Quaternary Carrier Orthogonal SNCK Communication Technology

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Abstract-In order to increase bandwidth efficiency of band limited communication system, a new multi-band digital modulation scheme based on Quaternary Carrier Orthogonal Sinusoidal Non-linear Chirp Keying (QCO-SNCK) is proposed. Firstly, by analyzing the orthogonality of SNCK modulated waveform samples, 4 mutually orthogonal waveform samples are selected as a set of new orthogonal subcarriers. Secondly, by using coherent demodulation method in the receiver, the quaternary wireless digital communication system has been achieved. Then the MATLAB software simulation platform is built to analysis the performance of the QCO-SNCK system. Theoretical and simulation results show that: when the communication channel bandwidth is limited, the bandwidth efficiency of QCO-SNCK system is 2 times wider than that of SNCK. Compared with Quadrature Phase Shift Keying (QPSK), the bandwidth efficiency of QCO-SNCK system has adjustable performance and higher flexibility. In addition, QCO-SNCK system has a strong ability of resisting Doppler frequency shift (DFS) which can be applied to wireless communication system with high rate mobile communication terminals.

Keywords - multi-band digital modulation; QCO-SNCK; DFS; bandwidth efficiency; high rate mobile communication

I. INTRODUCTION

Recently, non-single-frequency wave modulation technology developed rapidly, such as line frequency modulation and sinusoidal frequency modulation [1-2]. By studying the Doppler shift effect on the communication system performance, choose the Non-Single-Frequency wave instead of the traditional Single-Frequency wave as carriers, which has a good ability to inhibit Doppler frequency shift (DFS) to improve the robustness of the mobile wireless communication system in the mobile terminal high-speed motion scenes. Such as SNCK, the frequency variation curve of the modulated signal waveform samples are sine models. SNCK modulated wave can transmit high speed data in high dynamic scenarios with a good ability to resist anti-multipath and DFS.

Meanwhile, in order to improve the bandwidth efficiency of communication system, multi-band digital modulation technologies were proposed. When the channel bandwidth is limited, multi-band can increase the information transfer rate and the bandwidth efficiency. At present, QPSK has been widely used in various kinds of communication systems, such as satellite radio. 3G standard (WCDMA, CDMA2000, and TD-SCDMA) also uses QPSK modulation on the down link [3-4].

Take the SNCK signal as the research object in this paper, to pursue the higher bandwidth efficiency in communication channel bandwidth limited circumstances, a new multi-band digital modulation technology which is suitable for high dynamic scenarios was proposed, it's the Quaternary Carrier Orthogonal SNCK, i.e. QCO-SNCK. The first part of the article is introduction, the second part is SNCK modulation overview and the selection method of basis orthogonal functions, the third part introduces the principle and implementation scheme of QCO-SNCK modulation technology, the fourth part gives the simulation results and performance analysis of the QCO-SNCK modulation technology, the last part comes to the conclusion.

II. TECHNICAL PRINCIPLE

A. SNCK Modulation Overview

SNCK modulation technique use 2 orthogonal time-domain waveform samples as carriers [5]. The 2 frequency curves of the waveform samples are sinusoidal type. The classic expression is:

$$\begin{cases} f_1(t) = f_c + \frac{B}{2}\sin\left(\frac{2\pi t}{T}\right),\ 0 \le t < T \\ f_2(t) = f_c - \frac{B}{2}\sin\left(\frac{2\pi t}{T}\right),\ 0 \le t < T \end{cases} \quad (1)$$

Where $f_1(t)$ and $f_2(t)$ represent digital information code "0" and code "1" respectively, f_c is the center frequency of the modulated signal, B is the bandwidth of the modulated signal, $T=1/R_b$ is the symbol interval, R_b is the information transmission rate. As shown in Fig .1, the frequency curves use different polar to load information.

