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Anti - follower jamming analysis of multi - sequence frequency hopping in AWGN channel

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Abstract. The modulated signals sent by conventional frequency-hopping systems are easily affected by follower jamming. Multi-sequence frequency-hopping is a frequency hopping communication system that uses channels to represent messages. It has good anti-follower jamming performance.Compared with differential frequency hopping, which uses user data to determine the transmission frequency, increasing frequency hopping sequence as a constraint can better suppress out-of-band jamming. In order to further study the effect of multi-sequence frequency hopping under follower jamming, a new multi-sequence frequency hopping transmission model under AWGN channel is established, the principle of multi-sequence frequency hopping anti-jamming was analyzed, and the performance of multi-sequence frequency hopping under follower jamming with different parameters is studied. The oretical analysis and simulation results show that multi-sequence frequency hopping can gain about 2.47-2.7dB when the SNR is 13.35dB and the BER requirement is 10^(-4), compared with the conventional frequency hopping.

1. The introduction

Conventional frequency-hopping systems avoid jamming by modulating the information to the hopping carrier wave. When the current frequency-hopping point was interfered, the receiver will not be able to properly demodulate the user data. Therefore, conventional frequency hopping system is easy to be affected by follower jamming. Under the condition of the modulation information is interfered, we can determine the modulation information channel through time-frequency analysis method[1], this shows some inherent characteristics of the channel (" channel descriptor "[2]) more likely to be receivied correctly. Therefore, using the channel characteristics of the difference between information may have greater jamming tolerance[2]. Differential frequency hopping (DFH)[3], message-driven frequency hopping (MDFH)[4], m-level m-element frequency shift keying (MMFSK)[5], self-coding spread spectrum[6], multi-sequence frequency hopping system (MSFH)[7] and other anti-follower jamming communication methods contain this idea.

Most of these communication methods[3]-[6] generally use broadband reception because they only use the channel determined by the user data and the receiver can not obtain the prior information of the current use channel. Taking the DFH technology as an example, the broadband receiving mode brings difficulties in network planning and hardware overhead[8], which is worse than the conventional frequency hopping in the case of the code-by-symbol decoding mode. MSFH represents messages through channels and has strong anti-follower jamming ability. Compared with DFH, the channel used by MSFH is jointly determined by user data and frequency hopping sequence. MSFH receiver can use the narrow-band receiving method because the receiver uses the frequency of the previous hop as the

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prior information and combines the frequency hopping sequence to predict the possible location of the next hop. Therefore, in the face of non-follower jamming, MSFH has better anti-jamming effect than DFH[9].

Existing studies on MSFH anti-follower jamming are mainly carried out in an ideal environment without considering channel noise conditions, which is far from the actual situation. For further research on MSFH follower jamming resistance,in this paper, we analyze the anti-jamming principle of MSFH, propose a MSFH follower jamming under AWGN channel transmission model and derive the MSFH error performance under different noise environment with follower jamming. Compared with conventional frequency hopping system through simulation, we further study MSFH follower jamming resistance in different environment.

2. Establishment of system model

MSFH represents information through the hopping frequency points corresponding to the frequency-hopping sequence, m ($m \geq 2$, $m = 2^R$,R is the number of data bits) frequency hopping sequences can constitute m channels, and each hop represents $\log_2 m$ bits information. Taking the binary- sequence frequency hopping system (R = 1, m = 2) as an example, Orthogonal frequency hopping sequences FS_0 and FS_1 correspond to sub-channel 0 representing user data "0" and sub-channel 1 representing user data "1", respectively. At a certain moment t, if the data "0" is sent, the frequency synthesizer will output the sinusoidal signal of frequency $f(0,t)$ corresponding to frequency hopping sequence FS_0 ; otherwise, the frequency $f(1,t)$ corresponding to frequency hopping sequence FS_1 will be output. As shown in figure 1, when the user data currently being sent is "10010", the transmitter sends the sine signal with the corresponding frequency of $f_1 f_6 f_5 f_3 f_1$ in turn.

