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Research on DQPSK Carrier Synchronization based on FPGA

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Abstract. *Digital modulation-demodulation technique in modern digital communication system plays a very important role. Carrier synchronization is also one of the key technologies of digital wireless communication. As a kind of four phase shift keying modulation method, QPSK has strong anti-interference ability of the suppressed carrier, which is widely used in digital wireless communications. On this basis, this article describes a Costas-loop coherent carrier extraction algorithm based on Arctangent phase detection. It designs a digital intermediate frequency receiver system based on software radio thought. The system consists of data acquisition module, digital down converter (DDC) and digital demodulation module. And use the differential coding to solve the QPSK carrier phase fuzzy problem. And also illustrate the basic principle of DQPSK in detail. It makes simulation verification by Matlab for DQPSK demodulation. Simulation results show that the simulation model could correctly implement DQPSK signal carrier synchronization.At last, it is implemented on the FPGA platform.Implementation results show that the system can be applied to practical engineering.*
Keywords: FPGA; DQPSK; Phase Fuzzy; Costas Loop; Carrier synchronization;

1. **Introduction.** Software radio technology has developed to be the third generation communication technologies after communication technology and digital communication technology. Its core idea is to make broadband A/D and D/A near to the antenna as close as possible and use the software to realize the wireless function as much as possible [1]. In a digital communication system, for long-distance communications and wireless mobile communication system, it usually needs to use digital modulation technology in the transmitter to make baseband signal transform into frequency signal, and then transmitted the signal. At the receiving terminal, the received signal is processed by the demodulation process and finally the baseband signal we need is recovered.

While DQPSK is a widely used modulation in wireless communication. It has outstanding features, such as high spectrum utilization, good spectrum characteristics, strong anti-jamming capability, high transmission speed and so on. And use the differential coding to solve the QPSK carrier phase fuzzy problem. DQPSK has been widely used in wireless communication. Then the paper uses FPGA to implement it, and applies it to the practical projects, such as satellite communications, military industry and so on.

2. **General design of the system.** The input of the system is the intermediate frequency signal after modulation transmitter; the output are digital signals after demodulation. The system consists of the data acquisition, digital down converter (DDC) and digital demodulation module.

The data acquisition part converts analog signal to digital signal; DDC module can get I/Q two orthogonal signals of baseband frequency by multiplying the digital intermediate frequency signal by the sine and cosine signal produced by numerical control oscillator (NCO). Then I/Q two orthogonal signals complete the process of extraction and filtering; Digital demodulation module will complete QPSK signal demodulation. The overall design of QPSK demodulation system is shown in figure 1. This paper focused on the design of digital demodulation module.

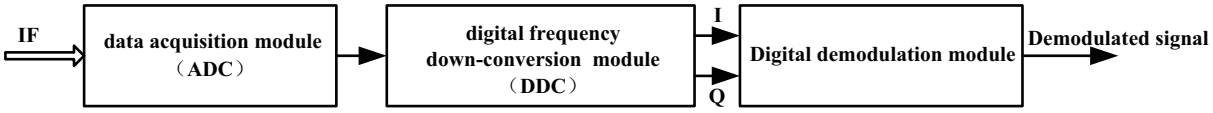


FIGURE 1. General design of Intermediate frequency digital receiving system.

3. **DQPSK signal demodulation principle.** The modem is usually using phase-locked loop to recovery the reference carrier. When the phase-locked loop is locked, it will be multiple phase ambiguity, this makes the demodulation data may occur the inversion about 0 and 1 completely. This is mainly due to the QPSK use the absolute carrier phase to transfer information, it greatly increases the modem design difficulty, and it becomes great deficiency in QPSK modulation.

DQPSK is developed a kind of modulation technology based on QPSK [2]. For the phase ambiguity problem of carrier recovery, DQPSK modulation use the differential coding in the transmitter, that is to say, converting the original information code to a relative code, and using carrier phase relative changes to express transmitted information. In this way, the receiver can according to the carrier phase relative changes to demodulate signal, thus avoiding the need about the phase and frequency's recovery should be accordance, it is also overcome the inversion about 0 and 1. Therefore the actual use of QPSK modulation is the differential coding modulation in this paper, namely the DQPSK modulated [3] (Differentially encoded Quadrate Phase Shift Keying, DQPSK).

