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A Rapid Capture Method of Frequency Hopping Communication System in Airborne Data-Link

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Abstract. In frequency hopping communication systems, synchronization of frequency hopping sequences is a prerequisite for ensuring normal communication. In this paper, a rapid frequency hopping synchronization capture method is designed based on MSK modulation. A method of solving the constant false alarm threshold is given, and a set of high performance synchronization codes are selected. We assessed the effectiveness of the proposed process by simulation based on MATLAB and Vivado, and it can complete rapid synchronous capture in the frequency hopping communication system.

1. Introduction

Frequency hopping is a communication method in which the carrier frequency of signal changed by a predetermined pattern. Compared with fixed-frequency, frequency-hopping has great anti-interference ability and poor intercept probability, which can make the information detection, interception and interference difficult, and ensure the concealment and reliability of communication. In addition, the transmitting and receiving frequency has changed rapidly, which can effectively counteract the fading of signals and multipath interference caused by signal delay. Currently, frequency hopping communication has been widely used in military and civilian fields.

Synchronization of frequency hopping is a prerequisite for ensuring normal communication. At present, signal synchronization is one of the most critical and difficult technique in communication system [1]. Therefore, the quality and speed directly affect the performance of the frequency hopping communication system. With the improvement of frequency hopping technology, it is of vital importance to study the key technologies of frequency hopping synchronization and capture synchronous pulses rapidly [2].

In this paper, we have introduced some common frequency hopping capture algorithms at first. Then we propose a rapid frequency hopping capture algorithm based on MSK modulation pulse, and provide the solution of constant false alarm decision threshold and a set of high performance synchronization codes. Finally, the simulation results of the proposed process certificate its effectiveness and complete rapid synchronous capture of frequency hopping communication system.

2. Synchronous Capture Algorithm

The frequency hopping synchronization can be simply classified into independent channel method, reference clock method, synchronous prefix method, and self-synchronization method. Compared with other methods, the self-synchronization method does not require independent channel to transmit synchronization information, and the receiver completes synchronization by extracting the hidden synchronization information from the frequency-hopping signal.

The capture mode is mainly divided into serial search capture, parallel search capture, and complex search capture. The serial search capture technology can achieve easily but it takes a long time to capture. The parallel search capture technology can complete synchronous capture rapidly, but the technical implementation is relatively complicated [3].

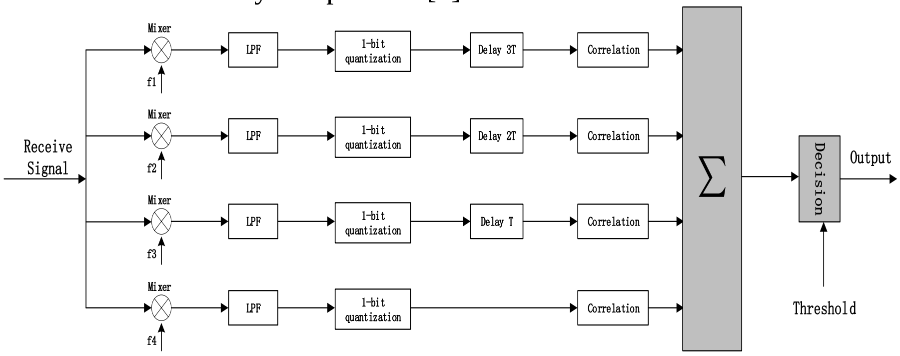

Figure 1. 4-way parallel capture structure

Based on a data-link system, this paper proposes an improved rapid frequency hopping capture method. The system structure is shown in Figure 1. Four-channel parallel capture mode has been adopted in this system, which uses four MSK frequency hopping pulses to complete the synchronous capture of the system. The hopping sequence generation of the entire communication system has a complete algorithms, which can make the hopping patterns of the four synchronization pulses completely different with subsequent message sequences. We can reduce the misjudgment probability by setting proper threshold of the constant false alarm decision. In addition, based on the constant envelope characteristics of the MSK modulated pulse, the sync pulse can be quantized rapidly, which make the synchronous capture faster. The next section will focus on the analysis of the constant false alarm decision threshold, the MSK pulse fast quantization method, and the synchronization codes selection.

