SIMULATION OF QPSK LARGE FREQUENCY OFFSET CARRIER RECOVERY BASED ON FFT

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Abstract: In aerospace telemetry, there is usually a large Doppler frequency offset, and the receiver QPSK demodulator cannot perform carrier recovery. So the large frequency offset compensation is needed. In this paper, a large frequency offset extraction method using fast Fourier transform and phase lock loop is proposed. Based on the QPSK modulation signal, a complex signal containing frequency offset information is constructed, and then the value and the sign of frequency offset is calculated by fast Fourier transform. At last, the phase error will be eliminated by PLL. The utility model has the advantages of high estimation accuracy, large capture range and short lock time. The good performance of this method for large frequency offset carrier recovery is manifested in the simulation. It can be applied to signal synchronous demodulation in satellite communication.

Keywords: quadrature phase shift keying (QPSK); large frequency offset; carrier recovery; fast Fourier transform (FFT); simulation

Introduction

QPSK modulation is easy to implement and has good anti-jamming performance and spectrum utilization, so it is widely used in digital satellite communication systems. Coherent signal demodulation technology is usually used to demodulate QPSK signal. This technology has strict requirements for synchronization of the carrier signal, so carrier recovery is a key part for coherent demodulation. In the spaceflight communication system, the Doppler large frequency offset caused by the relative motion between the ground receiver and the spacecraft has a great influence on the carrier recovery, which can cause the failure of receiver demodulation. The traditional large frequency offset capture technologies are: the frequency lock loop (FLL), the frequency scanning and so on. The FLL technology is proposed in reference [1]. Carrier frequency will be traced directly by FLL, and its discriminator outputs the carrier frequency error and has good dynamic performance. But frequency lock loop has poorer performance than PLL in precision. A method of combining FLL and PLL is proposed in the paper [2].Taking into account the frequency discrimination range and tracking accuracy, this method will make the carrier tracking loop order and parameters increase resulting in difficulties in design and adjustment. The frequency scanning method is proposed in the work [3], the method is simple, and it can be used in high and low signal to noise ratio of the occasion. But it needs pre-established scan range and step size. In this paper, a large frequency offset carrier recovery method based on FFT is proposed, it uses FFT algorithm to calculate the absolute value and symbol of the carrier frequency offset accurately. Then the carrier frequency offset will be compensated, combined with the PLL to improve phase accuracy. Fewer parameters, larger capture range, and less lock time are the advantages of this method.

Carrier recovery design and principles

The design block diagram of QPSK large frequency offset carrier recovery based on FFT is shown in Fig. 1.

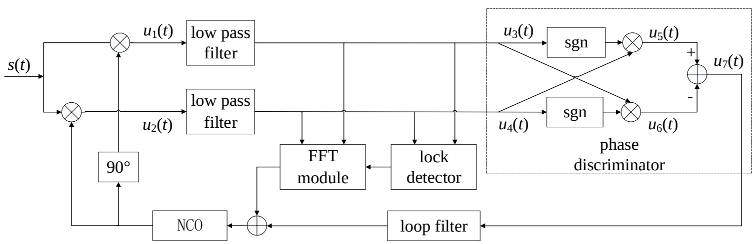


Fig.1. Realization diagram for QPSK large frequency offset carrier recovery.

First of all, QPSK signal will multiply with local carrier generating two signals by passing low-pass filter. The lock detector is used to detect whether the carrier frequency offset is within the bandwidth of the PLL filter or not, and if not, the carrier frequency offset can be identified as a large frequency offset. The FFT processing module will be switched on by lock detector. A complex signal containing frequency offset information is constructed with two signals mentioned above by the FFT processing module. FFT operator will be done to get the spectrum after collecting in a certain number of points, the spectrum is single sideband spectrum related to sign of carrier frequency offset. The value and sign of carrier frequency offset can be calculated by searching for the peak which corresponds to the frequency in the spectrum. Finally, the frequency offset will be compensated to the numerically controlled oscillator (NCO), the offset between the NCO center frequency and input carrier frequency will be within PLL bandwidth. After the large frequency offset compensation, FFT processing module will be switched off. The phase offset will be eliminated by PLL. When the discriminator output error tends to be zero, QPSK carrier frequency offset recovery is achieved. Each module principles are illustrated below.