Demodulation of DQPSK signal can be represented by a block diagram show in figure 2.

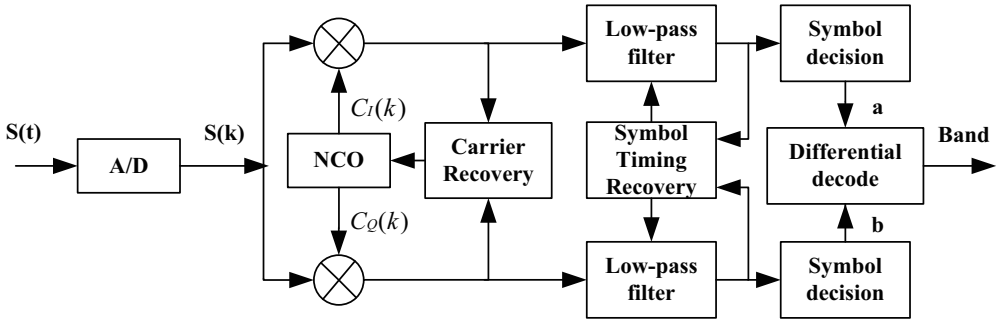


FIGURE 2. Demodulation of DQPSK Signal.

DQPSK signal can be represented as equation (1).

$$s(t) = a(t)\cos(\omega_i t + \theta_0) - b(t)\sin(\omega_i t + \theta_0) \tag{1}$$

After the sampling, the signal expression is as equation (2).

$$s(k) = a(k)\cos(\omega_i k + \theta_0) - b\,(k)\sin(\omega_i k + \theta_0) \tag{2}$$

Numerical control oscillator (NCO) produces the local carrier that is expressed as equation (3) and equation (4).

$$C_I(k) = \cos\left(\omega_c k + \theta_0 + \theta_e(k)\right) \tag{3}$$

$$C_Q(k) = sin\left(\omega_c k + \theta_0 + \theta_e(k)\right) \tag{4}$$

ω_c is the local carrier frequency, θ_0 is the initial phase of local carrier. Making ω_c for reference frequency to rewrite formula equation (5) is equation (6).

$$s(k) = a(k)\cos(\omega_c k + \theta_1) - b\,(k)\sin(\omega_c k + \theta_1) \tag{5}$$

$$\theta_1 = (\omega_i - \omega_c)k + \theta_0 \tag{6}$$

Then DQPSK signal is multiplied by carrier through I and Q channels. After low pass filtering the signal can be represented as equation (7) and equation (8).

$$y_I(k) = (a(k)/2)\cos\theta_e(k) + (b(k)/2)\sin\theta_e(k) \tag{7}$$

$$y_Q(k) = (-a(k)/2)\sin\theta_e(k) + (b(k)/2)\cos\theta_e(k) \tag{8}$$

Among the two formulas, $\theta_e(k) = \theta_1 - \theta_0$ is the phase and angle difference made by the frequency offset and phase offset from modulated carrier and local carrier. Obviously, when the local recovery phase carrier and the modulated carrier reach the same frequency and phase, $\theta_e(k) = 0$. Then, the I and Q signals are sampled separately from the original base band signal shaping filter [4]. After bit synchronous and extracting, it can respectively ruling out two ways of code. Then it can demodulate out the original signal by parallel-serial conversion.

4. **Carrier synchronization based on the Improved Costas loop.** Costas loop is a phase locked loop which is very widely used in engineering practice. Riter has proved that the best device to follow low SNR suppressed carrier signal is Costas loop and the square ring. Look at the point of DQPSK demodulation algorithm mentioned above, it has got the two orthogonal signals which used in the phase discrimination in Costas loop, the overall loop structure is the form of Costas loop. In this paper, we have improved it. The improved Costas loop principle diagram is shown in figure 3.

