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Performance Analysis of the Optimal Multitone Jamming for a MFSK-FH System

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Abstract. The analysis and evaluation of jamming becomes very important with the strain of spectrum resources and the intensification of electronic countermeasures. In order to deepen the understanding of the mechanism of multitone jamming (MTJ) on multiple frequency shift keying and frequency-hopping (MFSK-FH) system, as well as support the communication equipment to improve the anti-jamming ability, the optimal MTJ pattern for a MFSK-FH system is analyzed in this paper. Firstly, the incoherent demodulation receiving model of MFSK-FH system under MTJ is established. Then, the optimal jamming channel, optimal jamming phase and optimal jamming tone number are discussed in detail. Finally, the simulation results of bit error rate (BER) performance are given.

Keywords. MFSK-FH system, multitone jamming (MTJ), optimal jamming channel, optimal jamming phase, optimal jamming tone number

1. Introduction

With the increasing tension of spectrum resources and the development of communication countermeasure technique, the confrontation game between communication jamming and anti-jamming is gradually intensified [1][2]. Frequency-hopping (FH) communication system is widely used for its excellent anti-jamming ability, low intercept probability and networking capability [3][4].

The technique of jamming and anti-jamming for FH communication system has become a research hotspot. Typically, the most studied jamming patterns are partial band noise jamming (PBNJ) and multitone jamming (MTJ). The bit error rate (BER) performance of multiple frequency shift keying and frequency-hopping (MFSK-FH) system under the PBNJ are discussed in [5] and [6]. On the other hand, the theoretical BER performance of MFSK-FH system with a product merging receiver under MTJ are presented in [7] and [8]. In [9], the effect of MTJ on BER performance of FH system in Rayleigh fading channel with a product merging receiver are given. In [10], the BER performance of FH system using a maximum likelihood receiver with mixed PBNJ and MTJ in Rayleigh fading channel are studied, and theoretical and simulation analysis are carried out. On this basis, literature [11] further studied the influence of time and frequency migration on the FH system. In [12], the anti-PBNJ performance of differential

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frequency hopping (DFH) system in Rice fading channel are analyzed, and the upper bound of theoretical BER are deduced and verified by numerical results. In [13], a minimax anti-jamming strategy in a quadrature phase-shift keying (QPSK)-FH satellite communication system is developed, and two jamming strategies are evaluated: single-tone jamming (STJ) and full-band MTJ.

With the deepening understanding of the jamming mechanism, the study of the optimal jamming pattern can not only guide the jamming equipment to produce the better jamming, but also support the communication equipment to improve the anti-jamming ability [14], [15]. Thus, this paper deeply analyzes the influence of MTJ on the BER of a MFSK-FH system, and discusses the optimal jamming channel, the optimal jamming phase, and the optimal jamming tone number.

The rest of this paper is organized as follows. A non-coherent demodulation receiving model of MFSK-FH system under MTJ is established in Section 2. In Section 3, the optimal MTJ for the MFSK-FH system is analyzed in detail, including the optimal jamming channel, the optimal jamming phase, and the optimal jamming tone number. Finally, the BER simulation results of the MFSK-FH system under different cases are given in section 4.

2. MFSK-FH System Model

MFSK system utilizes multi-frequency carrier to transmit multi-digit information. Due to its excellent anti-noise and anti-fading performance, it is widely used in FH communication systems, especially in medium-high speed FH systems [16].

This paper mainly discusses the anti-MTJ performance of MFSK-FH system, so it is assumed that the system has achieved accurate carrier synchronization, that is, the receiver does not consider the transmission delay and Doppler shift. The input signal of the non-coherent demodulation receiver can be expressed as:

$$s_m(t) = A\cos(2\pi f_m t + \varphi) + N(t) + J(t) \quad m = 1, 2, \cdots, M \tag{1}$$

where A is signal amplitude, f_m is the baseband frequency of each transmitted data symbol and its value is $\{f_1, f_2, \cdots, f_M\}$, φ is the random phase, $N(t)$ is Gaussian white noise, and $J(t)$ is the jamming.

Consider that jammers implement the MTJ for the communication system, which is generated by transmitting one or more tone jamming on the communication spectrum. Typically, it can be divided into STJ and MTJ. A STJ can be expressed as:

$$J_{STJ}(t) = A_J \cos(2\pi f_J t + \phi) \tag{2}$$

where A_J is the amplitude of the jamming signal, f_J is the frequency of the jamming signal, and ϕ is the random phase, which is uniformly distributed in the $[0, 2\pi)$.