A. COSTAS cross loop

The basic principle for carrier recovery is to use a modified Costas loop - COSTAS cross loop, suppose the QPSK signal $s(t)$ received is：

$$s(t) = I(t)\cos(\omega_c t + \varphi_0) + Q(t)\sin(\omega_c t + \varphi_0) \tag{1}$$

In the above equation, $I(t)$ and $Q(t)$ are divided in accordance with the even and odd order, they can be +1 or -1; ω_c is the carrier frequency; φ_0 is the modulation carrier initial phase.

$sin(\omega_c t + \varphi_1)$ is the local carrier, φ_1 is the local carrier initial phase. The low-pass filters output are:

$$u_3(t) = \frac{1}{2} I(t)\sin(\Delta\varphi) + \frac{1}{2} Q(t)\cos(\Delta\varphi) \tag{2}$$

$$u_4(t) = \frac{1}{2} I(t)\cos(\Delta\varphi) - \frac{1}{2} Q(t)\sin(\Delta\varphi) \tag{3}$$

In the above equations, $\Delta\varphi = \varphi_1 - \varphi_0$ is the phase offset between the local coherent carrier and the received carrier.

Phase detector output is as follows:

$$u_7(t) = \text{sgn}[u_3(t)] \cdot u_4(t) - \text{sgn}[u_4(t)] \cdot u_3(t) \tag{4}$$

Through calculation, discriminator output can be obtained as below:

$$u_7(t) = \begin{cases} -\sin\Delta\varphi & \Delta\varphi \text{ in the 8th and 1st regions} \\ \cos\Delta\varphi & \Delta\varphi \text{ in the 2nd and 3rd regions} \\ \sin\Delta\varphi & \Delta\varphi \text{ in the 4th and 5th regions} \\ -\cos\Delta\varphi & \Delta\varphi \text{ in the 6th and 7th regions} \end{cases} \tag{5}$$

COSTAS cross loop phase curve is similar to a saw tooth wave, and the subarea of $\Delta\varphi$ and the phase curve are given in the paper [4]. In addition, the ideal second-order ring performance is far superior to other second-order ring loops, so ideal second-order ring is adopted as loop filter in this paper.

B. Lock detector

FFT processing module will be calculated only once and will get an accurate value of carrier frequency offset, so a lock detector that can detect the carrier frequency offset is needed. When the carrier frequency offset is within the PLL filter bandwidth, the FFT processing module will be switched off. The FFT processing module will be switched on by the lock detector only when the carrier frequency is too large. This will reduce the resource overheated and improve the performance of the carrier recovery system when the carrier frequency is too small. The block diagram of the lock detector is shown in Fig. 2.

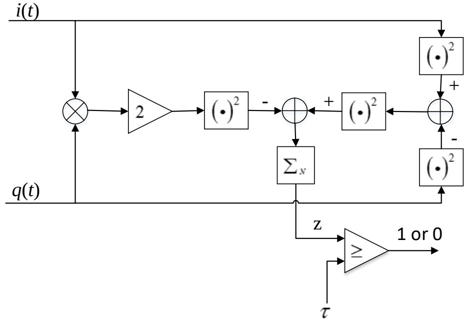


Fig.2 Structure diagram for lock detector.

The two signals input to the lock detector which are mixed and filtered by low-pass filter are:

$$i(t) = \frac{1}{2} I(t)\cos(\Delta\omega t + \Delta\varphi) - \frac{1}{2} Q(t)\sin(\Delta\omega t + \Delta\varphi) \tag{6}$$

$$q(t) = \frac{1}{2} I(t)\sin(\Delta\omega t + \Delta\varphi) + \frac{1}{2} Q(t)\cos(\Delta\omega t + \Delta\varphi) \tag{7}$$

In the above equations, $\Delta\omega$ is the frequency offset between the local coherent carrier and the received signal, and $\Delta\varphi$ is the phase offset between the local coherent carrier and the received signal.

The lock detector performs the following operations to remove the influences of I (t) and Q (t) so that the output is only related to the frequency offset and phase:

$$\left[2i(t)q(t)\right]^2 - [i^2(t) - q^2(t)]^2 = \frac{1}{4}\cos[4(\Delta\omega t + \Delta\varphi)] \tag{8}$$

When the loop is in the unlocked state, and the value of $\Delta\omega$ is not zero and the mathematical expectation of the above formula will be zero. In contrast, when the loop is locked, the mathematical expectations are not zero. So when the carrier frequency offset is large, lock detector will output 1, and the FFT processing module will be switched on. After the carrier is recovered, lock detector will output 0 and the FFT processing module will be switched off.

