A Study on One Fast Acquisition Method for DS/FH Hybrid Spread Spectrum Signal in Physical Layer of Aircraft Communication Network

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***Abstract*—In order to meet the requirements of large dynamic and short acquisition time of DS/FH hybrid spread spectrum signal in the physical layer of aircraft communication network, this article proposes a fast acquisition method based on digital wideband sampling and pseudo noise code phase search via Fast Fourier Transform (FFT) in frequency domain. This method highlights parallel reception on synchronous hopping frequencies, all-phase search on pseudo noise code phases, and sequential scanning on Doppler frequency of pseudo noise code. This method turns the 3D search process consisting of hopping frequency, pseudo noise code Doppler frequency, pseudo noise code phase into 1D search while performing DS/FH signal acquisition, as the theoretical analysis and calculated results indicated, the acquisition time performance by such method is improved in a large scale.**

Keywords—Aircraft Communication Network; DS/FH Hybrid Spread Spectrum; Fast Acquisition

I. INTRODUCTION

The aircraft communication network, a key supporting technology for new application modes such as UAS swarms autonomy and collaborative operations, Loyal wingman and Satellite constellation reconnaissance, has recently become a research focus. To meet the requirements of running in complex electromagnetic conditions, DS/FH hybrid spread spectrum signal with excellent anti-interference capability has been considered as a preferred choice in the physical layer of aircraft communication network. DS/FH hybrid spread spectrum signal acquisition is a 3D search process consisting of hopping frequency, pseudo noise code Doppler frequency and pseudo noise code phase, particularly, in the application of aircraft communication network, it has to meet the requirements on large dynamic signal and short acquisition time, which means the fast acquisition, as a key factor, determines the network availability.

At present, the main idea for fast acquisition method involving to DS/FH hybrid spread spectrum signal is to change the 3D search as a 2D search, such as frequency waiting search method [1], in which the receiver is waiting at one hopping frequency while performing pseudo noise code acquisition, the acquisition time is in direct proportion to frequency hopping pattern period, only applicable to DS/FH hybrid system with shorter frequency hopping pattern period. The fast frequency identification method [2] [3] [4] [5] improves frequency hopping rate at receiver (H times of transmitter) on the base of waiting search method, capable of quick scanning for the signal received, and shortening the frequency hopping acquisition time, however, it is subject to the pseudo noise code acquisition time. Pseudo noise code parallel acquisition method [6], a method based on PMF-FFT or frequency domain code phase acquisition, changes the 2D search through code phase and Doppler frequency to a 1D search, however, it fails to improve the hopping frequency search rate.

In combination with the design characteristics of physical layer in an aircraft communication network, this article, based on wideband digital sampling and pseudo noise code phase search via Fast Fourier transform(FFT) in frequency domain, achieved parallel acquisition for synchronous hopping frequency and pseudo noise code phase, and changed 3D search to 1D search on Doppler frequency, thus significantly improved average acquisition time performance.

II. WAVEFORM DESIGN AT PHYSICAL LAYER

This article aims at the study of an aircraft communication network using the Dynamic Time Division Multiple Access (D-TDMA) scheme. With a hybrid spread spectrum mode of both FH and DS spread spectrum applied to physical layer in this network, it is capable of excellent low-interception probability and anti-interference performance, and at least 12 users permitted online at the same time , with time frame period of 1s, consisting of 16 time slot(s) for each time-frame and 62.5ms for each time slot period.

The structure of time frame and time slot, as shown in Fig 1, consists of 6 hops of synchronous segment, 12 hops of duty segment, 96 hops of data segment and 1.7ms propagation guard interval.

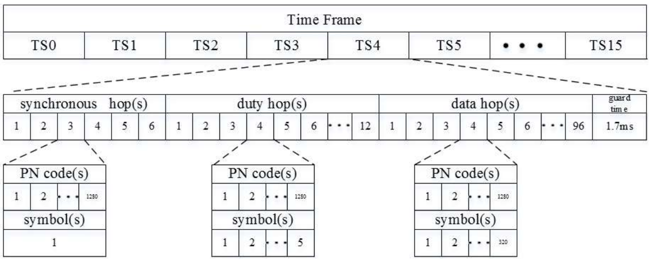

Fig. 1. Physical layer time frame and time slot structure

All hopping periods are defined as 0.53ms, pseudo noise code rate as 2.4Mcps, and the code length as 1280. Each hop of synchronous segment modulates 1280 pseudo noise code chips and 1 information symbols; each hop of duty segment modulates 1280 pseudo noise code chips and 5 information symbols; each hop of data segment modulates 1280 pseudo noises code chips and 320 information symbols.

