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Multistage Pulse Jamming Suppression Algorithm for Satellite Navigation Receiver

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Abstract
A novel multistage pulse jamming suppression algorithm was proposed to solve the anti-pulse jamming problem encountered in navigation receivers. Based on the characteristics of the short duration of pulse jamming and distribution characteristics of satellite signals, the pulse jamming detection threshold was derived. From the experiments, it was found that the randomness of pulse jamming affects jamming suppression. On this basis, the principle of the multistage anti-pulse jamming algorithm was established. The effectiveness of the anti-jamming algorithm was verified through experiments. The characteristics of the algorithm include simple determination of jamming detection threshold, easy programming, and complete suppression of pulse jamming.

Keywords
Anti-jamming, Multistage, Pulse Jamming, Satellite Navigation Receiver

1. Introduction

The satellite navigation signal is very weak and can be easily interfered with, intentionally or unintentionally. To ensure that the satellite navigation receiver works stably and reliably in a complex electromagnetic environment, it is necessary to enhance its anti-jamming ability [1]. As a common signal on the modern battlefield, pulse jamming is easy to generate. Moreover, the jamming energy is concentrated, and if the parameters are set properly, the performance of the satellite navigation receiver will deteriorate in a short time [2,3]. Recently, various wireless devices have been widely used, and the electromagnetic environment has become much more complex; therefore, pulse jamming may appear in specific application scenarios at any time. Radio ranging equipment, rangefinder, radar, digital communication equipment, microwave relay, earth exploration satellite, etc., may become potential sources of pulse jamming. In particular, because the satellite navigation frequency band is adjacent to the radar frequency band, it is easily affected by the pulse signal [4,5]. The influence of the pulse signal on the satellite navigation signal is a major problem. The pulse signal causes harmful jamming and malfunctioning of the navigation receiver. The effect of pulse jamming on the performance of the satellite navigation receiver was analyzed in [5], and it was determined that the pulse jamming signal with a period

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of 1 ms had a significant effect on the receiver. In [6], a suppression method based on statistical distribution detection was proposed. Based on the statistical distribution of analog-to-digital converter (ADC) output signal, the hypothesis test method is used to determine whether there is jamming. The method focuses on the detection of pulse jamming in the spread spectrum system. In addition, the method involves a lot of computation, and has a good effect on off-line processing; however, it is difficult to process in real time. The ADC word length is larger than the actual word length and counting the distribution of each bit of the ADC output signal requires a considerable amount of memory. In [7], a simplified jamming suppression method was proposed. In this method, a sampling signal larger than the detection threshold is regarded as pulse jamming and is zeroed. The method is easy to implement, but the discrimination threshold has to be provided in advance. The threshold value has a great impact on the algorithm performance, and the jamming detection accuracy is very limited. A pulse jamming detection algorithm based on the combination of digital automatic gain control (AGC) and ADC data was proposed in [8]. The algorithm is better than the threshold pulse jamming detection method and simpler than the complex detection method based on the statistical distribution of the signal. However, it requires increased control of the AGC, which increases the hardware complexity to a certain extent. A short-term pulse jamming suppression algorithm in the spatial domain is proposed in [9,10]; however, such algorithms are based on array antennas and are computationally complex.

To solve the problem of anti-pulse jamming in the satellite navigation receiver, a new method of pulse jamming suppression is proposed in this study. The main works of this paper are as follows: (1) based on the characteristics of the short duration of pulse jamming and Gaussian distribution of satellite navigation signal, the detection threshold of pulse jamming is derived, (2) the correctness of the theoretical conclusion is verified using simulations, (3) the anti-jamming effect is verified through experiments, and (4) a series of conclusions are drawn based on the experimental phenomena.

The proposed algorithm has the following characteristics: (1) without AGC participation, the pulse jamming suppression is carried out in the digital domain, which is easy to program, (2) the detection threshold of pulse jamming is easily determined, and (3) the detection probability of pulse jamming is effectively improved by cascading the multistage pulse jamming suppression, and the pulse jamming suppression is completed.

2. Multistage Pulse Jamming Suppression Algorithm

2.1 Pulse Jamming Detection Algorithm

The actual duration of pulse jamming is μs order, and the adjustment time of front-end AGC is ms order. If the signal is jammed, it will continuously exceed the threshold in a short time [8]. Because the power of noise $N(n)$ is much greater than that of satellite signal $S(n)$, $S(n)+N(n)$ can be approximated as Gaussian white noise, and $|S(n)+N(n)|$ obeys the Rayleigh distribution [11].