3. The Key Methods

3.1 Constant False Alarm Threshold

The choice of the decision threshold affects the quality of the capture algorithm directly. The receiver's capture decision is based on two assumptions:

$$\begin{aligned} &H_0 : x[n] = w[n] \qquad && n = 0,1,...,N-1 \\ &H_1 : x[n] = s[n] + w[n] \qquad && n = 0,1,...,N-1 \end{aligned}, \tag{1}$$

where $s[n]$ is a known signal, $w[n]$ is zero-mean complex Gaussian white noise with variance of σ^2 [4]. H_1 indicates that a synchronization pulse arrives at receiver currently, while H_0 indicates that no sync pulse arrives. The capture performance is usually measured by the false alarm probability p_f and the missed detection probability p_m .

In the interference-free AWGN channel, we assume that the parallel capture structure contains N sync pulses and each pulse contains L_x bits. After time-delay and down-conversion the nth baseband signal is as followed,

$$r_n(t) = A_n g_n(t-\tau_n) e^{j\triangle\theta} + w(t), \tag{2}$$

where $\triangle\theta$ is the unknown phase offset, τ is the unified time-delay with the group delay of the sync pulses. Supposing $r_{n,i}$ is the ith received symbol of the nth pulse, and $s_{n,i}$ is the synchronization pulse symbol known to the receiver. Then the output value of the matched filter can be expressed as,

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$$M_n(\tau) = \frac{\left|\sum_{i=0}^{L_x} r_{n,i+\tau} s_{n,i}^*\right|^2}{\sigma^2} \tag{3}$$

N sync pulses' matching filtering output values is accumulated as detection amount β in the parallel capture structure, and then compare with the threshold γ .When assumption H_0 is true, $\beta / 2$ satisfies the central chi-square distribution with a degree of freedom of 2 [5], and the false alarm probability expression is:

$$P_f = \frac{\tau(1, \gamma / 2)}{\Gamma(1)} \tag{4}$$

When assumption H_1 is true, β is a non-central chi-square random variable [5]. Then the probability of missed detection can be written as follows:

$$\begin{aligned} P_m &= \Pr[\beta < \gamma \mid H_1] = 1 - Q_1(\sqrt{\lambda}, \sqrt{\gamma}) \\ \lambda &= \sum_{n=0}^{N-1} \frac{L_x A_n^2}{\sigma^2} \end{aligned} \tag{5}$$

3.2 Rapid Quantization Algorithm

The phase quantization method is more effective for the constant envelope MSK signal. The phase quantization method in the non-coherent digital correlation detector is theoretically analyzed in [6], and it is proved that uniform phase quantization is the best quantization method.

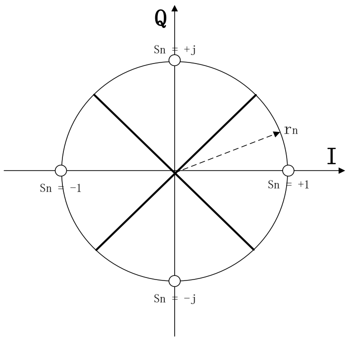

Figure 2. MSK four-phase quantization

Figure 2 shows that the phase of MSK waveform at the optimal sampling point is limited to $\{0, pi/2, pi, pi*3/2\}$, in other words the complex value $\{+1, -1, +j, -j\}$. Therefore, we can quantize the odd and even bits of the sync pulse sequence s_n as follows:

$$s_n = \begin{cases} (-1)^{n/2} g_n & when\ n\ is\ even \\ j(-1)^{(n-1)/2} g_n & when\ n\ is\ odd \end{cases}, \tag{6}$$

where g_n represents the synchronization pulse sequence information bits.

In the in-phase and quadrature components, the quantized sequence Sn contains only two values $\{+1, -1\}$. In the parallel capture, the in-phase and quadrature component of the received signal can be quantified as the value of +1 or -1.

$$r_n = \begin{cases} 1 \cdot \mathrm{sgn}[real(r(n))], & |real(r(n))| \ge |imag(r(n))| \\ j \cdot \mathrm{sgn}[imag(r(n))], & |real(r(n))| < |imag(r(n))| \end{cases}, \tag{7}$$

where $real(x)$ represents the in-phase component of the received signal, $imag(x)$ represents the quadrature component of the received signal, and $\mathrm{sgn}(x)$ is the sign function.