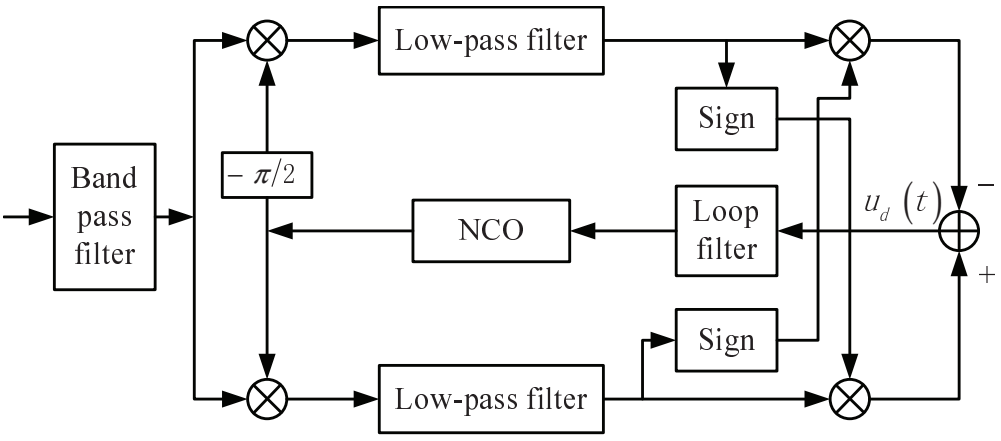


FIGURE 3. The schematic diagram of the Improved Costas loop.

4.1. **Phase detector.** For the DQPSK signal, as shown in figure 3, the output signal $u_d(k)$ of phase detector in the Costas loop principle diagram can be described as equation (9).

$$u_d(k) = sign(y_I(k)) \cdot y_Q(k) - y_I(k) \cdot sign(y_Q(k)) \tag{9}$$

Of which function $sign()$ are defined as equation (10).

$$sign(x) = \begin{cases} 1 & x > 0 \\ 0 & x = 0 \\ -1 & x < 0 \end{cases} \tag{10}$$

The characteristics of $u_d(k)$ as shown in figure 4. When the $\theta_e(k)$ is small, $sign(y_I(k)) \approx a(k)$, at the same time $sign(y_Q(k)) \approx b(k)$, so that formula can be simplified as equation (11).

$$u_d(k) = \begin{cases} -sin\theta_e(k) & -\pi/4 \le 0 < \pi/4 \\ cos\theta_e(k) & \pi/4 \le 0 < 3\pi/4 \\ sin\theta_e(k) & 3\pi/4 \le 0 < 5\pi/4 \\ -cos\theta_e(k) & 5\pi/4 \le 0 < 7\pi/4 \end{cases} \tag{11}$$

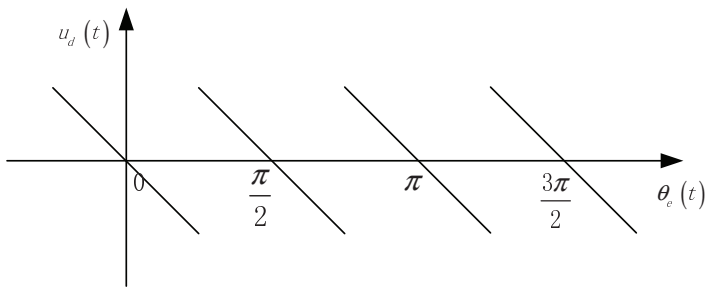


FIGURE 4. Characteristic of DQPSK Phase Detector.

From the analysis of the above formula, we can know that the phase detection gain of DQPSK demodulator is $\sqrt{2}$. For phase-locked loop, it can achieve the lock phase range without periodic jump, DQPSK demodulator is $[-\pi/4, \pi/4]$. From above of the phase characteristics we can know that Costas loop has the problem of phase fuzzy, when local carrier phase and receiving carrier have the phase difference such as 0, $\pi/2$, π, $3\pi/2$, the loop still lock [5]. But the question is easy to solve through differential coding, etc. Because it does not influence the realization and performance of modem and so it will not be discussed in this paper.

4.2. **Loop Filter.** Loop filter plays a very crucial role in Costas loop [6], which not only filter the leaked high frequency component of the phase detector, but also play a decisive role to the whole Costas loop parameters adjustment. The order and noise bandwidth of loop filter determine the performance of the loop filter. The characteristics of the loop filter are presented in table 1 [7]. Due to the first-order digital loop filter can produce steady state difference, the system error code performance get reduced. So it's difficult to actual implementation the third-order digital loop filter. But the second order digital loop filter is still be able to realize the steady state in the case of the infinitely-great dc gain and constant frequency offset, and the difficulty of implementing is appropriate. Considerate the implementation difficulty and the stability of the loop together, this system use the second order digital loop filter, the second order loop filter structure is shown in figure 5.