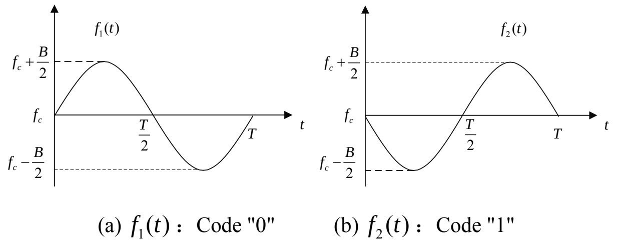


Figure 1. Schematic diagram of the frequency curve of SNCK modulated signal waveform samples

Assuming $D=BT$ (time-bandwidth product) as modulation parameter. To ensure the modulated signals have continuous phases, get the waveform samples as follows by integral of the frequency curve:

$$\begin{cases} s_1(t)=\sin\left[2\pi f_c t-\frac{D}{2}\cos\left(\frac{2\pi}{T}t\right)+\frac{D}{2}\right] \\ s_2(t)=\sin\left[2\pi f_c t+\frac{D}{2}\cos\left(\frac{2\pi}{T}t\right)-\frac{D}{2}\right] \end{cases} \tag{2}$$

Where $s_1(t)$ and $s_2(t)$ represent digital information code "0" and code "1" respectively, $0\le t<T$ .In order to make the phase of SNCK modulated signal waveform samples continuous, the center frequency should be an integer multiple of the symbol rate. If setting the parameter $M=T\cdot f_c$, then M should be a positive integer. The initial phase of modulated signal is generally set to 0 in digital communication system [6-7]. Therefore the phase correction $\pm D/2$ is added in (2). Fig .2 is a diagram of the SNCK modulated signal waveform sample which shows the continuous phase.

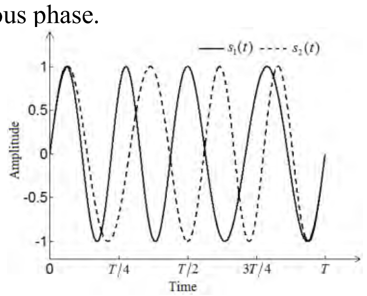


Figure 2. SNCK modulated signal waveform samples

B. Selecting Orthogonal Basis Functions

The best reception theory shows that the coherent demodulation can achieve good Bit Error Rate (BER) performance when the modulated signal samples are orthogonal to each other [8-9]. So if there is a set of mutually orthogonal SNCK modulated signal waveform samples by the correlation analysis of the binary SNCK waveform, then choose them as the orthogonal basis functions of multi-band orthogonal modulation, which can improve the communication system's transmission rate.

If the phase continuity of the modulated signal is ignored, (2) can be redefined as:

$$\begin{cases} s_1(t)=\sin\left[\omega_c t+\frac{D}{2}\cos\Omega t+\phi_1\right],\ 0\le t\le T \\ s_2(t)=\sin\left[\omega_c t+\frac{D}{2}\cos\Omega t+\phi_2\right],\ 0\le t\le T \end{cases} \tag{3}$$

Where $T=1/R_b$ is the symbol interval, R_b is the symbol transmission rate, $\omega_c=2\pi f_c$, f_c is the center frequency, $\Omega=2\pi/T$, ϕ is the time domain phase constant, $D=T\cdot B$ is the time-bandwidth product. Besides, the center frequency should be an integer multiple of the symbol rate, i.e. $T\cdot f_c=M$. Due to $f_c-(B/2)\ge 0$, the available range of D should be $0\le D\le 2M$.

The cross correlation coefficient of $s_1(t)$ and $s_2(t)$ in a symbol period is:

$$\begin{aligned} &\rho(D,\phi_1,\phi_2) \\ &=\int_0^T s_1(t)s_2(t)\mathrm{d}t \\ &=\int_0^T \sin\left(\omega_c t+\frac{D}{2}\cos\Omega t+\phi_1\right)\sin\left(\omega_c t+\frac{D}{2}\cos\Omega t+\phi_2\right)\mathrm{d}t \\ &=\frac{1}{2}\int_0^T\left\{\cos(\phi_1-\phi_2)-\cos\left[2\omega_c t+D\cos\Omega t+(\phi_1+\phi_2)\right]\right\}\mathrm{d}t \end{aligned} \tag{4}$$

