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A NOVEL FREQUENCY-MODULATED DIFFERENTIAL CHAOS SHIFT KEYING MODULATION SCHEME BASED ON PHASE SEPARATION*

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Abstract In frequency-modulated differential chaos shift keying (FM-DCSK), the separation of the chaotic reference and information-bearing wavelets is performed in time domain. This separation method not only limits the attainable data rate but also demands delay components in transceiver circuits. Due to the fact that wideband radio frequency (RF) delay lines are extremely difficult to implement with CMOS technology in ultra wideband communications, a new phase-separated FM-DCSK modulation scheme is presented in this paper to increase the data rate and to avoid the use of delay lines in both the transmitter and the receiver circuits. The feasible configurations of transmitter and detector are given. Besides, bit error rate (BER) performance of the proposed system is evaluated by both analysis and Monte Carlo simulations over additive white Gaussian noise (AWGN) channel.

Keywords Chaos communications, frequency-modulated differential chaos shift keying, delay lines, phase separation, bit error rate.

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1. Introduction

With perfect correlation properties required by spread spectrum systems, easy-to-generate and non-periodic chaotic signals recently have been applied to digital communications. Up to now, many modulation schemes based on chaos have been suggested and studied for different applications [2-6,9,11-14]. These chaos-based systems show not only better communication privacy but also high robustness against multipath degradation and self-interference [6,9].

To avoid the chaotic synchronization and channel estimation problems which are quite difficult to solve at the receiver side, transmitted-reference (TR) techniques in [10] have been widely adopted in most non-coherent chaotic modulation schemes, such as the well-known differential chaos shift keying (DCSK) in [5], frequency-modulated DCSK (FM-DCSK) in [6] and enhanced versions of DCSK in [13,14].

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Among all these schemes, FM-DCSK modulation can achieve almost best multipath performance with a simple autocorrelation detector and shows great potential in real applications [11]. However, the chaotic reference and information-bearing signals in FM-DCSK are separated in time domain and transmitted in two consecutive time slots, which not only limits the attainable data rate but also makes delay lines inevitably essential to both the transmitter and the receiver for the separation of the reference and information-bearing signals in FM-DCSK.

Considering that ultra wideband (UWB) radio frequency (RF) delay lines are quite difficult to integrate in CMOS technology, Walsh codes and chaotic sequences have recently been utilized by CS-DCSK in [12] and HCS-DCSK in [2] respectively to distinguish the chaotic reference and information-bearing signals in DCSK. Although these two schemes successfully removed wideband RF delay lines from their receivers, much more delay lines are introduced into their transmitters, making system design actually more sophisticated and hardly integration-friendly. Moreover, using Walsh codes or chaotic sequences for signal separation also brings CS-DCSK and HCS-DCSK extra requirements for code synchronization. Unfortunately, these new synchronization requirements are quite difficult to satisfy at the receiver side, which also greatly complicates the system design and inevitably limits the application of these two systems in many aspects.

For this reason, a novel and simple phase-separated FM-DCSK modulation scheme is designed here to avoid the difficult-to-implement code synchronization and all RF delay lines in transceiver circuits. In the proposed system, the chaotic reference and information-bearing signal are separated by orthogonal sinusoidal carriers rather than time delay, thus they can be transmitted simultaneously within same time slot. As a result, the demands of delay lines and switches have been eliminated in both the transmitter and receiver design. In FM-DCSK, bit duration is two time slots in which the reference and information-bearing signals are sent, respectively. However, in our new scheme, bit duration is one time slot in that the reference and information-bearing signals are sent simultaneously. Thus this new separation method based on orthogonal sinusoidal wavelets offers our system half-reduced bit duration, doubled attainable bit transmission rate and equivalent bit error rate (BER) performance in comparison to FM-DCSK.