Different frequency hopping patterns are used for synchronous segment, duty segment and data segment; however, the three frequency hopping patterns use the same time-base. The physical layer works with a frequency hopping bandwidth of 200MHz, and uses frequency hopping points, of which 6 frequency points are used in synchronous segment, 12 frequency points are used in duty segment, and all frequency points are used in data segment.

The physical layer of the network is applicable to the doppler frequency of not less than ±50kHz, with receiver sensitivity of -112dBm.

III. Design Principles for Fast Acquisition of DS/FH Signal

The acquisition methods for DS/FH signal are divided into two major categories, respectively sequence acquisition and parallel acquisition, in which the sequence acquisition requires less amount of hardware resources, however, one frequency or one pseudo noise code phase(or doppler frequency) can be solely acquired each time, with slow acquisition speed. Parallel acquisition is capable of acquiring multiple frequencies or pseudo noise code phases(or doppler frequencies) simultaneously, at the cost of more hardware resources for fast acquisition speed [4]. Through overall consideration of hardware resources and network performance, this article proposes a hybrid acquisition scheme where hopping frequency and pseudo noise code phase are subject to parallel acquisition and pseudo noise code doppler to sequence scanning, which assures engineering practice while shortening the acquisition time.

The acquisition scheme, as shown in Fig. 2 proposed in this article utilizes RF integrated transceiver(e.g. ADRV9009 from Analog Devices) to carry out wideband digital sampling on whole hopping frequency band, which can receive all of the hopping signals simultaneously, and this avoids two major disadvantages in analog channelization equipment (large volume and high power consumption) while assuring the synchronous acquisition of frequency. 6 pseudo noise code acquisition modules realize the parallel reception of synchronous signals by digital down conversion tuning on 6 hopping frequencies of synchronous segment. The acquisition results of 6 pseudo noise code acquisition modules are added together, after which the threshold decision is made to confirm the acquisition.

The applicable bandwidth of this scheme can be extend to more than 200MHz by parallel RF integrated transceivers.

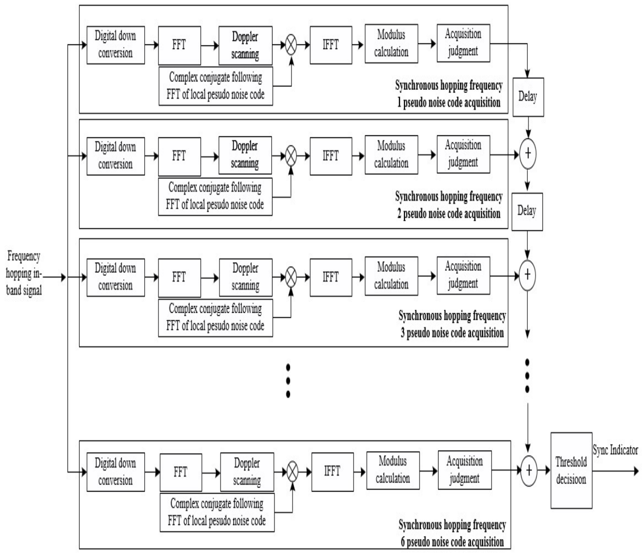

Fig. 2. Hybrid acquisition scheme of DS/FH signal

Since 6 synchronous hop(s) signals are received in a parallel mode, the signal acquisition is simplified as that of pseudo noise code. The digital down converter works at nominal frequency point of the synchronous frequencies, which is unable to eliminate the Doppler frequency due to relative motion of the aircrafts. In order to reduce the loss caused onto pseudo noise code correlation peak by Doppler frequency [7], the pseudo noise code acquisition must carry out 2D search through Doppler frequency and pseudo noise code phase. In order to shorten acquisition time, industry experts have proposed fast Doppler frequency search represented by partial matched filtering (PMF) method and the fast code phase search method represented by Fast Fourier Transform (FFT) of frequency domain.