Use the first kind of Bessel Function identity of trigonometric to make an analysis. The calculation result is:

$$\rho(D,\phi_1,\phi_2)=\frac{D}{2B}\cos(\phi_1-\phi_2) \tag{5}$$

It can be seen that the correlation coefficient is related to the D value and the phase difference of the waveform sample function, then the waveform orthogonal condition can be simplified as:

$$\rho(D,\phi_1,\phi_2)=\cos(\phi_1-\phi_2)=0 \tag{6}$$

That is:

$$\begin{cases} \phi_1-\phi_2=(2n+1)\pi/2, & \rho=0 \\ \phi_1-\phi_2=(2n+1)\pi, & \rho=-1 \end{cases} \tag{7}$$

There are always exist 4 ϕ values satisfying the orthogonality condition in a cycle from (7). Such as $\theta_i\in\{0,2\pi\}$. Take any two values from the set $\{0,\pi/2,\pi,3\pi/2\}$, the SNCK waveform sample $s_1(t)$, $s_2(t)$ is orthogonal ($\rho=0$) or super orthogonal ($\rho=-1$), among them, $\{0,\pi\}$ are just phases of the traditional SNCK sample. Therefore these 4 phases can be selected to constitute 4 orthogonal basis carriers $\{s_0(t),s_1(t),s_2(t),s_3(t)\}$. Then propose a new kind of Quaternary Carrier Orthogonal SNCK digital modulation method, the abbreviation is QCO-SNCK. The sub-carrier sample correlation values are in Table I.

TABLE I. THE SUB-CARRIER SAMPLE CORRELATION VALUES

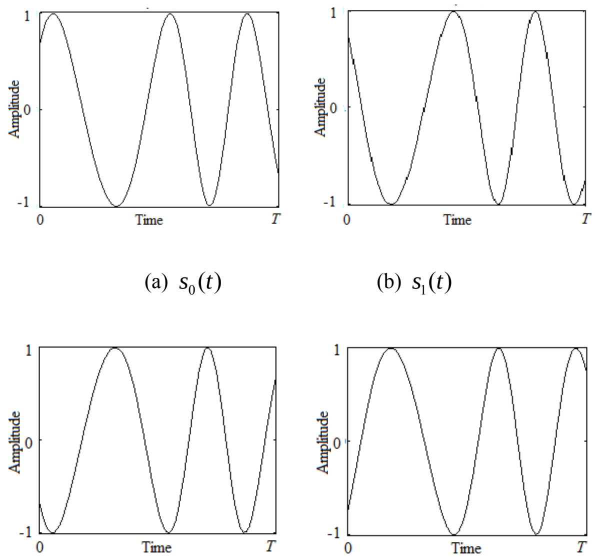
	$s_0(t)$	$s_1(t)$	$s_2(t)$	$s_3(t)$
$s_0(t)$	1	-1	0	0
$s_1(t)$	-1	1	0	0
$s_2(t)$	0	0	1	-1
$s_3(t)$	0	0	-1	1

III. QCO-SNCK Communication System Modulation Principle

From II.*B* analysis, the expression of QCO-SNCK waveform samples can be defined as:

$$s_n(t) = \sin\left[\omega_c t - \frac{D}{2}\cos\Omega t + n\cdot\frac{\pi}{2}\right] \quad (8)$$

Here, $0 \le t \le T$, $n = 0,1,2,3$, other parameters are the same as (3). Fig .3 shows the 4 time-domain waveform schematics of the QCO-SNCK modulated signal waveform samples.



(a) $s_0(t)$ (b) $s_1(t)$

(c) $s_2(t)$ (d) $s_3(t)$

Figure 3. 4 time-domain waveform schematics of QCO-SNCK modulated signal waveform samples.

If quaternary element is $C_n = a_n b_n$, then keying QCO-SNCK modulation block diagram is showed in Fig .4.