After quantization, we can only implement a simple addition and subtraction operation rather than a high bit width multiplication operation in the matched filter, which can greatly reduce the calculation amount and improve the calculation efficiency. Then the quantized detection statistic T_0 can be expressed as:

$$\begin{aligned} \mathrm{T}_0(\tau) &= \left|\sum_{i=0}^{L_x-1} r_{i+\tau} s_i^*\right| \\ &= \left|\sum_{i=0}^{L_x/2-1} (-1)^i g_{2i} r_{2i+\tau} - j\sum_{i=0}^{L_x/2-1} (-1)^i g_{2i+1} r_{2i+1+\tau}\right| \\ &= \left|\sum_{i=0}^{L_x/2-1} [(-1)^i g_{2i} r'^{I}_{2i+\tau} + (-1)^i g_{2i+1} r'^{Q}_{2i+1+\tau}] + j\sum_{i=0}^{L_x/2-1} [(-1)^i g_{2i} r'^{Q}_{2i+\tau} - (-1)^i g_{2i+1} r'^{I}_{2i+1+\tau}]\right| \end{aligned} \tag{8}$$

3.3 Selection of Synchronization Codes

Reasonable synchronization codes are of vital importance to ensure the communication frame being received successfully. The quantity and reliability of synchronous capture is mainly evaluated by the correlation performance between the capture codes [7]. Firstly, the autocorrelation function of the synchronization sequences needs to have sharp unimodal characteristics. Secondly, it is easy to distinguish from the information codes. Thirdly, the code length is appropriate to ensure transmission efficiency.

In practical engineering, we usually use pseudo-random sequences as synchronization codes. The selection of pseudo-random sequences usually includes the following characteristics:

（1）Balance: the number of 0 and 1 is nearly equal in the sequence;

（2）Run-length characteristics: the run-length of n accounts for $1/2^n$ of the total number of run-lengths;

（3）The random sequence cyclically shifts any element and only half of the elements are identical to the original sequence.

Under the condition of satisfying the above pseudo-random code characteristics, the synchronization codes also need to ensure good cross-correlation performance with the 32-group CCSK codes of the data segment. The four synchronization codes selecting from the m-sequence generated by the (11, 2, 0) primitive polynomial are shown in Table 1.

Table 1. Synchronization Codes Table

Sync code 1	Sync code 2	Sync code 3	Sync code 4
D9368715	38AC11FD	44DF498B	F498BC13

The XNOR operation results between the 4 synchronization codes and 32 CCSK codes have been shown in Figure 3. The selected pseudo-random synchronization codes have good cross-correlation performance with the data segment CCSK codes. Therefore, a reasonable setting of the correlation threshold can effectively reduce the interference of the data segment to the sync segment.

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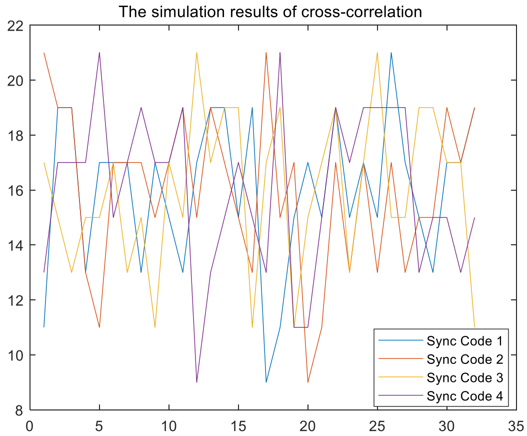

Figure 3. The simulation results of cross-correlation

4. Simulation Results

Based on a data-link frequency hopping communication system, we use a modified 4-parallel capture algorithm for synchronous capture. The sync structure contains a total four sync pulses, which are consist of 32-bits MSK modulated signals. After four times oversampling, the rapid quantization algorithm is used to quantize the synchronization pulse. Whether the synchronization is completed is determined by the relevant accumulated value and the threshold value.

MSK signals of chip rate 5 Mbps , 100 times modulation oversampling and 4 times synchronization oversampling are used in timing synchronization performance simulation. The synchronization correlation curve without phase deviation with the SNR of 5dB and 20dB is shown in Figure 4, which shows that the synchronous detection algorithm has a high correlation and the capture of the frequency hopping frame is completed at the synchronization point.