This article uses frequency domain Fast Fourier Transform (FFT) method, and its fundamental principles are as follows.

In order to search all code phases in pseudo noise code period simultaneously, it is necessary to circulate local pseudo noise code phase to correlate with the code received. The maximum correlation peak is generated as the local code is completely consistent with the pseudo code phase received, as shown in Fig. 3.

The process of cyclic convolution can be expressed as the following formula:

$$R(m)=\sum_{i=1}^{L}S(i)PN(i+m), m=0,1,\cdots,L-1 \quad (1)$$

Where: L is the length of relevant pseudo code sequence.

Obviously, large number of calculations are required if the above formula is calculated directly, which is directly proportional to L^2; however, the operation time will be greatly shortened if the cyclic convolution of time domain is converted to frequency domain and Fast Fourier Transform (FFT) is used for calculation. Its mathematical principle is as Eq. (2).

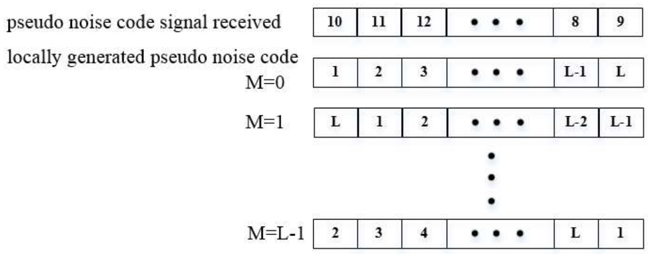

Fig. 3. Pseudo noise code phase search algorithm

$$\begin{aligned} R(m) &= \sum_{i=0}^{L-1} S(i)PN(i+m) \\ &= S(i) \otimes PN(-i) \\ &= IFFT(FFT(S(k)) \bullet FFT^*(PN(k)) \end{aligned} \tag{2}$$

This method uses cyclic convolution of time domain being equivalent to multiplication of frequency domain to complete one operation, with all pseudo noise code phase acquisitions. The amount of calculation is reduced from L^2 to L*1n L, which significantly reduces acquisition time. Doppler frequency acquisition is achieved by sequential frequency scanning, which reduces resource consumption.

The basis of acquisition for synchronous segment signals is carrier envelope of signals (modulus $|I^2+Q^2|$ followed by despreading and coherent integration of I and Q signals.) If the envelope exceeds threshold, it is determined that there is a signal at such frequency point, which is recorded as "1"; if the threshold is not exceeded, it is determined that there is no signal at such frequency point, which is recorded as "0". M-out-of-N joint detection is carried out for 6 frequency points afterwards. If the detection results of several frequency points exceed the threshold, it is determined that the synchronous segment signals is detected and the acquisition is successful; If the threshold is not exceeded, it is determined that the synchronous segment signals is not detected, and the acquisition shall continue.

IV. Analysis of Acquisition Performance

A. Analysis of coherent integration time, doppler frequency scanning interval and signal-to-noise ratio

The detection object for pseudo noise code acquisition refers to the coherent integration results of carrier signal following despreading. The so-called coherent integration is the accumulation of carrier signal in the pseudo noise code segment participating in despreading, and the amplitude (denoted by Ap(n)) is affected by Doppler frequency (denoted by f_e), coherent integration time (denoted by T_{coh}) and information symbol (denoted by D(n))[7].

$$Ap(n) = aD(n)\sin c(f_e T_{coh}) \tag{3}$$

Coherent integration is generally carried out as the information symbol remains unchanged. The amplitude of coherent integration result is only limited by Doppler residual and correlation integration, as shown in the Fig. 4. In order to control the loss in 3dB, it shall be achieved $f_e T_{coh} \leqslant 0.5$ generally. Considering the unmodulated information of synchronous segment, all of them can be used for coherent integration. This design selects the Doppler frequency scanning interval of 3.4 kHz (±1.7kHz), correlation loss of 10dB, and 30 frequency scanning points in total, which is able to cover the Doppler frequency range of ±50kHz.