In practical, STJ is usually unable to achieve the jamming effect for FH system. Jamming equipment always choose to produce MTJ to improve the jamming effect. Assume that the tone number of the MTJ is N_{MTJ}, then a MTJ can be expressed as:

$$J_{MTJ}(t) = \sum_{n=1}^{N_{MTJ}} A_n \cos(2\pi f_n t + \phi_n) \tag{3}$$

3. Performance Analysis of the Multitone Jamming

This section will analyze the jamming effect of MTJ on MFSK-FH system in detail, and discuss the optimal jamming channel, optimal jamming phase, and optimal jamming tone number from the perspective of the jamming equipment.

3.1. The Optimal Jamming Channel

The binary frequency shift keying (BFSK) system is adopted as an example to analyze the jamming effect of different jamming strategies. The spectrum structure of BFSK system contains two different frequency channels, denoted as data channel and idle channel respectively, represented by f_1 and f_2, as shown in Figure 1.

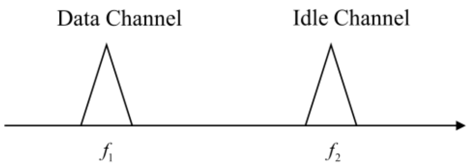


Figure 1. The spectrum structure of BFSK system.

The tone jamming of the jammer to the data channel and idle channel can be expressed as:

$$\begin{cases} J_1(t) = A_{J1}\cos(2\pi f_1 t + \phi_{J1}) \\ J_2(t) = A_{J2}\cos(2\pi f_2 t + \phi_{J2}) \end{cases} \tag{4}$$

where A_{J1} and A_{J2} are the amplitude of tone jamming signals of the data channel and idle channel respectively, and ϕ_{J1} and ϕ_{J2} are the phase of tone jamming signals of the data channel and idle channel respectively.

Assume that the frequency of tone jamming coincides perfectly with the carrier frequency of the transmitted signal. According to [14], the BER of BFSK system with a non-coherent demodulation receiver can be expressed as:

$$P_{b,FSK} = \frac{1}{4\pi}\int_0^{2\pi} \left[\begin{array}{l} Q\left(\frac{A_{J2}}{\sqrt{2P_N}}, \frac{D_1(\theta)}{\sqrt{2P_N}}\right) + Q\left(\frac{A_{J1}}{\sqrt{2P_N}}, \frac{D_2(\theta)}{\sqrt{2P_N}}\right) \\ -\frac{1}{2}\exp\left(-\frac{A_{J2}{}^2 + D_1^2(\theta)}{4P_N}\right) I_0\left(\frac{A_{J2}D_1(\theta)}{2P_N}\right) \\ -\frac{1}{2}\exp\left(-\frac{A_{J1}{}^2 + D_2^2(\theta)}{4P_N}\right) I_0\left(\frac{A_{J1}D_2(\theta)}{2P_N}\right) \end{array} \right] d\theta \tag{5}$$

where P_N is the noise power, $Q(a,b)$ is the Marcum Q function, and

$$\begin{cases} D_1^2(\theta) = A^2 + A_{J1}{}^2 + 2AA_{J1}\cos\theta \\ D_2^2(\theta) = A^2 + A_{J2}{}^2 + 2AA_{J2}\cos\theta \end{cases} \tag{6}$$

The jammer has three jamming strategies: jamming only the data channel, jamming only the idle channel, or jamming both the data channel and idle channel. The effects of these three different jamming strategies will be discussed below respectively.

- Jamming Only the Data Channel

In (4), only tone jamming $J_1(t)$ exists. let S represents the signal power, and P_J represents the jamming power, then, $A=\sqrt{2S}$, $A_{J1}=\sqrt{2P_J}$, $A_{J2}=0$. According to (5), the BER when jamming only the data channel can be obtained as:

$$P_{b,FSK}=\frac{1}{2}Q\left(\sqrt{\frac{P_J}{P_N}},\sqrt{\frac{S}{P_N}}\right) \tag{7}$$

Let $\upsilon=\frac{S}{P_N}$ denotes the signal-to-noise ratio (SNR) and $\xi=\frac{P_J}{S}$ denotes the jamming to signal ratio (JSR), the (7) can be expressed in the form of power ratio as:

$$P_{b,FSK}=\frac{1}{2}Q\left(\sqrt{\xi\upsilon},\sqrt{\upsilon}\right) \tag{8}$$