C_1 and C_2 are the coefficients of loop filter. C_1 mainly determines the size of the loop capture zone. C_2 determines the long-term tracking speed and capture speed of loop.

TABLE 1. Characteristics of the loop filter

Loop Order	noise bandwidth (Bn/Hz)	typical values of filter	Characteristic explain
first order	$\frac{\omega_0}{4}$	ω_0 $B_n = 0.25\omega_0$	Sensitive to the speed, all the values are stable for B_n, the application is more in the auxiliary code loop
second order	$\frac{\omega_0(1+a_2^2)}{4a_2}$	ω_0^2 $a_2\omega_0 = 1.414\omega_0$ $B_n = 0.53\omega_0$	Sensitive to acceleration, all the values are stable for B_n, it can be applied in the carrier loop of auxiliary and not auxiliary
third order	$\frac{\omega_0(a_3b_3^2 + a_3^2 - b_3)}{4(a_3b_3 - 1)}$	ω_0^3 $a_2\omega_0^2 = 1.1\omega_0^2$ $b_3\omega_0 = 2.4\omega_0$ $B_n = 0.7845\omega_0$	Sensitive to add acceleration, when $B_n \leq 18Hz$, it is stable, not more auxiliary carrier loop applications the application is more in the code loop of not auxiliary

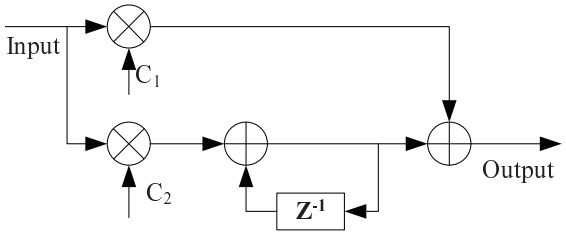


FIGURE 5. The structure of second order loop filter.

When C_2 is larger, the loop can be successful lock after a long time. When the choice of C_1 and C_2 is unsuitable, the loop lock won't get success, it unable to realize the carrier synchronization. The determination of the two coefficients is the key and difficult point for the entire Costas loop; it decides the performance of the whole loop. The calculation formula of C_1 and C_2 are as equation (12) and equation (13):

$$C_1 = \frac{1}{K_0 K_d} \frac{8\xi\omega_n T}{4 + 4\xi\omega_n T + (\omega_n T)^2} \tag{12}$$

$$C_2 = \frac{1}{K_0 K_d} \frac{4(\omega_n T)^2}{4 + 4\xi\omega_n T + (\omega_n T)^2} \tag{13}$$

From the calculation formula of C_1 and C_2 we can see that we just need to confirm the loop damping coefficient ξ the loop natural angular frequency ω_n, and the loop gain K_0K_d in order to find out the loop filter coefficient C_1 and C_2.

The equivalent noise bandwidth B_n of loop filter is one of the main parameters in the loop. It determines the size of the loop fast acquisition and phase jitter. The calculation formula of B_n is as equation (14).

$$\omega_n = \frac{8\xi B_n}{4\xi^2 + 1} \tag{14}$$

From the formula, you just need to determine the value of the equivalent noise bandwidth B_n in order to determine the value of natural angular frequency ω_n. Same as the selection of damping coefficient, we also need to have comprehensive consideration in the face of this contradiction. In most systems, the general selection is $B_n \leq 0.1R_b$, R_b shows the information data rate.

K_0 shows the gain of NCO, that is to say, the control sensitivity of NCO, it meets the equation (15).

