Anti-follower jamming performance analysis of dual sequence frequency hopping in Gaussian white noise channel

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Abstract. With the increasingly severe wireless communication confrontation, the traditional conventional frequency hopping (CFH) system has poor performance in anti-follower jamming, so a new dual frequency hopping mode is proposed from the perspective of frequency hopping principle. Firstly, the communication model and anti-jamming principle of the dual sequence frequency hopping (DSFH) system are introduced. Secondly, the typical follower jamming model and its parameters in communication are summarized, and the anti-follower jamming performance of different parameters of the system under follower jamming is analyzed. Finally, the CFH and DSFH system are compared. Bit error rate performance under different parameter conditions. The results show that under the AWGN channel, the anti-follower jamming performance of the DSFH system is better than that of CFH, and the value of the bit error rate is lower than that of CFH.

1. Introduction
With the rapid development of military informatization and digitalization, wireless communication is an important means of ensuring operations and command on the battlefield [1]. Frequency hopping (FH) communication technology with pseudo-random hopping of carrier frequency is due to its strong robustness and Adaptability has become the most important means of communication in modern combat [2]. However, with the accelerated development of communication electronic countermeasures and wireless equipment in military and civilian use, its application in the military field has been severely restricted [3]. When faced with follower jamming, FH communication becomes as fragile as fixed frequency communication due to the gain loss caused by jamming.

For this reason, scholars studying FH systems at home and abroad have carried out research on new communication mode systems based on FH principles. As a result, some communication methods began to use the characteristic difference between channels to express the idea of information [4-5], and launched the anti-jamming performance of the new frequency hopping system. For example, differential frequency hopping, dual sequence frequency hopping and other anti-jamming system.

Based on a typical Gaussian white noise channel, this paper first proposed a new type of DSFH transmission model and analyzed anti-jamming principle; secondly, it introduced the follower jamming model and its influencing parameters, and analyzed the error code under different jamming parameters Performance; Finally, compared with the CFH system, the error rate performance of follower jamming under different jamming factors is analyzed.
2. DSFH model and anti-jamming principle

2.1. System composition and working principle

In the DSFH communication system, the entire FH frequency band $W_B$ includes $N$ orthogonal FH frequency points. There are two channels between sending and receiving, that is, channels 0 and 1 to represent data messages 0 and 1. In a FH time slot, the two channels each occupy a frequency point, and this frequency point is determined by the FH sequence corresponding to the channel.

In Figure 1, DSFH selects sub-channels 0 and 1 by sending symbols 0 and 1, and determines which FH sequence corresponds to a FH to control the frequency hopping carrier. At time $t$, if symbol 0 is sent, channel 0 is used to send, that is, a single-frequency signal is sent on the current frequency $f(0,t)$ of $FS_0$; On the contrary, if symbol 1 is sent, it will be sent by channel 1. After channel selection, the final transmitted signal $s(t)$ is $s_0(t)$ and $s_1(t)$. Assuming that the frequency of the FH sequence $FS_0$ is $(\ldots, f_1, f_2, f_3, f_4, \ldots)$ and the frequency of the FH sequence $FS_1$ is $(\ldots, f_5, f_6, f_7, f_8, \ldots)$, when the transmitted symbol data is $(\ldots, 0, 1, 0, 1, \ldots)$, the frequency synthesizer sequentially synthesizes the signal with the frequency $(\ldots, f_5, f_6, f_7, f_8, \ldots)$.

According to the DSFH transmission structure model, the transmitted symbol information directly selects the carrier frequency synthesized by the FH sequence, and is transmitted by the antenna through the radio frequency front-end processing. Assume that the transmitted symbol is $i$, the interval between adjacent frequency points is $1/T_s$, and the transmitted symbol energy is $E_s$. Then the baseband equivalent expression of the transmitted symbol at time $t$ is:

$$s(t) = \sqrt{2E_s/T_s} e^{j2\pi f(i,t)t}, i = 0, 1$$

(1)

$s(t)$ can only be transmitted to the air after passing through a band-pass filter and up-conversion. Due to noise, fading and jamming in the air channel, the equivalent expression of the received signal is:

$$r(t) = \alpha_s e^{j\theta} s(t) + n(t) + n_j(t)$$

(2)

Among them, $\alpha_s$ and $\theta$ respectively represent the signal fading and the phase difference, $n(t)$ represents the additive white Gaussian noise with and $n_j(t)$ represents the jamming signal.

As shown in Figure 2, the receiver receives in parallel on the two narrowband receiving channels with frequency interval hopping. The principle is the same as that of the CFH synchronization module. DSFH generates local hops at the receiving end that are synchronized with the transmitter frequency hopping sequences $FS_0$ and $FS_1$. Frequency sequence. During a frequency hop, the channel $i$ detection decision $r_i$ can be expressed as:
It can be obtained from the detection decision amount $r_i$, using the simplest hard decision method $Y = r_0 - r_1$, that is, when $Y \geq 0$, it is determined that the transmitted symbol information is 0. Otherwise, it’s judged as 1.