- Jamming Only the Idle Channel

Since the jammer does not know which side of the data channel is the idle channel, a factor of 1/2 will exist. Similarly to the above analysis, the BER when jamming only the idle channel can be obtained as:

$$P_{b,FSK}=\frac{1}{2}\cdot\frac{P_N+P_J}{2P_N+P_J}\exp\left(-\frac{S}{2P_N+P_J}\right) \tag{9}$$

The (9) can be expressed in the form of power ratio as:

$$P_{b,FSK}=\frac{1}{2}\cdot\frac{1+\xi\upsilon}{2+\xi\upsilon}\exp\left(-\frac{1}{\frac{2}{\upsilon}+\xi}\right) \tag{10}$$

- Jamming Both the Data Channel and Idle Channel

In (4), both $J_1(t)$ and $J_2(t)$ exist, that is, $A=\sqrt{2S}$ and $A_{J1}=A_{J2}=\sqrt{2P_J}$. According to (5), the BER when jamming both the data channel and idle channel can be derived as:

$$P_{b,FSK}=\frac{1}{2\pi}\int_0^{2\pi}\left[\begin{array}{l}Q\left(\sqrt{\frac{P_J}{P_N}},\frac{D(\theta)}{\sqrt{2P_N}}\right)\\ -\frac{1}{2}\exp\left(-\frac{2P_J+D^2(\theta)}{4P_N}\right)I_0\left(\frac{\sqrt{2P_J}D(\theta)}{2P_N}\right)\end{array}\right]d\theta \tag{11}$$

where

$$D^2(\theta)=2S+2P_J+4\sqrt{SP_J}\cos\theta \tag{12}$$

The (11) can be expressed in the form of power ratio as:

$$P_{b,FSK} = \frac{1}{2\pi}\int_0^{2\pi}\left[\begin{array}{l} Q\left(\sqrt{\xi\upsilon}, \sqrt{\upsilon+\xi\upsilon+2\upsilon\sqrt{\xi}\cos\theta}\right) \\ -\frac{1}{2}\exp\left[-\left(\frac{1}{2}\upsilon+\xi\upsilon+\upsilon\sqrt{\xi}\cos\theta\right)\right] \\ \cdot I_0\left(\xi\upsilon^2+\xi^2\upsilon^2+2\xi\upsilon^2\sqrt{\xi}\cos\theta\right) \end{array}\right] d\theta \tag{13}$$

The integral in the (13) has no known solution in closed form, so it must be solved numerically.

3.2. The Optimal Jamming Phase

The phase relationship between tone jamming and transmission signal is an important factor, which affects the jamming performance. If a STJ generates at the data channel, the vector superposition result of the jamming and signal may enhance the energy of the transmission signal, or may reduce the energy of the transmission signal, which depends on the phase relationship between the jamming and signal.

The vector relationship between the tone jamming and transmission signal is shown in Figure 2. As shown in Figure 2, the amplitude of vector superposition result is obviously smaller than that of the transmission signal, indicating that the energy of transmission signal is suppressed and the jamming purpose is achieved. The amplitude of vector superposition result is obviously greater than that of the transmission signal, indicating that the energy of transmission signal is enhanced and the jamming purpose is not achieved.

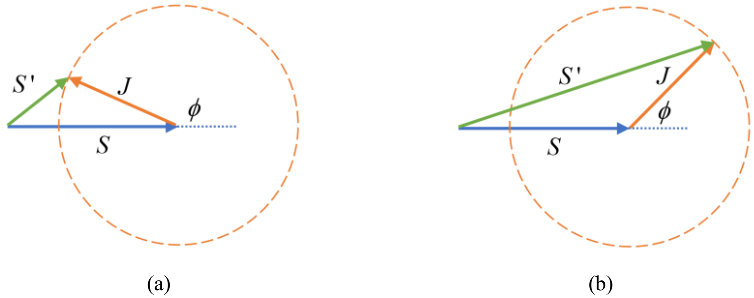


Figure 2. The vector relationship between the tone jamming and transmission signal. (a) The transmission signal energy is suppressed. (b) The transmission signal energy is enhanced.

Consider that jamming both the data channel and idle channel, and the tone jamming can be expressed as (4). From the definition of JSR, the jamming power can be expressed as: $P_J = \xi \cdot S$, then the jamming amplitude can be obtained as: $A_{J1} = A_{J2} = \sqrt{2\cdot\xi\cdot S}$. In (4), assume that jamming phase ϕ_{J1} and ϕ_{J2} is uniformly distributed over $[0, 2\pi)$, and its probability density function is $p(\phi) = \frac{1}{2\pi}$.