$$K_0 = 2\pi T f_s / 2^N \tag{15}$$

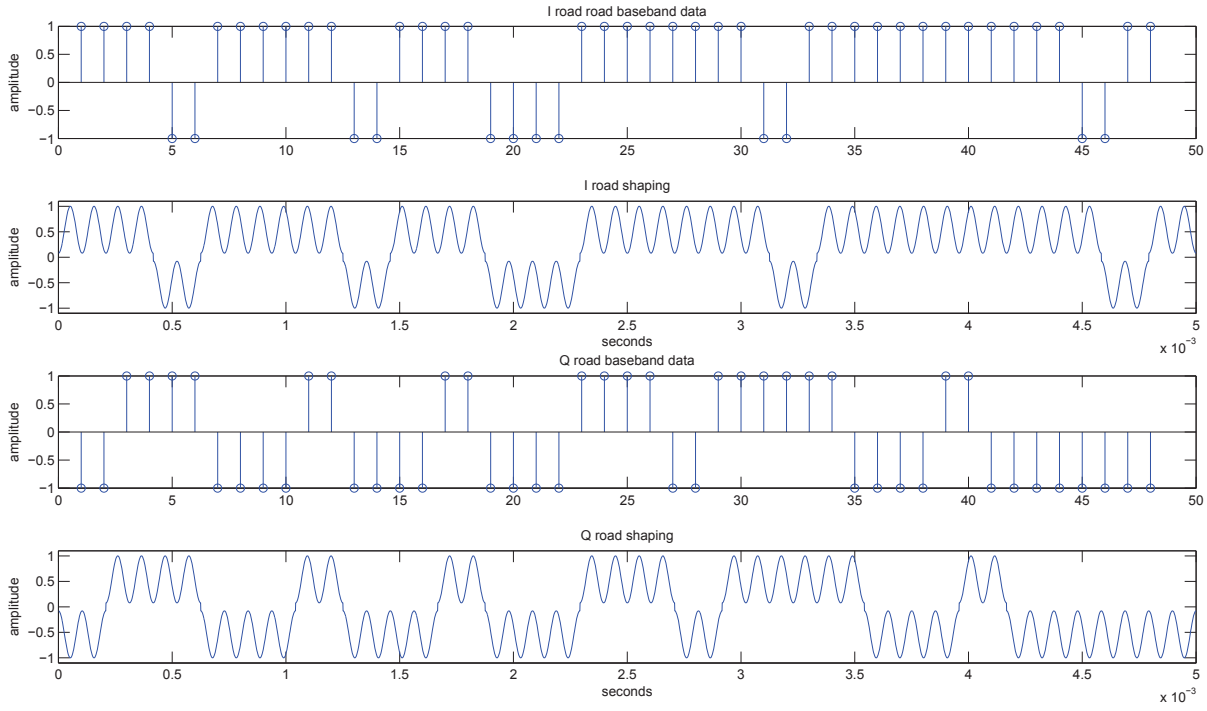
Among, f_s is the sampling frequency of NCO, N is the digits of NCO phase accumulator.

In the process of carrier synchronization, the controlled Y_k [8] signal can be get by making the output signals of phase discriminator go through the loop filter. So as to change the frequency of output signal, the phase difference is gradually reduced, and finally to zero, the purpose of the carrier synchronization is achieved.

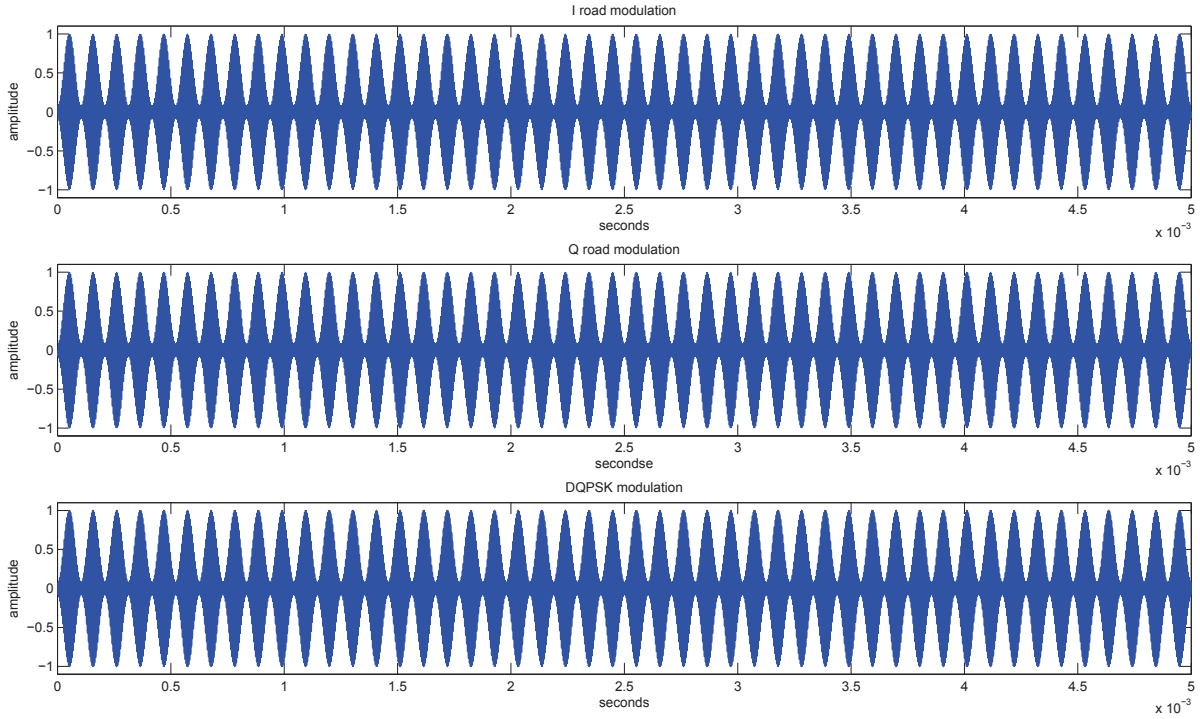
5. **Results and Analysis of Simulation.** In the simulation, DQPSK modulation uses the phase modulation method [9]. That is, the double bit code (a, b) of DQPSK convert into the I, Q two codes, and convert the absolute element into relative element, and then respectively do DBPSK modulation for it, then add two way modulation waveform to get the DQPSK signal [10].