Let $z = |S(n)+N(n)|$, and the variance of $|S(n)+N(n)|$ be σ^2, then the probability density function z is expressed as

$$f(z) = \frac{z}{\sigma^2} \mathrm{e}^{-\frac{z}{2\sigma^2}}, z > 0 \tag{1}$$

The probability of z less than the threshold T is given by

$$F(T) = \int_0^T f(z)\,dz = \int_0^T \frac{z}{\sigma^2} e^{\frac{z}{2\sigma^2}} dz = 1 - e^{\frac{T^2}{2\sigma^2}} \tag{2}$$

According to Eq. (1), the mean value of $|S(n)+N(n)|$ is denoted as

$$\mu = \int_0^{\infty} z f(z) \mathrm{d}z = \int_0^{\infty} z \frac{z}{\sigma^2} e^{-\frac{z}{2\sigma^2}} dz = \sqrt{\frac{\pi}{2}}\sigma \tag{3}$$

According to Eqs. (2) and (3), probability of Z<T is given by

$$F(T) = 1 - e^{-\frac{\pi T^2}{4\mu^2}} \tag{4}$$

From Eq. (4), it can be deduced that

$$F(T) = 1 - e^{-\frac{\pi}{4}\left(\frac{T}{\mu}\right)^2} \tag{5}$$

Eq. (5) shows that the probability of $|S(n)+N(n)|$ less than a certain threshold is related to the ratio of the mean μ to the threshold T and is not related to the mean value μ. Therefore, the mean value can be used to estimate the threshold value of pulse jamming detection. The calculation of the mean value is a conventional process in the digital domain, and little amount of calculation is involved.

When $T = 2\mu$, the probability of $|S(n)+N(n)| < T$ is 95.7%. When $T = 3\mu$, the probability of $|S(n)+N(n)| < T$ is 99.91%. From the above analysis, when the signal received is jammed, the probability that $|S(n)+N(n)| > 3\mu$ is 0.0009. At the significant level β=0.0009, the probability that $|S(n)+N(n)| > 3\mu$ is small, and therefore 3μ can be used as the jamming detection threshold.

A jammed signal is received when there is a large signal in the part that is polluted by jamming, thus, the above rule is broken. The undisturbed part still obeys the Rayleigh distribution and the jamming is easily detected. Therefore, the detection of pulse jamming is transformed into a hypothesis testing problem. The hypothesis testing can be described as follows:

$$\begin{cases} H_0 : J(n) = 0, \text{no jamming} \\ H_1 : J(n) \neq 0, \quad \text{jamming} \end{cases} \tag{6}$$

where $J(n)$ is the jamming.

Based on Eq. (5), the test statistic is expressed as

$$\xi = \{|S(n)+N(n)| > 3\mu\} \tag{7}$$

When $\xi = 0$, H_0 is true, otherwise H_1 is true. When H_0 is true, the signal is not jammed, and no processing is done. When H_1 is true, $|S(n)+N(n)|$ greater than 3μ is pulse jamming, and it is set to zero. The test is carried out again until hypothesis H_0 is true.

Fig. 1 illustrates the histogram of $|S(n)+N(n)|$ where the power of noise is -101 dBm, and the power of the signal is -130 dBm.

Fig. 2(a) shows the time domain waveform of $|S(n)+N(n)+J(n)|$, while Fig. 2(b) shows the histogram of $|S(n)+N(n)+J(n)|$. When the power of noise is -101 dBm, the power of the signal is -130 dBm, and the ratio of jamming power to signal power (JSR) is 70 dB.

The dashed lines in Figs. 1 and 2(b) denote 3μ, which is the threshold. It can be affirmed that the simulation results are consistent with the theoretical analysis.