The data channel contains the jamming and transmission signal, and the vector superposition result can be obtained as:

$$\begin{aligned} s_1(t)+J_1(t) &= \sqrt{2S}\cos(2\pi f_1 t+\varphi)+\sqrt{2\cdot\xi\cdot S}\cos(2\pi f_1 t+\phi_{J1}) \\ &= \sqrt{2S'}\cos(2\pi f_1 t+\phi') \end{aligned} \tag{14}$$

where S' is the total power of the final signal after vector superposition on the data channel, and can be expressed as:

$$
\begin{aligned}
S' &= \left[\left(1+\sqrt{\xi}\cos\left(\phi_{J1}-\varphi\right)\right)^2 + \left(\sqrt{\xi}\sin\left(\phi_{J1}-\varphi\right)\right)^2\right]\cdot S \\
&= \left(1+2\sqrt{\xi}\cos\left(\phi_{J1}-\varphi\right)+\xi\right)\cdot S
\end{aligned}
\tag{15}
$$

The idle channel only contains the tone and the jamming power is $\xi \cdot S$. If the jamming power on the idle channel is greater than the superposition signal power on the data channel, that is, $\xi \cdot S > S'$, the error of received symbol will occur. The probability of this situation can be derived as:

$$
\begin{aligned}
P_{phase} &= P\left\{\xi \cdot S > S'\right\} \\
&= P\left\{\xi \cdot S > \left(1+2\sqrt{\xi}\cos\left(\phi_{J1}-\varphi\right)+\xi\right)\cdot S\right\} \\
&= \frac{1}{\pi}\arccos\left(\frac{1}{2\sqrt{\xi}}\right)
\end{aligned}
\tag{16}
$$

The probability curve of (16) of received symbol error occurs when tone jamming hits under different JSR is shown in Figure 3. It should be noted that since the argument value of the *arccos* function cannot exceed 1, the lower bound of ξ is 1/4 (-6 dB). It can be seen from (16), the jammer can implement the tone jamming with a jamming power which is smaller than the signal power (no less than 6 dB), and the jamming purpose can still be achieved, but the premise is that the specific phase relationship must be satisfied.

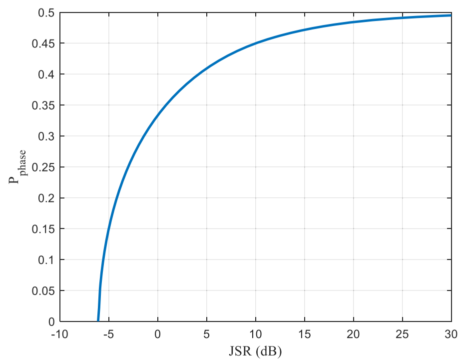


Figure 3. The probability of received symbol error occurs when tone jamming hits.

3.3. The optimal jamming tone number

For a MFSK-FH system, only using single-tone or two-tone jamming always cannot achieve the jamming effect, and large numbers of tonal jamming are needed to increase the number of interfered channels. Thus, the jamming tone number is a very important factor to evaluate the jamming effect, which is denoted by N_{MTJ}. To give an absolute indicator for evaluating the jamming effect, let $\rho = \frac{N_{MTJ}}{N_{FH}}$ represents the collision probability between the tone jamming frequency and the hopping frequency, where N_{FH} represents the number of hopping frequency.

For the jammer, there exists an optimal number of jamming tones, denoted as $N_{MTJ,\ opt}$, and its corresponding collision probability is denoted as ρ_{opt}. Assuming that the power of different tones of MTJ is equal, based on the analysis above, the average BER of MFSK-FH system under MTJ can be expressed as:

$$\begin{aligned} P_{b,FH} &= \rho P_{phase} P_{b,FSK} \\ &= \rho \cdot \frac{1}{\pi} \arccos\left(\frac{1}{2\sqrt{\xi'}} \right) \cdot P_{b,FSK} \end{aligned} \tag{17}$$

where ξ' in the (17) and the JSR used in $P_{b,FSK}$ is the equivalent JSR, satisfying $\xi' = \dfrac{\xi}{N_{MTJ}}$.