Based on the above theoretical analysis, we get the Matlab simulation results of the DQPSK signal carrier synchronization. The Matlab simulation waveform of DQPSK signal modulation is shown in figure 6. In figure (a), from top to down, respectively, I baseband data, I road baseband pulse shaping, Q baseband data and Q road baseband pulse shaping. In figure (b), from top to down, respectively, I road modulation, Q road modulation and DQPSK modulation.

To compare the modulation terminal code with demodulation code waveform, as shown in figure 7, the system can demodulation element information correctly.



(a)



(b)

FIGURE 6. Simulated Result of DQPSK Modulation.

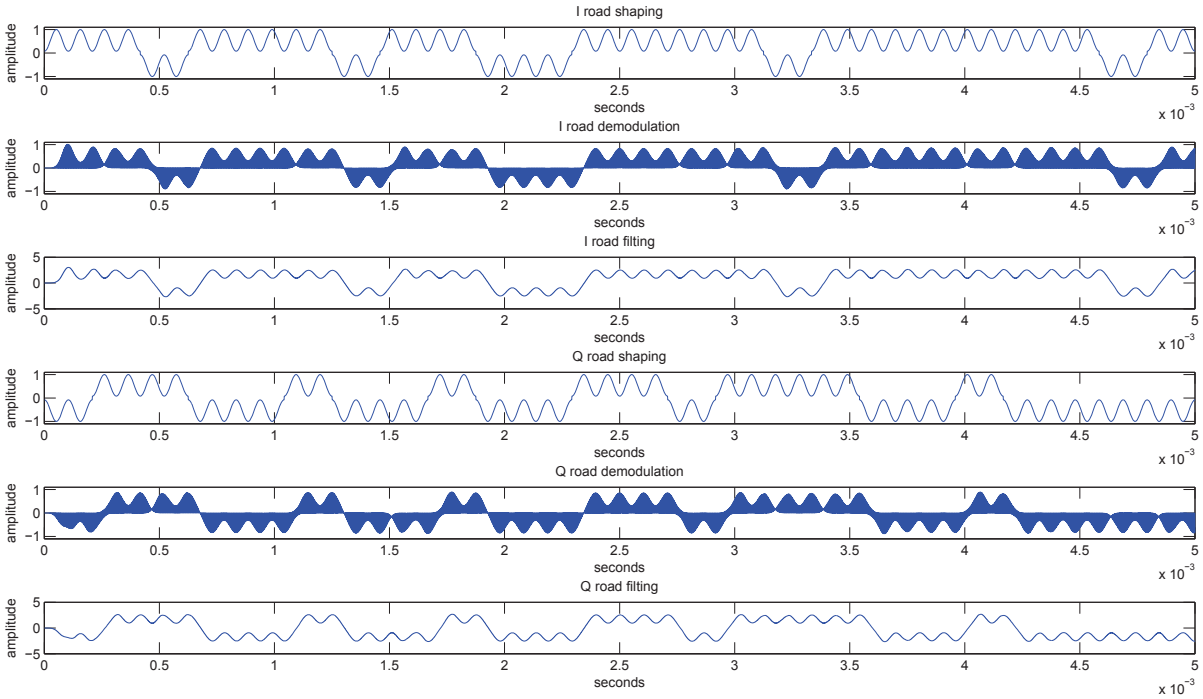


FIGURE 7. The Contrast between DQPSK Codes and Demodulated Signal.