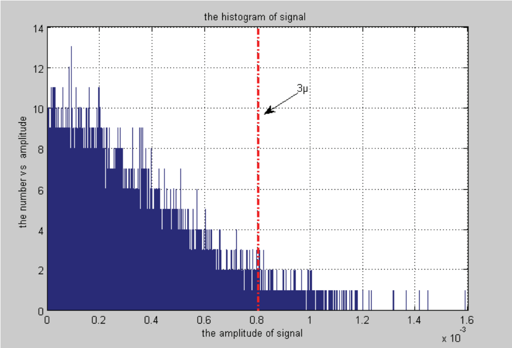
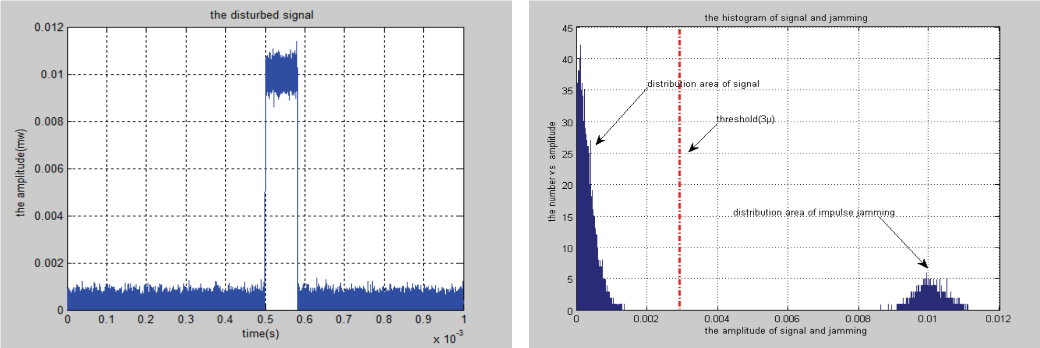


Fig. 1. Histogram of $|S(n)+N(n)|$.



(a) (b)

Fig. 2. (a) Time-domain waveform of $|S(n)+N(n)+J(n)|$ and (b) histogram of $|S(n)+N(n)+J(n)|$.

2.2 Multistage Pulse Jamming Suppression Algorithm

Owing to the randomness of duty ratio and appearance, the fluctuation characteristics of the envelope of pulse jamming, etc., the probability of missing the detection of a single jamming suppression is high. To improve the detection probability, the multistage jamming suppression method is adopted. The number of stage pulse jamming suppression algorithms depends on the actual jamming suppression effect.

The schematic diagram of the algorithm is shown in Fig. 3. Generally, there is a direct current (DC) component in the received signal. To estimate the jamming detection threshold accurately, the DC bias must be removed before the jamming suppression.

Fig. 4 demonstrates the schematic diagram of ith stage pulse jamming suppression which comprises setting the threshold, jamming detection, and jamming suppression. The pulse duty ratio is in the range of 1%–10%. If the pulse jamming in the time domain is set to zero, the energy loss of the satellite signal will be approximately 0.04–0.4 dB, which will not affect the functioning of the receiver. The threshold of each stage is 3μ, and if no jamming is detected, the input signal is output directly.

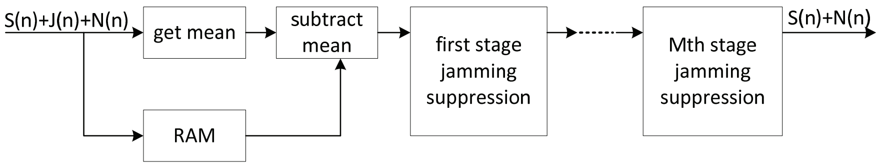


Fig. 3. Schematic diagram of the multistage time-domain pulse jamming suppression algorithm.

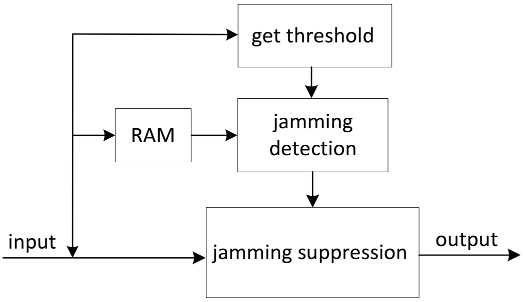


Fig. 4. Schematic diagram of *i*th-stage pulse jamming suppression.

3. Experiments

The experimental hardware platform was a four-element B3 anti-jamming antenna. One-stage and two-stage pulse jamming were used. Pulse jamming was generated by the signal source. The FPGA data after anti-pulse jamming were acquired using the chips-cop software. The anti-jamming effects of different duty ratios and JSR were compared.

Fig. 5 shows the anti-jamming effect when one-stage pulse jamming suppression is adopted; the power of pulse jamming is -60 dBm, JSR is 100 dB, period of pulse is 10 µs, pulse width is 1 µs, and duty ratio of the pulse is 10%. A few and large amplitudes of pulse remains can be seen in Fig. 5.