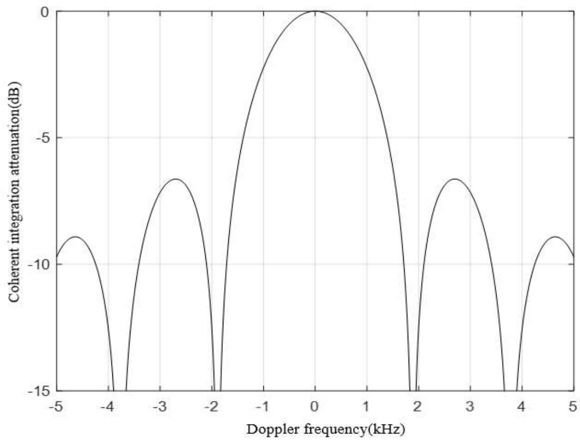

Fig. 4. Coherent integration attenuation due to doppler frequency and coherent integration time

As for the aforesaid pseudo noise code fast acquisition algorithm, the number of pseudo noise code chips involved in acquisition operation determines coherent integration time. This article provides overall considerations on acquisition time, detection performance and doppler residual scanning interval of 3.4kHz. Therefore, the coherent integration time T_{coh} is 0.53ms.

The carrier power to noise power spectral density ratio after low noise amplifier is deifined as Eq.(4):

$$\begin{aligned} C/N_0 &= C/kT_0F \\ &= 10\log_{10}(C) - 10\log_{10}(kT_0) - 10\log_{10}(F) \end{aligned} \tag{4}$$

Where C is the carrier power, k is the Boltzmann's constant, which is equal 1.379×10^{-23}, T_0 is the reference temperature, which is equal 290K, F is the noise figure of receiver. Subject to the reception carrier power is -112dBm and noise figure of receiver is 3dB, the reception C/N0 = -112dBm-(-174dBm/Hz+3dB)=59dBHz。

The carrier power to noise power ratio or Signal-to-Noise Ration after coherent integration is deifined as Eq.(5):

$$\begin{aligned} C/N &= C/N_0T_{coh} \\ &= 10\log_{10}(C/N_0) - 10\log_{10}(T_{coh}) \end{aligned} \tag{5}$$

According to the foregoing conditions, C/N = 59dBHz-$10\log_{10}(1/0.53\text{ms})$-10dB=16dB.

B. Analysis of acquisition probability and false alarm probability of pseudo noise code acquisition module

The detection for one pulse of synchronous segment is one of typical binary signal detection, and the relationship between its detection probability and false alarm probability is as Eq.(6)[8].

$$P_d = Q[\sqrt{2SNR}, \sqrt{-2\ln(P_{fa})}] \tag{6}$$

Where: P_d denotes detection probability; P_{fa} denotes false alarm probability; Q denotes Marcum Q function; SNR denotes signal-to-noise ratio, i.e. C/N mentioned in the previous text. As shown in Fig. 5, when the signal-to-noise ratio is 16dB and the false alarm probability is 1×10^{-6} as calculated, the detection probability is 0.99986.

C. Analysis of Joint detection probability and false alarm rate

The M-out-of-N method is used for joint detection on the basis of parallel reception of synchronous frequency points so as to further reduce the probability of false alarm. The total false alarm probability and total detection probability of N tests are respectively Eq. (7), Eq. (8)[9].

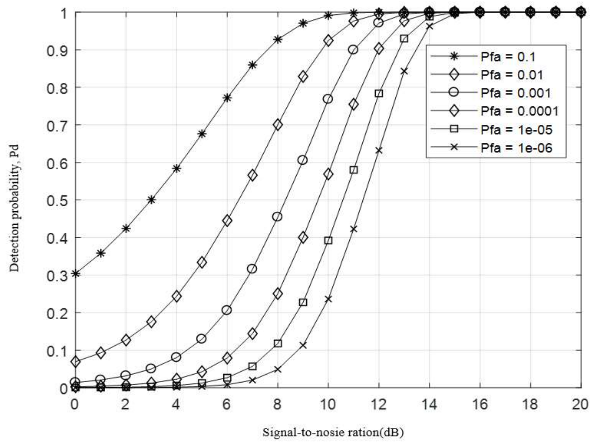

Fig. 5. Relationship between detection probability, false alarm probability and Signal-to-Noise Ratio of single pseudo noise code acquisition module

$$P_D = \sum_{n=M}^{N} C_N^n P_d^n (1-P_d)^{N-n} \quad (7)$$

$$P_{FA} = \sum_{n=M}^{N} C_N^n P_{fa}^n (1-P_{fa})^{N-n} \quad (8)$$

Subject to the pseudo noise code acquisition module detection probability of 0.99986 and false alarm probability of 1×10^{-6}, 6 synchronous frequencies are used for joint detection, and the total detection probability reaches close to 1 and the total false alarm probability reduces to 1.5×10^{-11} as 2 frequency points exceed threshold.