### 2.2. Analysis of system anti-jamming principle

Similar to the conventional system, the DSFH system also uses the non-coherent detection method commonly used in FH communication and receives it in a narrow-band manner. They all represent information based on the presence or absence of signal energy on a fixed frequency point. The difference is that the data frequency and the dual frequency of the CFH system are in the same channel, and the follower jamming signal can interfere at the same time as long as it is aligned with this channel. Two frequency points. The DSFH system uses pseudo-random sequence as the channel. Compared with the CFH system, no information modulation is required, and the frequency interval between the two channels changes pseudo-randomly, even if the jamming signal tracks the data channel frequency. It is also difficult to estimate the dual channel state, which will increase the energy detection probability of the useful signal.

### 3. Follower jamming model and anti-jamming performance

#### 3.1. Follower jamming

Follower Jamming needs to detect the carrier frequency of the frequency hopping signal, and the frequency of the follower Jamming signal hops synchronously with the carrier frequency. The signal characteristics of the two are largely similar in the time domain and the frequency domain, and the jamming signal is correlated with the carrier signal with a certain probability $\beta$. Under the condition of a certain jammer power, the influence of follower jamming on the frequency hopping system is mainly determined by three parameters: (1) The jamming bandwidth ratio $\rho_J$, which represents the ratio of the jamming signal bandwidth to the FH range bandwidth of the FH system, which affects the jamming Signal strength and jamming success rate; (2) Jamming time ratio $\rho_T = T_J / T_h$, which represents the ratio of the time $T_J$ affected by follower jamming to the FH system during a frequency hopping time to the dwell time $T_h$ of each hop of the frequency hopping signal; (3) The jamming success rate $\beta$ represents the probability that the FH system will be successfully tracked by the jamming signal for each frequency hop.

#### 3.2. Anti-jamming performance

In the DSFH system, the symbol energy is the same as the bit energy. If $\alpha_s = 1$, the signal-to-noise ratio is $\gamma = E(\alpha_s^2) E_s / N_o = E_s / N_o$ and its signal-to-interference ratio is $\gamma_J = E(\alpha_s^2) E_J / N_J = E_J / N_J$. To ensure generality, suppose that the user information of the $l$ hop of DSFH is "0", and it occupies data channel 0 for transmission. This article mainly examines the noise jamming performance. For the AWGN channel, according to the formula (2), the receiving expression is:

$$r(t) = e^{\alpha_s} s(t) + n_j(t)$$  \hspace{1cm} (4)

No consideration of thermal noise in the channel: $n(t) = 0$.

Different from the CFH, the DSFH system uses two channels to receive signals. Any jamming will affect the status of the channel and the error ratio performance. Based on the above analysis, the channels can be divided into four situations: $J_1$ is the data channel, and the dual channel is not interfered; $J_2$ means that the data channel is not disturbed and the dual channel is disturbed; $J_3$ is that the data channel
is disturbed and the dual channel is not disturbed; \( J_4 \) is that the data channel and the dual channel are disturbed; because the two channels have different frequencies, they are also independent of jamming. Assume that the random variable \( j_0 \) represents the state of sub-channel 0, and \( j_1 \) represents the state of sub-channel 1.

When \( j_0 \) is set to 0, it means that the channel is not interfered, otherwise it is interfered. The relationship between \( J_i \), \( j_0 \) and \( j_1 \) is shown in Table 1:

Table 1. The relationship between one-hop jamming status and sub-channel status

| State | \( J_1 \) | \( J_2 \) | \( J_3 \) | \( J_4 \) |
|-------|------|------|------|------|
| \( j_0 \) | 0    | 0    | 1    | 1    |
| \( j_1 \) | 0    | 1    | 0    | 1    |

Use \( P(J_i) \) to represent the probability of different channel states \( J_i \), and \( P_e(j_0, j_1) \) to represent the conditional probability of error occurrence when sub-channels 0 and 1 are in the two states, then the bit error rate of the DSFH system can be written as:

\[
P_e = \sum_{i=1}^{4} P(J_i)P_e(j_0, j_1) \tag{5}
\]

When there is no jamming, the probability density function of sub-channel 0 and 1 decision is \( \delta \) distribution:

\[
p(r_0 \mid 0) = \delta(r_0 - 4E_S^2) \tag{6}
\]

\[
p(r_1 \mid 0) = \delta(r_1) \tag{7}
\]