Fig. 6 shows the anti-jamming effect when two-stage pulse jamming suppression is adopted; the power of pulse jamming is -60 dBm, JSR is 70 dB, period of pulse is 10 µs, pulse width is 1 µs, and duty ratio of the pulse is 10%. The jamming is almost completely suppressed, as shown in Fig. 6. It can be noted that under the same experimental conditions, the effect of two-stage jamming suppression is better than that of one-stage jamming suppression.

Fig. 7 shows the anti-jamming effect when two-stage pulse jamming suppression is adopted; the power of pulse jamming is -30 dBm, JSR is 100 dB, period of pulse is 10 µs, pulse width is 1 µs, and duty ratio of the pulse is 10%. There is a small amount of residual, as shown in Fig. 7.

Fig. 8 shows the anti-jamming effect when two-stage pulse jamming is adopted; the power of the pulse jamming is -30 dBm, JSR is 100 dB, period of pulse is 10 µs, the pulse width is 0.5 µs, and duty ratio of the pulse is 5%. The jamming is almost completely suppressed as shown in Fig. 8.

Based on the experiments, we derived the following conclusions: (1) under the same experimental conditions, the effect of two-stage jamming suppression is better than that of one-stage jamming suppression, (2) under the same experimental conditions, when the jamming power is smaller, the suppression effect is better and the estimated threshold is more accurate, and (3) under the same experimental conditions, when the duty ratio is smaller, the suppression effect is better. This is because the smaller the duty ratio and amplitude of the pulse, the more approximate the Rayleigh distribution of $|S(n)+N(n)|$ and the higher the threshold estimation accuracy.

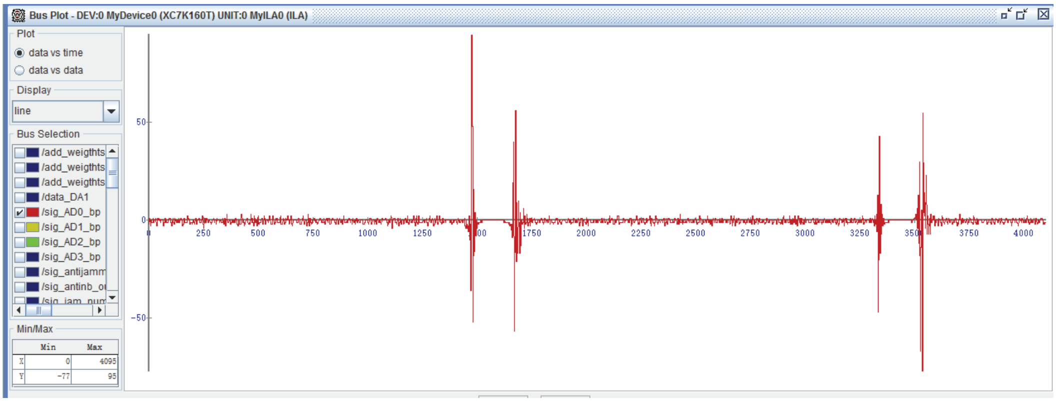


Fig. 5. Anti-jamming effect of one-stage pulse jamming suppression with JSR of 70 dB and duty ratio of 10%.

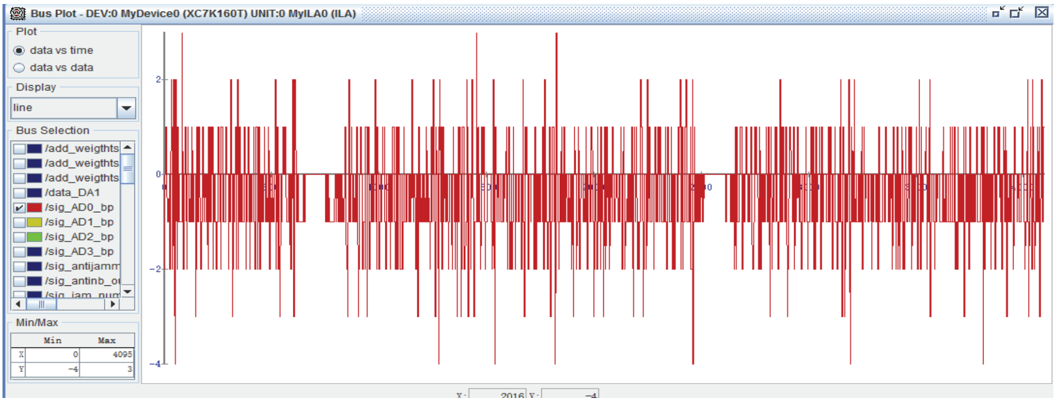


Fig. 6. Anti-jamming effect of two-stage pulse jamming suppression with JSR of 70 dB and duty ratio of 10%.