The remainder of this paper is organized as follows. In Section 2, the basic idea of phase-separated FM-DCSK modulation is described. In Section 3, the signal-space diagram of the proposed scheme is compared to that of FM-DCSK, and bit error rate formula of phase-separated FM-DCSK system over AWGN channel is given. For the purposes of BER performance validation and comparison, relevant computer simulations are performed for both FM-DCSK and the proposed system in section 4. Finally, conclusions are given in Section 5.

2. PRINCIPLE OF PHASE-SEPARATED FM-DCSK SCHEME

In classic FM-DCSK [6], each bit duration is divided into two equal time slots. A frequency modulated (FM) chaotic signal serving as carrier is transmitted in the first time slot, while an identical or inverted copy of the carrier is sent in the second time slot. At the receiver, data bit can be recovered by evaluating the correlation between the first and second halves of received signals in each bit duration. Thus delay lines are required by FM-DCSK transceivers.

To remove those delay lines, a parallel and simultaneous transmission solution is designed in this section, where the reference and information-bearing wavelets in classic FM-DCSK could be transmitted within a single time slot. Since signal separation performed by Walsh codes or chaotic signals in [12] and [2] greatly increases the complexity cost of synchronization, orthogonal sinusoidal carriers are utilized here to separate the chaotic reference and information-bearing signals for simple implementation and minimized mutual interference.

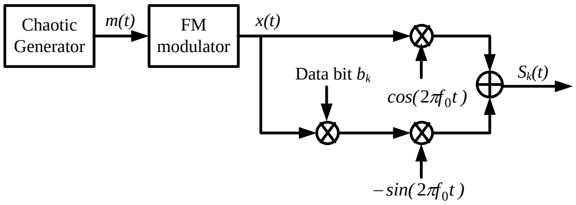

Figure 1. Modulator.

Figure 1 gives the block diagram of the phase-separated FM-DCSK modulator. As the reference and data signals here are not separated by time delay, the need of delay lines has been avoided in this modulator. Besides, no switching is performed in Figure 1 and thus a continuous operation of the transmitter is allowed.

In this modulator, the discrete chaotic signal is first converted into the following continuous signal $m(t)$ by using a zero-order hold circuit with holding time determined by chip duration T_c

$$m(t) = \sum_{i=(k-1)M}^{kM-1} x_i rect(t - iT_c). \tag{2.1}$$

Where x_i denotes the chaotic samples, M is the number of chips in one time slot, and $rect(\cdot)$ is the rectangular pulse function.

Then the obtained signal $m(t)$ is fed into a FM modulator to generate a wideband RF band-pass signal with constant power as the message bear

$$x(t) = \sqrt{\frac{2}{T_s}} \cos\left(2\pi[f_c t + K_f \int_0^t m(\tau)d\tau]\right). \tag{2.2}$$

In which, f_c is the center frequency of the FM modulator output, K_f denotes the gain of the FM modulator, and T_s is the time slot duration.

Finally, the chaotic reference signal in (2.2) and its identical or inverse version that carries data bit will be separately modulated onto in-phase and quadrature sinusoidal carriers. If the transmission of a single isolated data bit b_k is considered, the transmitted phase-shifted FM-DCSK signal is represented by

$$S_k(t) = \sqrt{E_b} x(t) \cos(2\pi f_0 t) - b_k \sqrt{E_b} x(t) \sin(2\pi f_0 t), \quad (k-1)T_s < t \leq kT_s. \tag{2.3}$$

Here, f_0 is the frequency of carrier and E_b is the bit energy. In this paper, it is assumed that $f_0 \gg 1/T_c$ and f_0 is a multiple of T_c.