In figure 7, from top to down, respectively, I road shaping, I road demodulation, I road filtering, Q road shaping, Q road demodulation and Q road filtering.

Finally, the paper has made the FPGA implementation for the main modules of carrier synchronization loop.

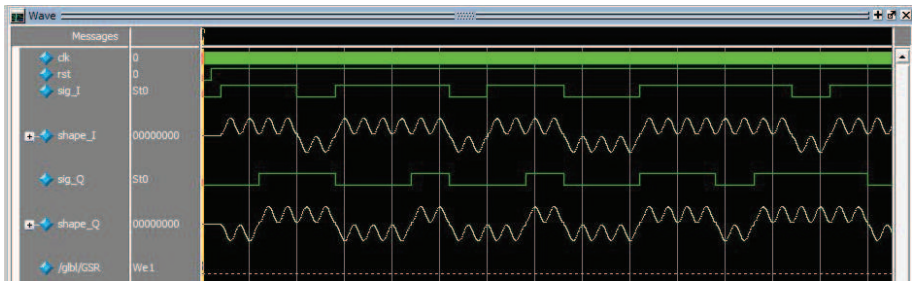


FIGURE 8. Simulation of two baseband signals and shaping signals.

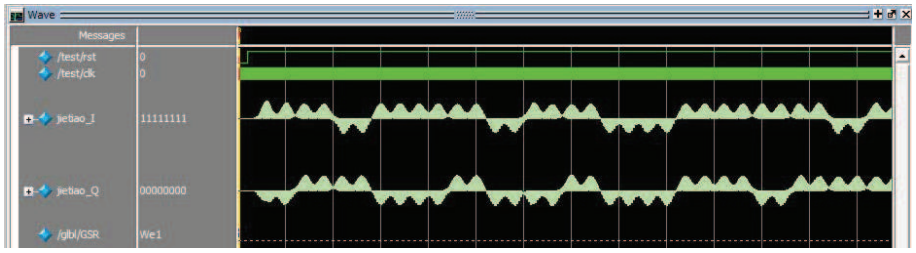


FIGURE 9. Simulation of two demodulation signals.

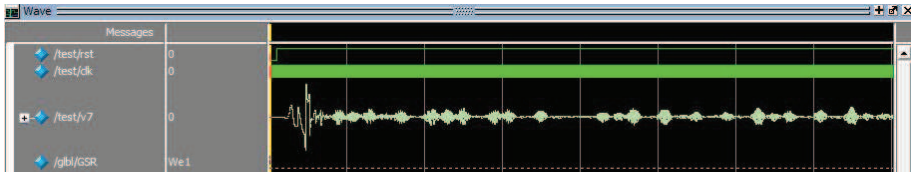


FIGURE 10. Simulation of detect phase signal.

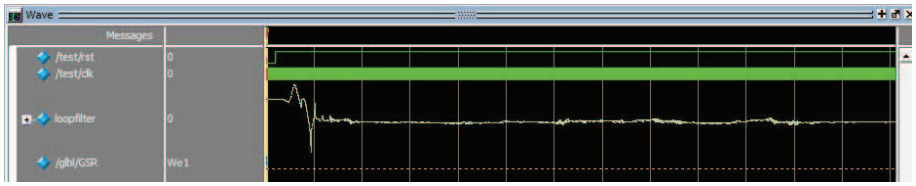


FIGURE 11. Simulation of loop filter signal.

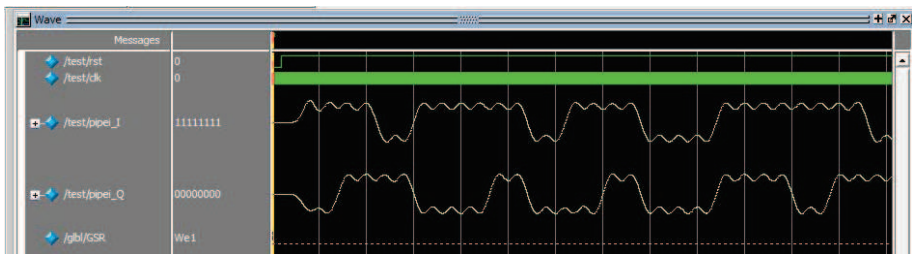


FIGURE 12. Simulation of two matched filter signals.