D. Analysis of average acquisition time

The average acquisition time for DS/FH signal under single dwell sequential search adopt hopping frequency waiting search method is as Eq. (9)[10]:

$$\overline{T} \approx \frac{(2-P_d)(KP_{fa}+1)MQt_D}{2P_d} + \frac{(N-1)T_h}{2} \quad (9)$$

Where: N, M and Q denote the number of frequency hopping points, number of search units for Doppler and code phase respectively, with signals uniformly distributed on each unit. T_h denotes frequency hopping gap. t_D denotes dwell time. K is the penalty factor for false alarm. The formula indicates that the average acquisition time for hopping spread spectrum signal is composed of two parts: DS 2D acquisition contribution and FH acquisition contribution.

The average acquisition time for DS/FH signal under single dwell sequential search adopt fast frequency identification method is as Eq. (10)[2]:

$$\overline{T} \approx \frac{(2-P_d)(KP_{fa}+1)MQt_d}{2P_d} + \frac{(N-1)T_h}{2H} \quad (10)$$

Where: H is the ratio of receiver hopping rate to transmitter hopping rate.

With respect to the method proposed in this article, 6 synchronous hopping frequencies are subject to parallel acquisition, and the pseudo noise code phase of each frequency point is subject to parallel search. It can be considered that both N and Q are 1, M is 30, and the average acquisition time degenerates into the average acquisition time for one-dimensional acquisition of doppler frequency, is as Eq. (11).

$$\overline{T} \approx \frac{(2-P_D)(KP_{FA}+1)Mt_D}{2P_D} \quad (11)$$

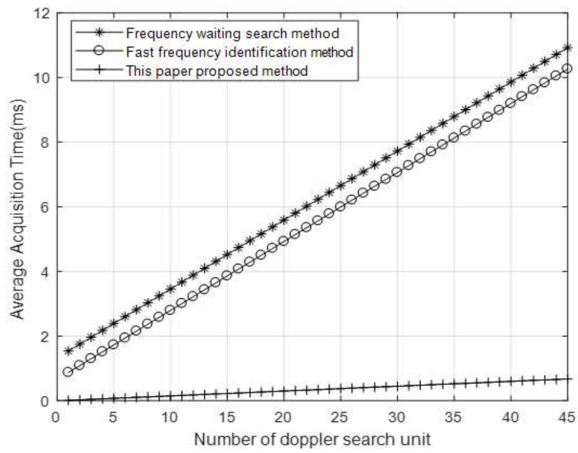

Fig. 6. Simulation result of average acquisition time for three methods

FPGA device is used to carry out pseudo noise code frequency domain FFT and IFFT calculation, with single dwell time reaching 30μs. Subject to the total detection probability of 1 and total false alarm probability of 1.5×10^{-11}, the average acquisition time approximately 0.45ms, which greatly improves performance compared with the average acquisition time in frequency waiting search method 7.7ms or fast frequency identification method 7.0ms(under the condition where N is 6, M is 30, Q is 1024, H is 2, t_D is single dwell time of one chip cycle, P_d is 0.99986, P_{fa} is 1×10^{-6}).

Fig 6 shows that the method proposed by this paper has the best average acquisition time performance, which at the cost of requiring largest amount of hardware resources.

V. Conclusions

This article proposes a fast acquisition method based on digital wideband sampling and frequency domain Fast Fourier Transform (FFT) of direct sequence spread spectrum pseudo noise code for aircraft communication network and carries out calculation and analysis on relevant design parameters. The results indicate that the average acquisition time can be improved from 7.0ms as required for conventional sequential method to 0.45ms, which greatly improves its performance.

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