C. FFT frequency offset estimation algorithm

As a common tool for digital signal processing, FFT has been widely used in the field of spectrum analysis with its fast operation and low signal to noise ratio threshold.

On the basis of equations (10) and (11), sinusoidal signals including frequency offset and phase offset are obtained by the following operation:

$$2q(t)i(t)\cdot[q^2(t) - i^2(t)] = \frac{1}{4}\sin[4(\Delta\omega t + \Delta\varphi)] \tag{9}$$

Equation (11) and (12) are combined to be a complex signal x(t):

$$x\left(t\right) = \frac{1}{4}\cos[4(\Delta\omega t + \Delta\varphi)] + \frac{j}{4}\sin[4(\Delta\omega t + \Delta\varphi)] \tag{10}$$

Amplitude-frequency characteristic $X(\omega)$ of $x(t)$ can be obtained by FFT:

$$X(\omega) = \frac{\pi}{4}\delta(\omega - 4\Delta\omega) \quad , \tag{11}$$

where $\delta(t)$ is the impulse function and its expression is:

$$\delta(t) = \begin{cases} 1 & t = 0 \\ 0 & t \neq 0 \end{cases} \tag{12}$$

The estimated value $\Delta\omega$ of the corresponding carrier frequency offset is obtained by searching the peak value in the amplitude-frequency characteristic, and this is added as the carrier recovery compensation to the frequency control of the NCO. In practical applications, the above operations are performed in discrete domain. It is supposed that the signal $x(t)$ corresponds to the discrete domain signal $x(n)$, and the amplitude-frequency characteristic $X(\omega)$ corresponds to $X(k)$. The amplitude-frequency characteristic $X(k)$ of $x(n)$ can be obtained by N points FFT operation. When $X(k)$ reaches the maximum value, the frequency value which the value of k corresponds to is the carrier frequency offset estimated absolute value, and because the discrete Fourier transform of the complex signal is a unilateral spectrum, so when the k value is between 0 and $N/2$, the sign of carrier frequency offset is positive, and when the k value is between $N/2$ and N, the sign of carrier frequency offset is negative.

Simulation and validation by Simulink

The carrier recovery loop simulation model built in Simulink is shown in Fig. 3. In the model, the QPSK modulation signal with symbol rate of 1Mbps, carrier frequency of 10MHz and sampling rate of 40MHz is generated by QPSK Modulator. AWGN Channel is the additive white Gaussian noise channel, and can control the signal to noise ratio of input. An integral shaking filter is introduced as the Low.., and reduces the occupation of resources. According to the Doppler frequency offset range given in citation [5], the maximum carrier frequency offset absolute value in this design is set to 200 kHz. In addition, in order to ensure a certain frequency offset estimation accuracy and reduce the FFT calculation, the value of FFT calculation point is set to 1024, and the FFT resolution is about 391 Hz.The residual frequency error will drop into the bandwidth of loop filter after compensation. FFT Processor, Lock Detector, Loop Filter module are FFT processing module, lock detector, loop filter, the model of the internal structures can refer to their principle. The loop filter bandwidth is set to be 1 kHz.

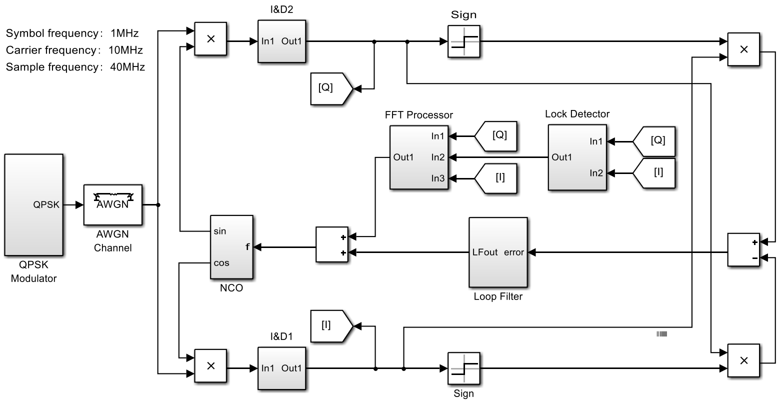
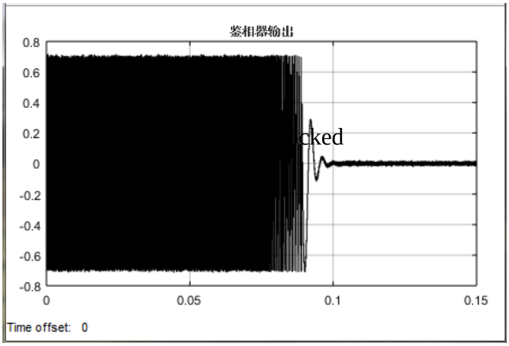