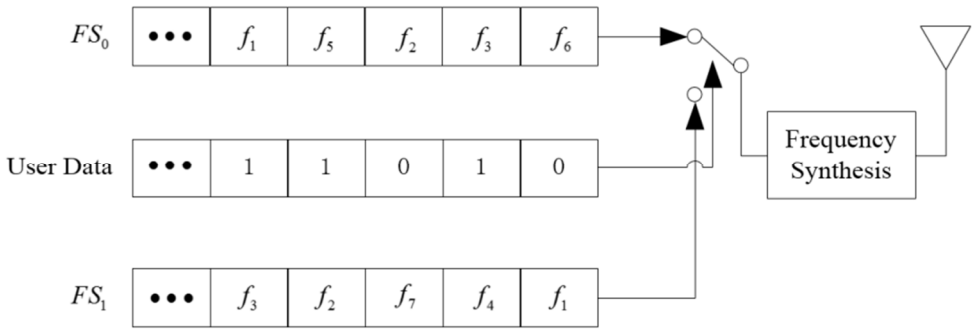


Figure 1. MSFH System Transmission Structure Diagram.

According to the above introduction, if the frequency hopping time slot length of MSFH is T and the symbol energy is E_S , then the equivalent expression of the transmitted signal is:

$$s(t) = \sqrt{2E_S / T_S}\, e^{j2\pi f_i t} \quad i = 0,1 \tag{1}$$

Regardless of the transmission time of the signal in the channel, the received signal after passing the AWGN channel can be equivalent represented as:

$$r(t) = s(t) + n(t) + n_J(t) \tag{2}$$

Where $n(t)$ is additive gaussian white noise in the channel, unilateral power spectral density is N_0 , and $n_J(t)$ is jamming signal.

The receiving end uses the same frequency hopping sequences FS_0' and FS_1' , and keeps synchronization with the frequency hopping sequences FS_0 and FS_1 . At time t , the corresponding frequency $f(0,t)$ of sub-channel 0 representing user data "0" and the corresponding frequency $f(1,t)$

of sub-channel 1 representing user data "1" are filtered and incoherent energy detect. Square rate detection is adopted to detect the energy of the filtered signal. The judgment quantity R_i represents the energy detection result of the channel representing " i " of user data:

$$R_i = \left| \int_0^T r(t) s_i^*(t) dt \right|^2 \quad i = 0,1 \tag{3}$$

$s_i^*(t)$ is the conjugate of sending signal $s_i(t)$, equivalent demodulation process:

$$s_i^*(t) = \sqrt{2E_S / T_S}\, e^{-j2\pi f_i t} \quad i = 0,1 \tag{4}$$

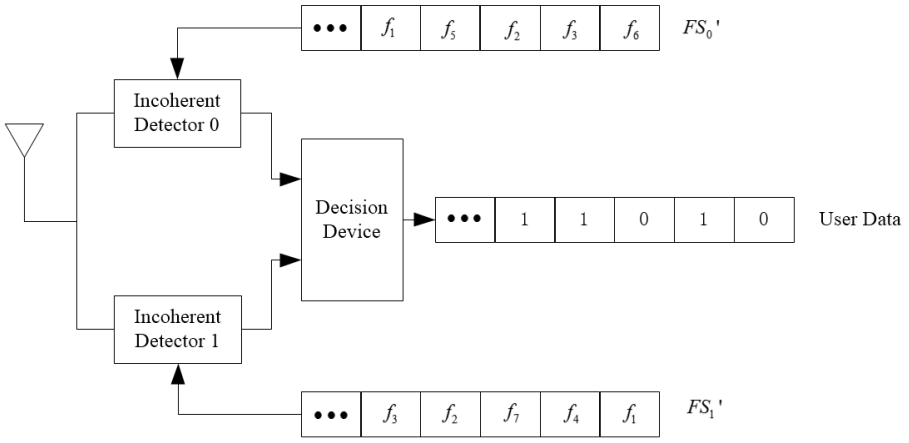


Figure 2. MSFH System Receiving Structure Diagram.

The user data is demodulated by means of hard decision, and the currently sent user data is judged by comparing the signal energy of the two frequency points. When $R_0 > R_1$, the currently sent data is judged as "0", while the currently sent data is judged as "1", as shown in figure 2, the restored user data is "10010" .