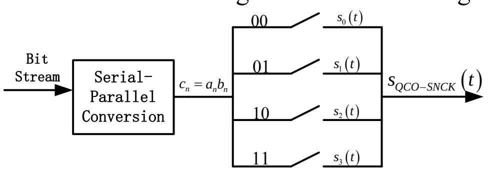


Figure 4. QCO-SNCK keying modulation implementation

As shown above, assume that the n-th modulated quaternary symbol is $C_n = a_n b_n$, First make the serial quaternary digital bit stream into two lines parallel binary data respectively through the serial-parallel conversion. Then mapping by column: Code "00" mapped $s_0(t)$, Code "01" mapped $s_1(t)$, Code "10" mapped $s_2(t)$, Code "11" mapped $s_3(t)$. Each modulated waveform samples are arranged to form a new sequence in the order of the original quaternary symbols, then this new sequence is the QCO-SNCK modulated signal.

A. *System Overall Block Diagram*

The whole communication system block diagram is showed in Fig .5, mainly composed by the originator modulation module, channel module, the receiver demodulation module [10]. In the originator, first the QCO-SNCK waveform samples are generated by the modulated signal waveform samples generator, up converting on the RF module, then transmitted to the wireless channel. In the receiver, firstly the received signal is respectively connected with the local carrier related:

$$\int_0^T s_i(t)s_j(t)\mathrm{d}t = \rho_{ij} \quad (9)$$

Where j take 0, 1, 2, 3respectively gain the correlation coefficients ρ_{i0} , ρ_{i1} , ρ_{i2} , ρ_{i3} , taking the maximum correlation value to the decision device to find out $\rho_{ij} = \max[\rho_{i0}, \rho_{i1}, \rho_{i2}, \rho_{i3}]$ corresponding j . Finally, the received data information can be obtained according to the mapping rules agreed well.

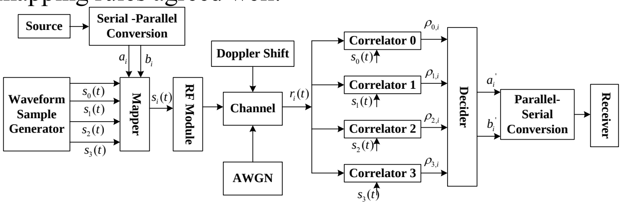


Figure 5. QCO-SNCK system overall block diagram

IV. Performance Analysis

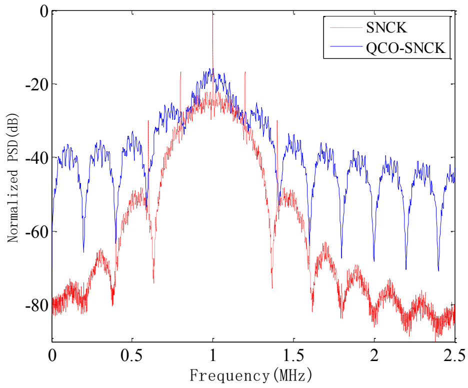
In order to make a performance analysis of the QCO-SNCK modulation technique, to establish a MATLAB software simulation model according to Fig .5 and the parameter shown in Table II. There are two different parameters setting in two scenes in Table II for comparative analysis. Scene I is a parameter setting of two different modulation methods under the same modulation bandwidth, in this case the information rate of QCO-SNCK modulation is 2 times faster than that of SNCK. However, in the Scene II, the two modulation methods have the same information rate, but the latter's bandwidth is 2 times wider than that of the former. Because the modulation coefficient is fixed, the Bandwidth efficiency of QCO-SNCK modulation in two scenes is 2 times higher than that of SNCK modulation.