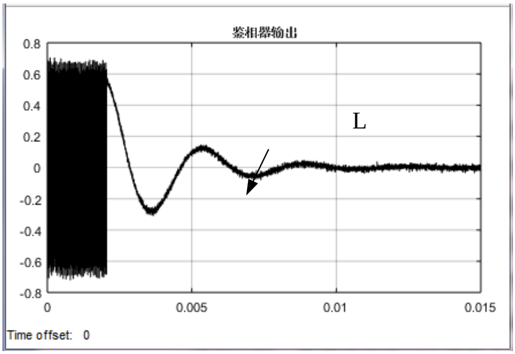
Fig.3 Simulation model for QPSK carrier recovery in Simulink.

In the simulation process, the frequency offset between local carrier and received carrier is set to 10 kHz, and the effectiveness of the FFT algorithm is simulated. In order to get better simulation results, the simulation time is set to 0.15 s when the carrier algorithm does not use FFT recovery. As the FFT algorithm is used, the simulation time is set to 0.015 s. The final simulation result of the carrier recovery model is shown in Fig. 4.

From the error output curve of the phase detector in Fig. 4, the error convergence process can be clearly seen. The design of the carrier recovery is verified by the simulation. At the same time, a comparison between using and not using the FFT algorithm is made by the simulation results. The lock time of the PLL is reduced by FFT algorithm from about 0.1 s to 0.01 s, and the effectiveness of the FFT algorithm is proved.



(a) Discriminator output when no using the FFT algorithm, simulation time is 0.15 s



(b) Discriminator output when using FFT algorithms, simulation time is 0.015 s

Fig.4 Simulation results for carrier recovery model.

Conclusions

In this paper, a QPSK large frequency offset carrier recovery method based on FFT is introduced. This method is designed on the basis of COSTAS cross-ring; the lock detector and FFT spectrum estimation algorithm are added to improve the carrier acquisition speed and range. By simulation, the feasibility of this method is proved, and it can meet the requirement of QPSK large frequency offset carrier recovery. Compared with other large frequency offset carrier recovery methods, the advantages of this method are that the design idea is simple and the loop lock time can be greatly reduced. So it can be applied to the satellite communication signal receiving system.

References:

1. Kaplan E D. Understanding GPS: principles and application [M]. Boston: Artech House, 2006.
2. WANG Jun, SUI Xin. Carrier tracking loop with improved frequency discrimination and its performance analysis [J]. Systems engineering and electronic technology, 2012, 34(12): 2438-2443.
3. E H Satorius, Z Ye, T Ely. Carrier Acquisition and Tracking Requirements for Doppler Navigation[C].Aerospace Conference, 2003, 4:4_1631-4_1638.
4. WANG Wei, CHEN Hui. Principle and Simulation of carrier recovery in high speed data transmission [J]. Radio Engineering, 2005, 35(5): 43-44.
5. XIE Yan-hua. Estimation and compensation of Doppler frequency shift based on satellite mobile communication system [D]. Dalian: Dalian University, 2013: 21-22.

A STRUCTURE OF EXPERIMENT ON PROCESSING SIGNALS RECEIVED FROM SHIP NAVIGATION EQUIPMENT BY MEANS OF "S-AIS" PAYLOAD

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Abstract. The study focuses on the idea of experiment on processing signals received from ship navigation equipment by means of "S-AIS" payload.

Keywords: small spacecraft, nanosatellite, picosatellite, platform, cubesat, onboard communication system, ais

The term "nanosatellite" is applied to ultra-small spacecraft (USSC) with a mass less than 10 kg and the volume of basic unit smaller than 1 m^3. Construction of USSC has become clearly possible according to electronic components, which enables us to create spacecraft with mentioned sizes. During the last 15 years, hundreds of spacecraft have been launched, and a large number of them have been successfully exploited. The main problem of USSC construction refers