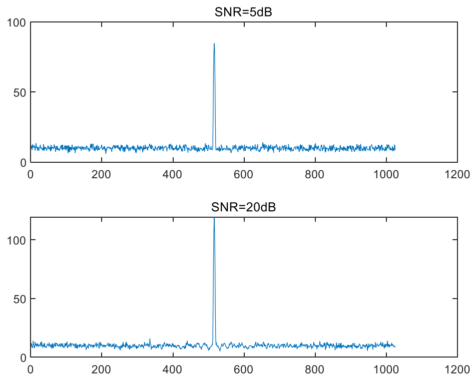

Figure 4. Synchronization Correlation Curve

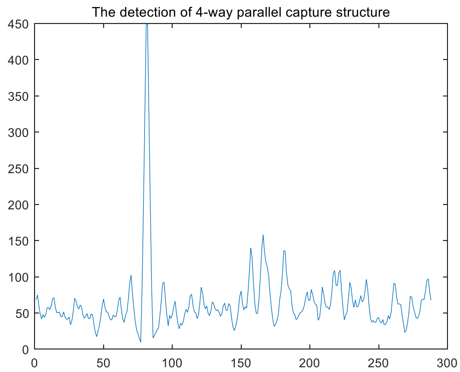

Figure 5. The detection of 4-way parallel capture structure

Multiple factors such as the false alarm probability, the missed detection probability, and the cross-correlation threshold between synchronous codes and data segment, play an important role in the comprehensive consideration of threshold setting. With engineering experience, we set the threshold as 380. Figure 5 shows the simulation result of matched filter detection value, where the SNR of the captured pulse is 20dB and the group delay is consistent. The results shows that the synchronous sequences have good auto-correlation, and the peak of correlation accumulation can be significantly higher than its side lobe value. Therefore, with a reasonable detection threshold settled, the algorithm can ensure the stability of synchronization performance of the receiver.

In the hardware implementation, we choose Xilinx XC7K410T as the signal processing core unit, which has rich logic resources and multiply-add operation units. The project is written by VHDL language and developed by VIVADO2017.4, which is Xilinx's proprietary design tool. We tested the performance of the improved system after adding other corresponding prerequisite modules. The results of the synchronous capture module are shown in Figure 6. The test results show that the 4-way parallel capture structure has good synchronous capture performance, and can accurately complete the parallel capture of sync pulses, and also has a good hardware implementation basis.

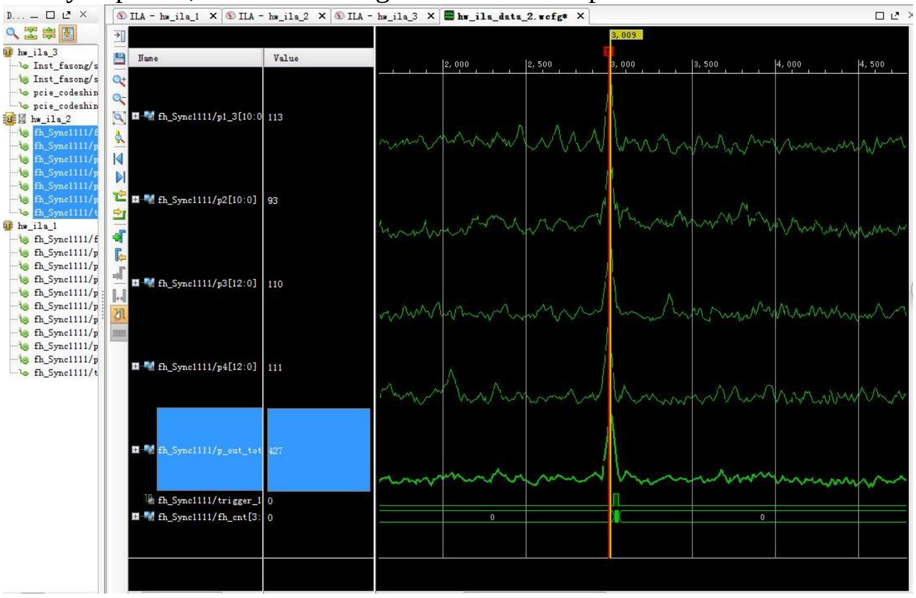

Figure 6. The results of parallel capture in VIVADO2017.4

5. Conclusion

Aiming at the synchronization capture problem of frequency hopping communication system, this paper introduces the solution of constant false alarm decision threshold and the rapid quantization algorithm of MSK pulse. We also give a set of high-performance synchronization codes and propose a 4-way parallel synchronization capture algorithm for a data-link system. The results of the simulation suggest that the algorithm has the ability to rapidly capture the frequency hopping synchronization pulse and can capture the pulse with relatively less system resources. Meanwhile, the algorithm also possesses fast and reliable synchronization performance together with a good hardware implementation basis, which can meet the rapid synchronization capture requirements of the frequency hopping data-link system.

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