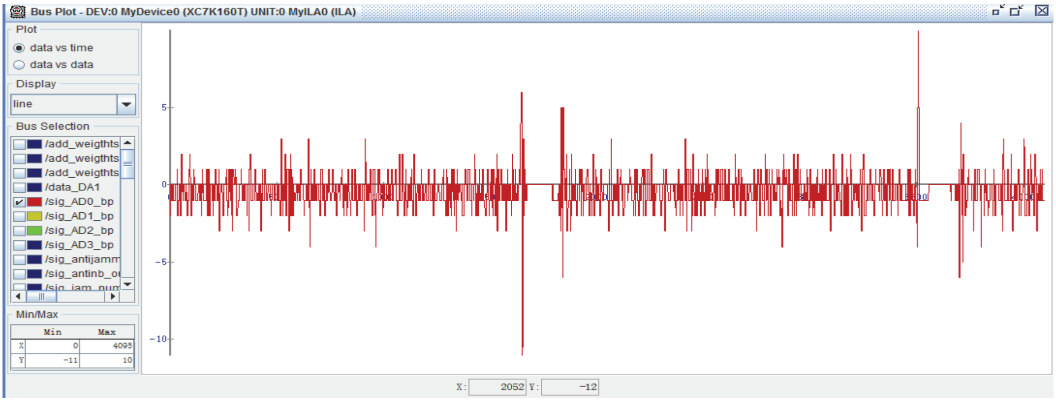


Fig. 7. Anti-jamming effect of two-stage pulse jamming with JSR of 100 dB and duty ratio of 10%.

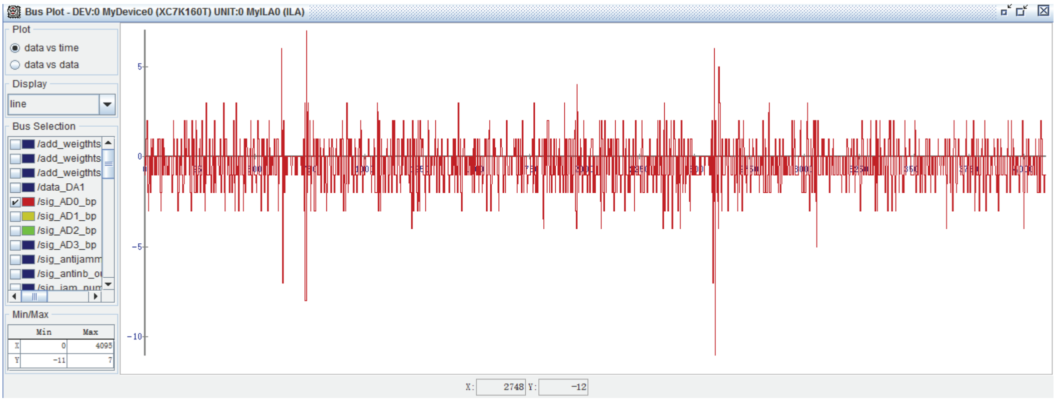


Fig. 8. Anti-jamming effect of two-stage pulse jamming suppression with JSR of 100 dB and duty ratio of 5%.

4. Conclusion

A new multistage pulse jamming suppression algorithm is proposed to solve the anti-jamming problem of the navigation receiver. The simulation results were consistent with the theoretical derivation. The following conclusions were obtained: (1) the effect of two-stage jamming suppression is better than that of one-stage jamming suppression, (2) when the jamming power is smaller, the suppression effect is better and the estimated threshold is more accurate, (3) when the duty ratio is smaller, the suppression effect is better, (4) if system source is enough, the algorithm can increase the filtering order to improve the interference suppression effect, thus making the processing flexible. In practical work, the anti-jamming stage can be determined based on actual needs to achieve the best anti-jamming effect, and (5) the algorithm has the characteristics of easy programming, simple threshold determination, and complete pulse jamming suppression.

The impulse jamming detection threshold of the algorithm was derived under the assumption of the Gaussian white noise. In the future, we will explore the impulse jamming suppression algorithm under a colored noise background.

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