In figure 8, sig_I and sig_Q are the baseband signals; shape_I and shape_Q are the signals after shaping. In figure 9, jietiao_I and jietiao_Q are the signals after mixing. In figure 10, v7 is the detect phase signal. In figure 11, loopfilter is the signal after loop filtering. In figure 12, pipei_I and pipei_Q are the signals after matched filtering.

When $f_c = 240\text{k}Hz$, $f_s = 960\text{k}Hz$, $baud = 10\text{k}bps$, it can be seen that the system eventually restore the original baseband signal successfully. Compared with the traditional Costas loop, the improved Costas loop can restore the original baseband signal very well in the case of lower signal to noise ratio, and it has lower bit error rate. The following figure 13 shows the bit error rate of two loops.

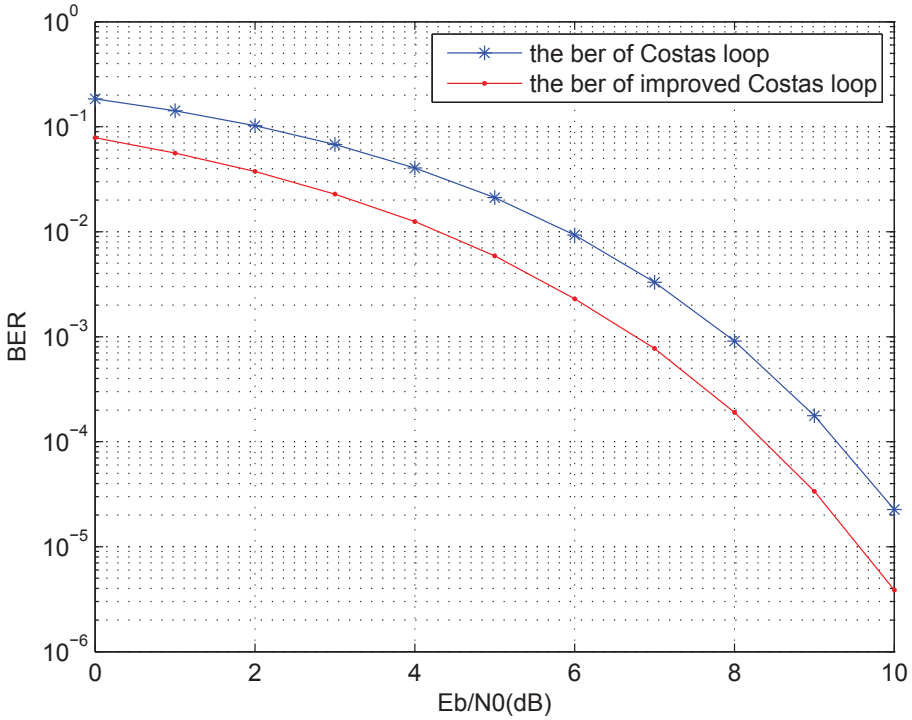


FIGURE 13. Simulation of two loops bit error rate.

As can be seen from the figure 13, the improved Costas loop has a lower error rate than the traditional Costas loop at the same SNR. It increased 10dB that the system signal to noise ratio calculated by MATLAB, which proves the plan design of this paper is rationality and realizability.

6. **Conclusion.** This paper has proposed a digital intermediate frequency receiver scheme based on software radio thought. Focusing on the DQPSK carrier synchronization based on the improved Costas loop method. It can adjust carrier frequency offset on time. In the process of symbol synchronization, a feed forward mode is adopted. The biggest advantage of feed forward is that it can achieve the symbol synchronization process in a very short time; it is very suitable for the burst communications. And it uses the differential coding to solve the QPSK carrier phase fuzzy problem. Then the paper has validated the DQPSK demodulation scheme is feasible based on the improved Costas loop by Matlab simulation. Finally, its practice through the FPGA hardware platform, and it proves the system is able to successfully applied to the actual software radio platform and work stable, and the bit error rate is small, which meets the actual demand.

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