensional pattern of UCA array based on MMSE-SMI algorithm

Figure 3 shows the simulated antenna pattern based on the MMSE-SMI beamforming algorithm, where the z-axis represents the normalized beam amplitude. In the simulation process, it is assumed that the expected signal direction is $(\varphi_0,\theta_0)=(72^{\circ},33^{\circ})$, and the arrival directions of two interfering users are $(\varphi_j,\theta_j)=(36^{\circ},230^{\circ})$ and $(20^{\circ},310^{\circ})$ respectively; Other parameters are set as follows: SNR=8dB, number of interfering users *K*=2, SIR=0dB, number of snapshots *N*=30. It can be seen from Figure 3 that the MMSE-SMI beamforming algorithm forms a large amplitude main beam in the direction of the desired signal, forms a null in the direction of the interference signal to receive the desired signal, and then suppress the interference signal. It is worth noting that when the desired signal direction and the interference signal direction are the same or correlated, the interference suppression method based on antenna array beamforming will fail, and only FH interference suppression will take effect.

The relationships between the output Signal-to-Interference-and-Noise-Ratio (SINR) of MFSK/FH-BF and the number of interference sources (*K*), the modulation order (*M*), and the number of snapshots (*N*) are shown in Figure 4. Figure 4 also shows the convergence of the MMSE-SMI adaptive algorithm with the number of snapshots *N*. It can be seen from Figure 4 that when the number of snapshots *N* is small, the MMSE-SMI adaptive algorithm can achieve a stable output SINR. Figure 4(a) shows the comparison results between MFSK/FH-BF system and the traditional MFSK-BF system (When *K*=1, the gain is about 1dB; when *K*=2, the gain is about 2dB). From the comparison results, it can be seen that MFSK/FH-BF system has a large gain when the number of snapshots *N* is small. This gain is caused by the suppression of partial interference by FH technology in the MFSK/FH-BF system. In addition, the output SINR of the system decreases with the increase of the number of interference sources *K*, which is consistent with the calculation result of Equation 12.



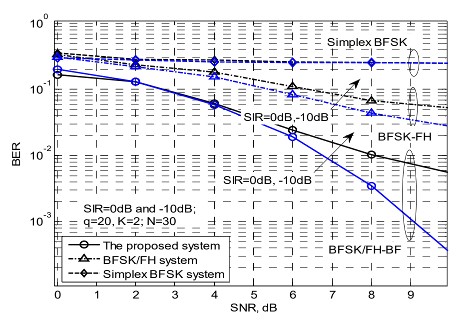
(a) BFSK



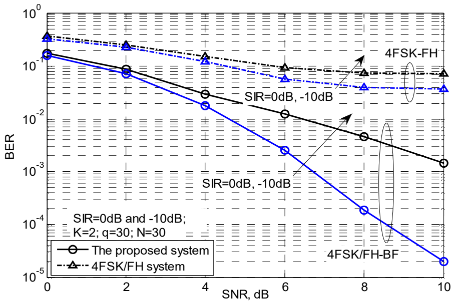
(b) 4FSK

Figure 4 Relation between output SINR of MFSK/FH-BF system and multiple parameters

Figure 5 shows the BER performance of the MFSK/FH-BF system based on the MMSE-SMI algorithm. For comparison purposes, the performance of the single-antenna MFSK-FH system and the single-antenna MFSK system are also shown in Figure 5. The simulation parameters are set as follows: q=20, K=2, SIR=0db and -10dB. Figure 5 (a) uses the binary FSK modulation (BFSK) system as an example for discussion. The simulation results show that the single antenna BFSK communication system without effective anti-interference ability has the worst performance. It was also found that the single antenna BFSK-FH system only has the anti-interference ability in the frequency domain, and the bit error rate performance is second. The BFSK/FH-BF system proposed in this paper can suppress interference from the Spatial-frequency domain, and its bit error rate performance is the best. The bit error rate performance of the system using 4FSK modulation is shown in Figure 5 (b), and the change rule of its system performance is basically consistent with that in Figure 5 (a), so it will not be repeated here.



(a) BFSK



(b) 4FSK

Figure 5 Error rate of MFSK/BF-FH system based on MMSE-SMI algorithm

The influence of the number of frequency points q on the performance of the BFSK/FH-BF system is shown in Figure 6. Increasing the frequency point q can improve the anti-interference ability of the system. In practical communication, it is unrealistic to increase the number of frequency points q without limit to obtain better anti-interference ability. Therefore, compared with the frequency domain method, the spatial domain technology based on the antenna array is a more effective anti-interference method. It is worth noting that when the desired signal direction is strongly correlated with the interfering signal or DoA is close, the spatial interference suppression capability of the BFSK/FH-BF system will fail, and the anti-interference performance is determined by the FH technology.

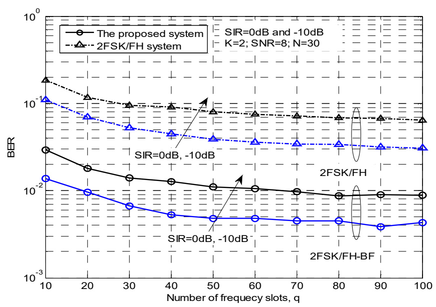


Figure 6 Influence of the number of FH frequency points q on the anti-interference performance of the system

IV. CONCLUSION

In this paper, a new communication system, MFSK/FH communication system based on antenna array adaptive beamforming is studied, which combines space-frequency and frequency domain technologies to combat the jamming and interference. A receiver model of an antenna array suitable for FH waveform is proposed to eliminate the orientation error caused by FH. By analyzing the FH signal and array signal, the changing relationship between multiple parameters (q, N, M, SNR, SIR, etc.) of MFSK/FH-BF system and system performance (BER and output SINR) are obtained. The methods and conclusions of interference suppression by FH and beamforming technologies are comprehensively explained and analyzed.

The simulation results show that the MFSK/FH-BF system based on the MMSE-SMI algorithm can achieve stable output SINR quickly and fully use the technical advantages of FH domain and antenna array spatial domain, which significantly improves the system's ability to resist various interference. The performance of the MFSK-FH system and MFSK-BF system using single technology is better than that of the MFSK-FH system. It is also worth noting that the MFSK/FH-BF receiver model and analysis method presented in this paper apply to other adaptive beamforming algorithms and antenna formations. They can be widely used in satellite, battlefield, and civil communication systems with complex communication environments. Although the performance of MFSK/FH-BF is evaluated by semi-analytical simulation, the theoretical performance will be derived in our future work, t

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