When interfered by noise follower, sub-channel 0 is Rice distribution, and sub-channel 1 is Rayleigh distribution:

\[
p(r_0 \mid 1) = \frac{1}{4E_S N_j \rho_T / \rho_J} \exp \left( -\frac{r_0 + 4E_S^2}{4E_S N_j \rho_T / \rho_J} \right) N(0, \sqrt{\frac{r_0}{N_j \rho_T / \rho_J}}) \tag{8}
\]

\[
p(r_1 \mid 1) = \frac{1}{4E_S N_j \rho_T / \rho_J} \exp \left( -\frac{r_1}{4E_S N_j \rho_T / \rho_J} \right) \tag{9}
\]

Where \( r_0 \mid 0/1 \) is expressed as the detection decision value when sub-channel 0 is in the \( j_0 = 0,1 \) state, and \( r_1 \mid 0/1 \) is expressed as the detection decision value when sub-channel 1 is in the \( j_1 = 0,1 \) state.

Since follower jamming interferes with the data channel with a certain probability \( \beta \), its dual channel is not easy to be tracked. Therefore, assuming that the dual channel is hit with the probability \( \rho_j \), the probability distribution of the occurrence of two channel states \( J_i \) is obtained:

\[
P(J_i) = (1 - \beta)(1 - \rho_J) \tag{10}
\]

\[
P(J_2) = (1 - \beta)\rho_J \tag{11}
\]

\[
P(J_3) = \beta(1 - \rho_J) \tag{12}
\]

\[
P(J_4) = \beta\rho_J \tag{13}
\]

This paper adopts the large hard decision method, therefore, the conditional decision error probability \( P_e(j_0, j_1) \) of the system in the jamming state \( J_i \) is:

\[
P_e(j_0, j_1) = P(r_0 \mid j_0 < \eta_i \mid j_i \mid J_i) = \int_{r_0}^{\eta_i} \int_{j_0}^{\eta_j} P(r_0 \mid j_0) P(r_1 \mid j_1) d_0 \mid j_0 P(r_0 \mid j_0) d_0 \mid j_0 \tag{14}
\]
Substitute the above formula into (5) to get the bit error rate under follower jamming:

\[
P_e = (1 - \beta) \rho_J \exp\left(\frac{-\gamma_J \rho_J}{\rho_T}\right) + \frac{1}{2} \beta \rho_J \exp\left(-\frac{\gamma_J \rho_J}{2\rho_T}\right)
\]  

(15)

4. Simulation analysis of parameters under follower jamming

4.1. Follower jamming bandwidth \( \rho_J \) performance analysis

Figure 3 compares the bit error rate of CFH and DSFH under \( \rho_J \) and set the jamming condition \( \rho_T = \beta = 1 \).

![Figure 3. Comparison of bit error rate between CFH and DSFH](image)

From the analysis of the figure, the bit error rate of DSFH is about an order of magnitude lower than that of CFH, and the bit error rate performance of DSFH is better under different jamming bandwidths. When the bit error rate reaches \( 10^{-5} \), its signal-to-interference ratio is generally about 1 to 2dB lower than CFH.

4.2. Follower success rate \( \beta \) performance analysis

Figure 4 compares the bit error rate of CFH and DSFH under \( \beta \), and set the jamming conditions \( \rho_T = 1 \), \( \rho_J = 1/16 \).

![Figure 4. Comparison of bit error rate between CFH and DSFH](image)

According to the graph analysis, the error rate of DSFH is about an order of magnitude lower than that of conventional frequency hopping, and the error rate performance of DSFH is better under different success rates. When the bit error rate reaches \( 10^{-5} \), its signal-to-interference ratio is about 2 to 3dB lower than that of CFH.
4.3. Follower time ratio $\rho_T$ performance analysis

Figure 5 compares the bit error rate of CFH and DSFH under $\rho_T$, and set the jamming conditions $\beta = 1$, $\rho_d = 1/16$.

![Graph: Comparison of bit error rate between CFH and DSFH](image)

Figure 5. Comparison of bit error rate between CFH and DSFH

Analyze from the graph and assume that the prior information received by the interferer is that the frequency hopping period is known and the specific start and end time are not known, and the power of the next hop to be interfered is not considered. It can be seen that the error rate of DSFH is more than an order of magnitude lower than that of CFH, and the error rate performance of DSFH is better under different time scales. When the bit error rate reaches $10^{-5}$, its signal-to-interference ratio is about 2dB lower than the CFH.

5. Conclusion

This paper analyzes the anti-follower jamming performance of the DSFH under the AWGN channel, and compares the bit error rate of the CFH under different influencing factors. The simulation results show that the DSFH error rate is generally lower than that of the CFH by about 1 to 3dB, which makes up for the poor anti-jamming performance of CFH communication in the face of complex electromagnetic environment interference, and also reflects the strong anti-jamming capability of the DSFH system. However, this article only considers the impact of typical interference under a single channel, and further studies on other interference under different channels are needed.

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