3. BER performance analysis

The signal is transmitted in AWGN channel, and the noise is zero mean gaussian white noise. The follower jamming is modeled as a zero mean gaussian random process with a certain bandwidth. The probability of follower jamming tracking success is β , the ratio of jamming time is ρ_T , and the ratio of jamming bandwidth is ρ_W .Assuming that the currently sent user data is 0, the sent signal is at the frequency point corresponding to frequency hopping sequence FS_0 (data channel is sub-channel 0, dual channel is sub-channel 1). As shown in table 1 (0 represents that the corresponding channel is not interfered and 1 represents that the corresponding channel is interfered), MSFH 's error condition is divided into four states. Under follower jamming, MSFH 's error probability of channel judgment is:

$$P_{e_MSFH} = P_1 P_{e1} + P_2 P_{e2} + P_3 P_{e3} + P_4 P_{e4} \tag{5}$$

Table 1. Relationship between jamming state G_j and channel states during a frequency hopping.

Jamming state	G_1	G_2	G_3	G_4
Channel 0 (data channel)	0	1	0	1
Channel 1 (dual channel)	0	1	1	0

Among them:

P_1 is the probability of G_1 ; P_{e1} stands for the conditional probability of error in the event of G_1 .

P_2 is the probability of G_2 ; P_{e2} stands for the conditional probability of error in the event of G_2 .

P_3 is the probability of G_3 ; P_{e3} stands for the conditional probability of error in the event of G_3 .

P_4 is the probability of G_4 ; P_{e4} stands for the conditional probability of error in the event of G_4 .

The probability of jamming of the data channel (channel 0) is the probability of successful tracking of the follower jamming β. Since there is no signal in the dual channel, the influence of the follower jamming on the dual channel judgment can be equivalent to the jamming of part of the frequency band with the proportion of jamming time ρ_T and the proportion of jamming bandwidth ρ_W, we can get:

$$P_1 = (1-\beta)(1-\rho_W) \tag{6}$$

$$P_2 = \beta\rho_W \tag{7}$$

$$P_3 = (1-\beta)\rho_W \tag{8}$$

$$P_4 = \beta(1-\rho_W) \tag{9}$$

Assume that the bandwidth of frequency hopping range is W, the power spectral density of gaussian white noise is N_0, and the number of corresponding frequency hopping points is N. The equivalent unilateral power spectral density of the jamming is $N_J = J/W$, and J is the total power of the follower jamming. It is assumed that the bandwidth of the follower jamming is an integer multiple of the bandwidth occupied by a single frequency-hopping point. The number of frequency points affected by the jamming is $\rho_W N$ ($\rho_W N$ is an integer), and the power spectral density of the jamming in the jamming part is N_J / ρ_W. In the current use sub-channel 0 as a data channel, $r_{i|j}$ is defined as the judgment quantity of the channel i (i =0,1) in state j (j=0 means no jamming, j=1 means jamming), and it can be obtained:

$$p(r_{0|0}) = \frac{1}{4E_S N_0}\exp(-\frac{r_0 + 4E_S^2}{4E_S N_0})I_0(\frac{\sqrt{r_0}}{N_0}) \tag{10}$$

$$p(r_{0|1}) = \frac{1}{4E_S(N_J\rho_T/\rho_W + N_0)}\exp(-\frac{r_0 + 4E_S^2}{4E_S(N_J\rho_T/\rho_W + N_0)})I_0(\frac{\sqrt{r_0}}{N_J\rho_T/\rho_W + N_0}) \tag{11}$$

$$p(r_{1|0}) = \frac{1}{4E_S N_0}\exp(-\frac{r_1}{4E_S N_0}) \tag{12}$$

$$p(r_{1|1}) = \frac{1}{4E_S(N_J\rho_T/\rho_W + N_0)}\exp(-\frac{r_1}{4E_S(N_J\rho_T/\rho_W + N_0)}) \tag{13}$$