TABLE II. Simulation Parameter Settings

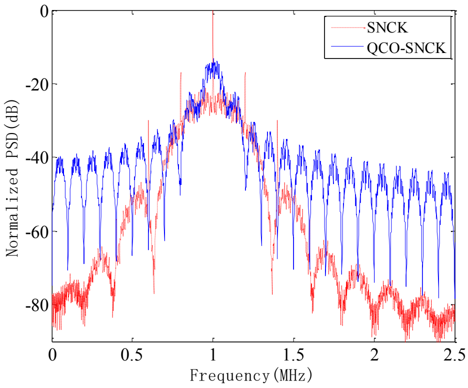
	Center Frequency f_c	1 MHz
	Sampling Rate f_s	8 MHz
	Modulation Factor D	1
Scene I (The Same Bandwidth)	Bandwidth B	200 kHz
	Information Rate $R_{b-\mathrm{SNCK}}$	200 kbit/s
	Information Rate $R_{b-\mathrm{QCO\text{-}SNCK}}$	400 kbit/s
Scene II (The Same Rate)	Information Rate R_b	200 kbit/s
	Bandwidth B_{SNCK}	200kHz
	Bandwidth $B_{\mathrm{QCO\text{-}SNCK}}$	100kHz

A. *Power Spectral Density Characteristics*

To compare the performance of QCO-SNCK modulated waveform and SNCK modulation technique, setting parameters according to Table II, sending 1 kbit binary data randomly, the modulated signal Power Spectral Density (PSD) curves based on the average period Welch has been showed in Fig .6.



(a) Scene I: the same modulation bandwidth



(b) Scene II: the same information rate

Figure 6. Power Spectral Density curves of QCO-SNCK signal

Fig .6 (a) shows that, when the two different modulation methods have the same modulation bandwidth, SNCK modulated signal has a strong power of carrier leakage and harmonic line spectral component with occupied bandwidth expansion. Compared with SNCK modulated signal, QCO-SNCK modulated signal has a very low harmonic line spectral power with higher sidelobe amplitude and slower attenuation in the frequency domain. Besides, the Bandwidth efficiency of QCO-SNCK modulation is 2 times higher than that of SNCK modulation. Fig .6 (b) shows that, when the two different modulation methods have the same information rate and the modulation coefficient *D* is a fixed value, SNCK modulation needs wider bandwidth, while the QCO-SNCK modulated has a higher energy concentration, and the Bandwidth efficiency of QCO-SNCK modulation is still 2 times higher than that of SNCK modulation. Slow the side-lobe amplitude of the modulated signal PSD by filtering technology to optimize the QCO-SNCK modulated signal [11].

B. BER Features

- AWGN Channel

To illustrate the feasibility of QCO-SNCK modulation technology further, focus on the above parameters setting in the Scene I, sending 100 kbit binary data randomly, the BER simulation curves for two communication systems can be got respectively. Due to the BER of the SNCK communication system only related to the cross correlation between carriers ρ and the Signal-to-Noise Ratio (SNR) E_b/N_0 , just one scene need to be discussed. Assuming that the symbol has been fully synchronized, the communication channel is Additive White Gaussian Noise (AWGN) channel [12], the BER simulation curves show in Fig .7, the abscissa E_b/N_0 is each bit SNR.

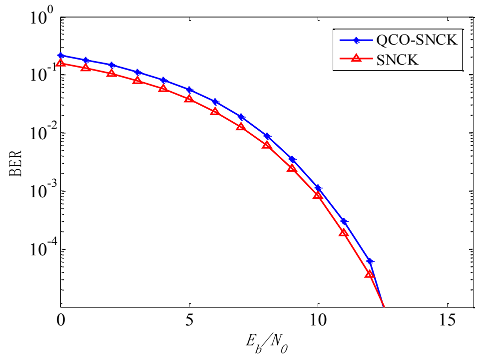


Figure 7. the BER simulation curves in the AWGN channel

Fig .7 shows that, the BER performance of QCO-SNCK is 2dB worse than SNCK in the same modulation bandwidth with the BER reach below 10^{-4}, this is caused by the larger PSD sidelobe amplitude, but both the information rate and the bandwidth efficiency of QCO-SNCK modulation system are 2 times than that of SNCK. In addition, the application of the non-coherent demodulation can be considered to improve the SNR factor and reduce the BER of QCO-SNCK communication.