A feasible phase-separated FM-DCSK detector utilizing differentially coherent demodulation in [7] is designed in Figure 2. In order to estimate the reference

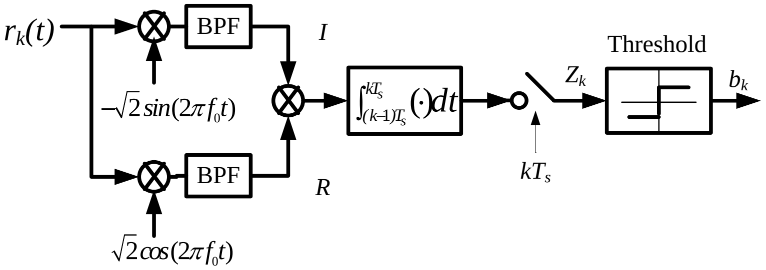

Figure 2. Block diagram of phase-separated FM-DCSK detector.

signal, received signal $r_k(t)$ is first multiplied with the synchronized inphase carrier and then passes through an ideal band-pass filter (BPF) centered on f_c with total RF bandwidth of $2B$, which is assumed to be large enough to pass the message bearer in (2.2) without any distortion. At the same time, the corresponding information-bearing signal transmitted within the same time interval is also estimated by using similar operations except that the synchronized inphase carrier is replaced by quadrature one.

For simplicity, it is assumed that the received signal is only corrupted by stationary white Gaussian noise $n(t)$ with zero mean and a double side power spectral density of $N_0/2$.

$$r_k(t) = s_k(t) + n(t). \tag{2.4}$$

With assumption that perfect carrier synchronization has been achieved in the detector shown in Figure 2, the outputs of the upper and lower ideal BPF for information bit b_k can be described as

$$I = b_k\sqrt{\frac{E_b}{2}}x(t) + n_s(t), \tag{2.5}$$

$$R = \sqrt{\frac{E_b}{2}}x(t) + n_c(t). \tag{2.6}$$

Where $n_c(t)$ and $n_s(t)$ denote the sample functions of the filtered noise that corrupt the reference and information-bearing chips of the received signal, respectively. According to [1], it can be proved that $n_c(t)$ and $n_s(t)$ are independent and identical distributed stationary Gaussian processes having the following power spectral density

$$S_{N_c}(f) = S_{N_s}(f) = \begin{cases} \frac{N_0}{2}, & if\ |f \pm f_c| \le B, \\ 0, & otherwise. \end{cases} \tag{2.7}$$

Finally, the recovered reference and information-bearing signals will be correlated over a duration time of T_s so that the information bit b_k could be recovered according to the sign of the correlation value.

The corresponding observation variable is

$$Z_k = \int_{(k-1)T_s}^{kT_s}\left(\sqrt{\frac{E_b}{2}}x(t) + n_c(t)\right)\cdot\left(b_k\sqrt{\frac{E_b}{2}}x(t) + n_s(t)\right)dt. \tag{2.8}$$

3. PERFORMANCE ANALYSIS

As the BER performance of a modulation scheme is determined by both the constellation of message points in the signal-space diagram and the type of demodulator [7], Figure 3 shows the signal-space diagram for phase-separated FM-DCSK. Here, the two chaotic basis functions $g_1(t)$ and $g_2(t)$ are

$$g_1(t) = x(t)\cos(2\pi f_0 t) + x(t)\sin(2\pi f_0 t), 0 < t < T_s, \tag{3.1}$$

$$g_2(t) = x(t)\cos(2\pi f_0 t) - x(t)\sin(2\pi f_0 t), 0 < t < T_s. \tag{3.2}$$

Considering that $f_0 >> 1/T_c$ and f_0 is a multiple of T_c, it can be easily proved that $g_1(t)$ and $g_2(t)$ are orthogonal.

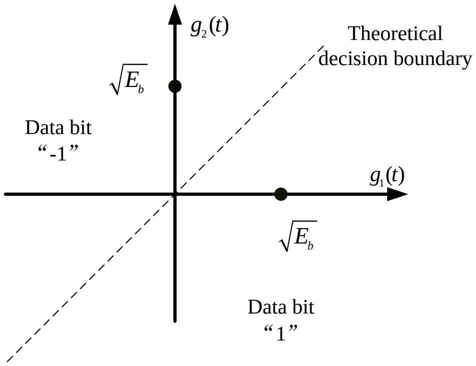

Figure 3. Signal-space diagram for phase-separated FM-DCSK.