According to the rule of hard decision:

$$P_{e1} = P(r_{1|0} > r_{0|0} \mid r_{0|0}, r_{1|0}) \tag{14}$$

$$P_{e2} = P(r_{1|1} > r_{0|1} \mid r_{0|1}, r_{1|1}) \tag{15}$$

$$P_{e3} = P(r_{1|1} > r_{0|0} \mid r_{0|0}, r_{1|1}) \tag{16}$$

$$P_{e4} = P(r_{1|0} > r_{0|1} \mid r_{0|1}, r_{1|0}) \tag{17}$$

According to the conditional probability to calculate P_{e1}:

$$P_{e1} = \int_0^\infty P(r_{1|0} > r_{0|0} \mid r_{1|0})P(r_{0|0})dr_{0|0} = \int_0^\infty (\int_{r_{0|0}}^\infty P(r_{1|0})dr_{1|0})P(r_{0|0})dr_{0|0} = \frac{1}{2}\exp(-\frac{E_S}{2N_0}) \tag{18}$$

Similarly, by calculating P_{e1}, we can get P_{e2}, P_{e3}, P_{e4}:

$$P_{e2} = \frac{1}{2}\exp(-\frac{E_S}{2(N_J\rho_T/\rho_W + N_0)}) \tag{19}$$

$$P_{e3} = \frac{1+(\rho_T N_J)/(\rho_W N_0)}{2+(\rho_T N_J)/(\rho_W N_0)}\exp(-\frac{E_S}{N_0(2+(\rho_T N_J)/(\rho_W N_0))}) \tag{20}$$

$$P_{e4} = \frac{1}{2+(\rho_T N_J)/(\rho_W N_0)}\exp(-\frac{E_S}{N_0(2+(\rho_T N_J)/(\rho_W N_0))}) \tag{21}$$

Substitute (6) - (9), (18) - (21) into (5) to obtain the anti-follower jamming BER of MSFH under AWGN channel.

It is easy to obtain the BER of conventional frequency hopping (FH-2FSK) using incoherent detection under follower jamming:

$$P_{e_FH-2FSK} = \frac{1}{2}(1-\beta)\exp(-\frac{E_S}{2N_0}) + \frac{1}{2}\beta\exp(-\frac{E_S}{2(N_J\rho_T/\rho_W + N_0)}) \quad (22)$$

4. Simulation results and analysis

We use Simulink to simulate the models established in the second and third sections. It is assumed that the frequency hopping number is 100, the frequency hopping band interval is 25kHz, and the frequency hopping sequences of the sender and receiver are strictly synchronized.In the simulation, the follower jamming is modeled as a zero-mean gaussian random process, the bandwidth is an integer multiple of the frequency-hopping point bandwidth, and the noise is a zero-mean gaussian white noise.The size of the SNR is 13.35dB, corresponding to the size of the gaussian noise in the channel when the undisturbed BER of MSFH and conventional frequency hopping (FH-2FSK) is 10^{-5} .

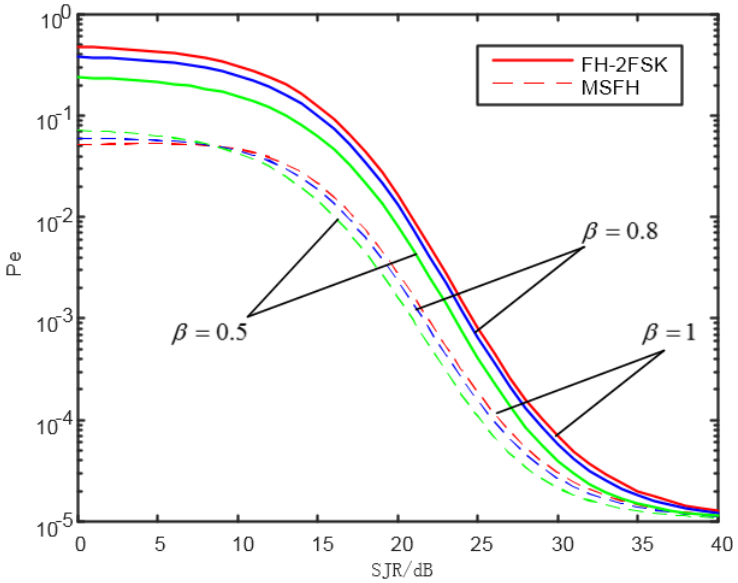


Figure 3. BER curves of MSFH and FH-2FSK under follower jamming.