- DFS Channel

Binary SNCK modulation technique has a strong ability of resisting DFS which can be applied to the wireless communication system with high rate mobile communication terminals. Extending to the multi-band, QCO-SNCK still has a certain ability to resist the DFS. Focus on the above parameters setting in the Scene I, assuming that the symbol has been fully synchronized, setting the relative speed are 50 km/h, 100 km/h, 300 km/h respectively, analysis the ability of resisting DFS by simulation, Fig .8 shows the BER curves in different conditions.

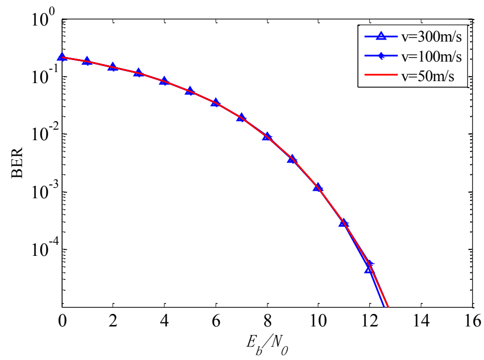


Figure 8. the BER simulation curves in different DFS speeds

From Fig .8, it can be seen that the BER curves under different DFS speeds almost overlapping, thus the QCO-SNCK modulation technology has a certain ability to resist DFS [13].

C. Bandwidth Efficiency

Bandwidth efficiency is not only an indicator describing the relationship between the data transfer rate and the bandwidth, but also an indicator measuring the effectiveness of digital communication system [14]. Bandwidth efficiency of digital communication systems is defined as: the ratio of information transmission rate and the system bandwidth. So the bandwidth efficiency of QCO-SNCK is:

$$\eta_{\text{QCO-SNCK}} = R_b / B = R_B \log_2 N / B = 2 / D \quad (10)$$

Here, B is desired transmission bandwidth, R_b is information transmission rate, R_B is Baud rate, and $D = BT$ is time-bandwidth product.

- Compared with SNCK

From the above equation, the bandwidth efficiency of QCO-SNCK system is related to the parameter *D*. The smaller the value is, the higher the bandwidth efficiency will be. When the bandwidth of communication channel is limited, the information transmission rate and bandwidth efficiency of QCO-SNCK system will be 2 times than that of SNCK. In theory, the QCO-SNCK modulated subcarriers are orthogonal to each other, value *D* is not affected by the correlation of waveforms. In order to obtain the higher bandwidth efficiency, the selection of value *D* should be as small as possible. However, the validity and reliability of the system are always conflicting, the BER performance of communication system gets worse with the decrease of the value *D*, so we can't choose the minimum *D* value blindly, we should take a balance point within the scope of the *D* value, so that high frequency bandwidth efficiency can be got in an acceptable range of BER sacrifice.

- Compared with QPSK

As for QPSK, The first zero bandwidth is $B = R_b$, at this time the Bandwidth efficiency is $\eta = 1$ B/Hz. While the Bandwidth efficiency of QCO-SNCK is 2 times the inverse of the modulation coefficient *D*, so we can reduce the modulation factor *D* value appropriatly to improve the bandwidth efficiency in the case where the system reliability allows. For example, if $D = 1$, then $\eta = 2$ B/Hz. Then the Bandwidth efficiency of QCO-SNCK could be higher than QPSK and have adjustable performance.

V. CONCLUSION

In this paper, a Quaternary Carrier Orthogonal SNCK modulation technique has been proposed based on analyzing the orthogonality of SNCK modulated waveform samples. The BER performance of the proposed approach has been evaluated via simulation of the whole wireless communication system. Although the BER performance of QCO-SNCK is 2dB worse than SNCK. However, the proposed approach has higher bandwidth efficiency with adjustable performance, which improves system flexibility. Besides, it also has a certain ability resisting DFS, which can be applied to a wireless communication system with high rate mobile communication terminals. Therefore, further research can be done on the quaternary SNCK technique based on non-coherent demodulation and SNCK parallel transmission scheme in future.

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