Interestingly, the above signal-space diagram coincides with the signal-space diagram of differentially coherent FM-DCSK given in [8], leading to a conclusion that these two schemes can be characterized by identical signal-space diagrams.

In FM-DCSK, two orthogonal basis functions required to express the elements of the signal set can be given by

$$\widetilde{g_1}(t) = \begin{cases} \frac{1}{\sqrt{2}}x(t), & 0 < t < T_s, \\ \frac{1}{\sqrt{2}}x(t-T_s), & T_s < t < 2T_s, \end{cases} \tag{3.3}$$

$$\widetilde{g_2}(t) = \begin{cases} \frac{1}{\sqrt{2}}x(t), & 0 < t < T_s, \\ -\frac{1}{\sqrt{2}}x(t-T_s), & T_s < t < 2T_s. \end{cases} \tag{3.4}$$

With differentially coherent demodulator in [7], the observation variable in FM-DCSK is described by

$$\widetilde{Z_k} = \int_{(2k+1)T_s}^{2(k+1)T_s} \left(\sqrt{\frac{E_b}{2}}x(t-T_s) + \xi(t-T_s)\right) \cdot \left(b_k\sqrt{\frac{E_b}{2}}x(t-T_s) + \xi(t)\right) dt. \tag{3.5}$$

Where $\xi(t)$ is the sample function of a white Gaussian noise process having a double-sided power spectral density of $N_0/2$ and filtered by the ideal band-pass channel filter with RF bandwidth of $2B$.

Comparing the observation variables in FM-DCSK and phase-separated FM-DCSK (see (2.8) and (3.5) respectively), it can be found that the probability density functions of observation variables in these two schemes are identical.

Based on the relationship between the FM-DCSK and phase-separated FM-DCSK signal-space diagrams and the comparison between the observation variables of the FM-DCSK and phase-separated FM-DCSK demodulators, it can be concluded that FM-DCSK is actually the counterpart of phase-separated FM-DCSK and these two schemes show equivalent BER performances provided that same system parameters, i.e., $2B$ and T_s, are chosen in both systems.

With noise performance of FM-DCSK given by [7], the exact bit error rate formula for phase-separated FM-DCSK is given as

$$BER = \frac{1}{2^{2BT_s}} \exp(-\frac{E_b}{2N_0}) \sum_{i=0}^{2BT_s-1} \frac{(\frac{E_b}{2N_0})^i}{i!} \times \sum_{j=i}^{2BT_s-1} \frac{1}{2^j} \binom{j+2BT_s-1}{j-i}. \quad (3.6)$$

4. SIMULATION RESULTS

In this section, the noise performance of phase-separated FM-DCSK and FM-DCSK systems are evaluated by Monte Carlo simulations over AWGN channel. In our simulations, full RF band-pass models are used for both schemes. Details of system parameters are given as follows: all chaotic samples are generated by the logistic map $x_{i+1} = 1 - 2x_i^2$ in [9], the chip rate $1/T_c$ is 20MHz, the carrier frequency $f_0 =$ 400MHz, FM gain $K_f = 7.8$MHz/V and $f_c = 36$MHz.

To verify (3.6), the BER performance of phase-separated FM-DCSK obtained by computer simulations is compared with the predictions calculated from (3.6) in Figure 4. All results are given in terms of bit error probability versus E_b/N_0 in decibels. Here, the bandwidth of band-pass filters in phase-separated FM-DCSK detector is fixed at 17MHz, and the slot durations T_s are 1 and $2\mu s$, respectively. It is obvious in Figure 4 that there is a good agreement between analytical predictions and the results obtained by Monte Carlo simulations. Besides, with fixed bandwidth of BPFs in detector, BER performance of phase-separated FM-DCSK degrades as T_s increases. This fits the relationship between bit error rate and T_s given in (3.6) quite well.