Thus, the optimal jamming tone number can be obtained as:

$$N_{MTJ,\ opt} = \arg\max_{\rho} \rho \cdot \frac{1}{\pi} \arccos\left(\frac{1}{2\sqrt{\xi'}} \right) \cdot P_{b,FSK} \tag{18}$$

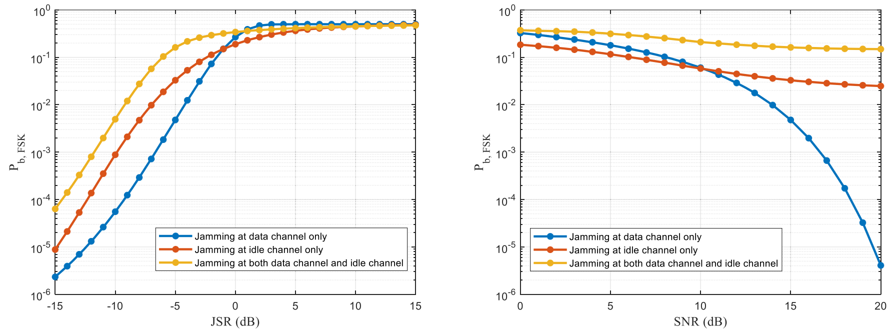
Ignore the effect of noise, and assume that jamming tone is generated only on the idle channel for each MFSK transmission symbol. Under this circumstance, if the jamming power on the idle channel is greater than the transmission signal power on the data channel, the jamming purpose can be achieved, that is, $P_{J,\min} = S$, where $P_{J,\min}$ represents the minimum jamming power required to achieve the jamming purpose. Then, the optimal jamming tone number can be obtained as:

$$\rho_{opt} = \left\lfloor \frac{P_J}{P_{J,\min}} \right\rfloor \tag{19}$$

where $\lfloor \cdot \rfloor$ is the round-down operation.

4. Simulation

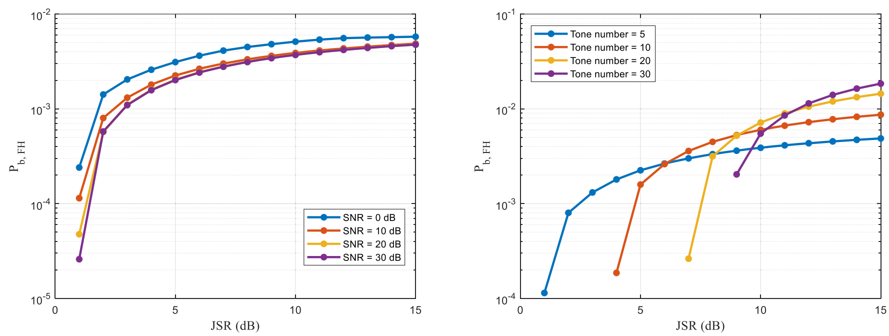
Figure 4 shows the BER performance of FSK system under three different jamming channel strategies. As can be seen from Figure 4, the jamming effect of jamming both the data channel and idle channel is the best, followed by the jamming effect of only jamming the idle channel, and the jamming effect of only jamming the data channel is the worst. When the JSR is large or the SNR is small, the jamming effect of the three strategies is similar, indicating that the system has been seriously interfered at this time. It should be noted that, if the jammer only interferes at data channel, the communication equipment can reduce the BER by improving the SNR. However, if the jammer only interferes at idle channel or interferes at both data channel and idle channel, the improvement of SNR of communication equipment has little influence on the reduction of BER.



(a) (b)

Figure 4. BER results of FSK system under three different jamming channel strategies. (a) Different JSR. (b) Different SNR.

Figure 5 shows the BER performance of MFSK-FH system under MTJ. As can be seen from Figure 5, improving the SNR can reduce the BER under MTJ, but when the SNR is small, the reduction is more obvious. When the SNR is high, improving the SNR has little effect on the BER. When the jamming power of the jamming equipment is constant, the optimal jamming effect can be achieved by choosing the appropriate jamming tone number, which is related to the actual JSR.



(a) (b)

Figure 5. BER results of MFSK-FH system under MTJ. (a) Different SNR. (b) Different jamming tone number.

5. Conclusion

In this paper, the optimal MTJ pattern for a MFSK-FH system is analyzed in depth. Based on the incoherent demodulation receiving model of MFSK-FH system with MTJ, the optimal jamming channel, optimal jamming phase and optimal jamming tone number are discussed in detail. The simulation results show that the jamming equipment can implement the MTJ jamming with a jamming power which is smaller than the signal power (no less than 6 dB), and still achieve the purpose of jamming, but the premise is that the specific phase relationship must be satisfied. The work in this paper can deepen the understanding of the mechanism of MTJ on MFSK-FH system, which can help to guide the jamming equipment to better implement jamming, as well as support the communication equipment to improve the anti-jamming ability. Future work will focus on designing the communication scheme based on the discussion of the optimal MTJ pattern to improve the anti-jamming ability of the communication system.

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