Figure 3 shows the variation curves of the BER of MSFH and FH-2FSK with the signal-to-dry ratio in the jamming tracking success rate of 0.5, 0.8 and 1, respectively. As can be seen from the figure, compared with conventional frequency hopping, MSFH has an obvious gain in anti-follower jamming. Meanwhile, the higher the tracking success rate of follower jamming is, the better the anti-jamming performance of MSFH is.

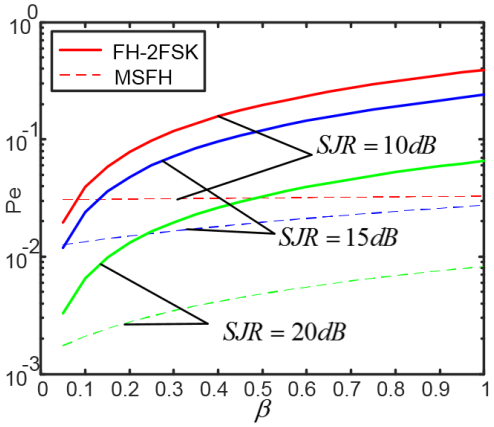


Figure 4. Influence of β on MSFH and FH-2FSK 's BER.

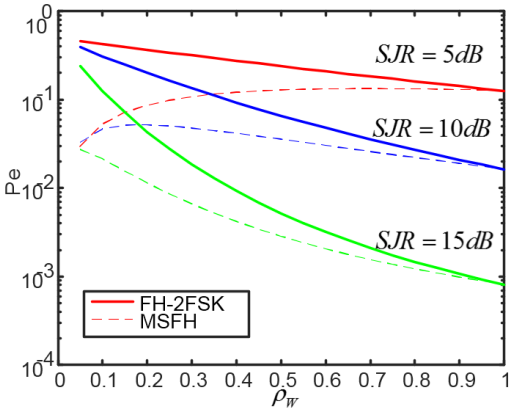


Figure 5. Influence of ρ_W on MSFH and FH-2FSK 's BER.

Figure 4 shows the curve of BER changing with the tracking success rate β under the follower jamming which SJR is 10dB, 15dB and 20dB. With the increase of β, the BER of conventional frequency hopping increases obviously, while that of MSFH increases slowly. It is noted that when the follower jamming power is large, the MSFH's BER is almost unaffected by β, which indicates that MSFH can hardly produce error code caused by the data channel is tracked by the jamming, and the main source of the error code is that the dual channel is hit by the follower jamming with a low probability.

Figure 5 shows the impact of follower jamming bandwidth ratio ρ_W on MSFH 's BER under the condition of $\beta = 1$. It can be seen that in the limit case of $\beta = 1$, follower jamming turns into broadband jamming, and MSFH has no gain compared with conventional frequency hopping.For conventional frequency hopping, when the jamming power is constant, the narrower the follower jamming bandwidth is, the more concentrated the power is, and the better the jamming effect is. The follower jamming is mainly caused by the random collision of the interfering signals in the dual channel, which indicates that MSFH has a strong anti-follower jamming ability.

5. Conclusion

In this paper, a model of MSFH anti-follower jamming in AWGN channel is established, the BER formula of MSFH anti-follower jamming is derived, and the influence of follower jamming parameter changes on MSFH is analyzed. Simulation results show that MSFH can gain about 2.47-2.7dB when SNR is 13.35dB and BER is required to be 10^{-4}, compared with conventional frequency hopping. MSFH has good anti-follower jamming ability and is an excellent anti-follower jamming communication method. Through simulation analysis, MSFH has a strong ability to resist narrow-band follower jamming and a small anti-jamming gain against the type of broadband non-follower jamming. This is because MSFH uses energy detection and cannot distinguish the source of energy at the corresponding frequency point in the judgment. When the dual channel is affected by the jamming of non-follower type, the judgment will be greatly affected. It is considered to add the check information into the MSFH signal to improve the error performance when the dual channel is disturbed.

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