Figure 5 compares the simulated BER performances of FM-DCSK and phase-separated FM-DCSK. In this figure, the slot time of both systems are fixed at $2\mu s$, while the RF bandwidth $2B$ of both channel filter in FM-DCSK and the BPFs in phase-separated FM-DCSK are varied (from the top to the bottom, $2B$ is 34MHz and 17MHz respectively). It can be clearly observed in Figure 5 that BER performance of phase-separated FM-DCSK is always identical to that of FM-DCSK, which also coincides with our analysis in Section 3.

5. CONCLUSION

In this paper, a novel parallel and simultaneous signal transmission mode is designed and applied to FM-DCSK. The unique novelty of the proposed scheme is that the chaotic reference and information-bearing signals in FM-DCSK are kept to be orthogonal and transmitted in the same time slot via I/Q channels. Without any performance loss, the new scheme removes all delay lines completely from both the transmitters and the receivers and achieves doubled bit rate in comparison with FM-DCSK. The exact bit error rate formula for the proposed system over AWGN channel is given, which is also verified by Monte Carlo simulations. Analysis

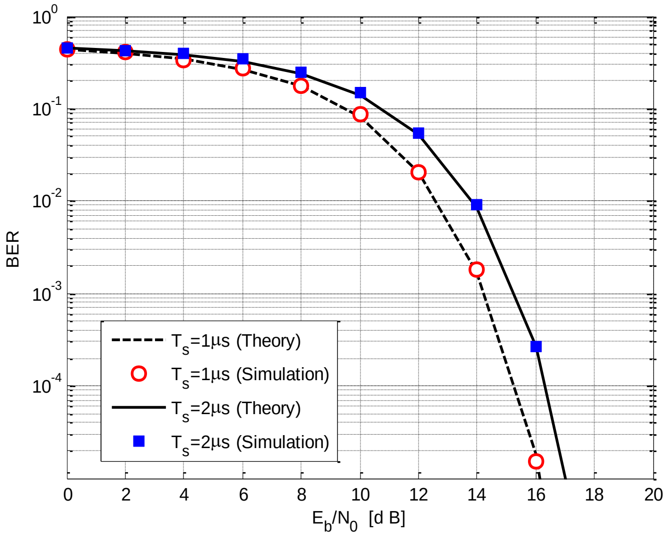

Figure 4. Theoretical and simulated BER performance curves of phase-separated FM-DCSK for different slot durations.

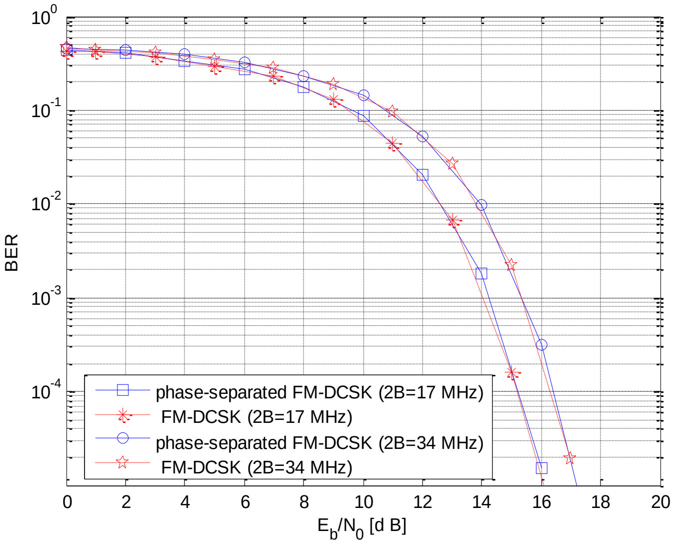

Figure 5. BER performance comparsion between FM-DCSK and phase-separated FM-DCSK schemes.

and simulation results show that original FM-DCSK system and its counterpart equipped with our signal transmission method (i.e., phase-separated FM-DCSK system) have identical BER performances.

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