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Research Article

Design and Implementation of a Chaotic Scheme in Additive White Gaussian Noise Channel

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A new chaotic scheme named Flipped Chaotic On-Off Keying (FCOOK) is proposed for binary transmission. In FCOOK, the low correlation value between the stationary signal and its mirrored version is utilized. Transmitted signal for binary 1 is a chaotic segment added to its time flipped (mirrored) version within one bit duration, while in binary 0, no transmission takes place within the same bit duration. The proposed scheme is compared with the standard chaotic systems: Differential Chaos Shift Keying (DCSK) and Correlation Delay Shift Keying (CDSK). The Bit Error Rate (BER) of FCOOK is studied analytically based on Gaussian approximation method. Results show that the BER performance of FCOOK outperforms DCSK and CDSK in AWGN channel environment and with various E_b/N_o levels. Additionally, FCOOK offers a double bit rate compared with the standard DCSK.

1. Introduction

In recent years, chaotic signals become natural candidates for spreading narrow band information due to their wide-band characteristic. Thus, using chaotic signals to encode information, the resulting signals are spread spectrum signals having larger bandwidths and lower power spectral densities. Chaotic signals enjoy all the benefits of spread spectrum signals such as a difficulty of uninformed detection, mitigation of multipath fading, and antijamming. Moreover, a large number of spreading waveforms can be produced easily as a consequence of the sensitive dependence upon initial conditions and parameters variations. This provides a low cost and simple means for spread spectrum communications [1].

A number of modulation and demodulation schemes have been proposed for digital chaos based communications [2–5]. In most proposed methods, the basic principle is to map the digital symbols to nonperiodic chaotic basic signals. For instance, Chaos Shift Keying (CSK) maps different symbols to different chaotic basic signals, which are produced from various dynamical systems. If synchronized copies of the chaotic basis signals are available at the receiver, detection can be conducted by evaluating synchronization error [6] or based on a conventional correlator type [7, 8]. This class of detection is known as a coherent detection. An enhanced technique to improve BER is suggested in [9]. If synchronized copies of the chaotic basis signal are not available at the receiver, detection has to be done by noncoherent detection as in noncoherent CSK and Chaotic On-Off Keying (COOK). Detection depends on estimation of transmitted signal energy. However, determining an optimum threshold between signal elements is the major drawback due to noise power contribution [6, 7] and the noise performance can be increased only by increasing the distance between signal elements. This requires the transmitter to consume more energy for each bit to increase the distance between signal elements and the receiver. Noise performance in coherent system is superior to the noncoherent systems. On the other hand, accuracy in synchronization is required to be achieved in coherent systems, which is difficult task [8].

Another widely used technique for modulation is known as differential coherent systems where Differential Chaos Shift Keying (DCSK) and Correlation Delay Shift Keying (CDSK) [10] are the basic schemes. Each information bit is transmitted by the generation of twin chaotic segments; first signal is called reference and the second, which is modulated by the information bit, is called information bearing signal. Information detection is performed by correlating reference with the information signal over last half of bit duration. Therefore, half of the average bit energy is wasted with respect to noncoherent systems. An enhancement technique is suggested by using single reference signal for multiple bits transmission [11]. A generalized Correlation Delay Shift Keying scheme is suggested in [12] by producing several delayed versions of a chaotic signal; selected version is modulated with the information bits. Although the system requires bank of transmitter, it can achieve similar performance compared to that of DCSK at reasonable E_b/N_o range. Additionally, sending the reference signal and the information signal on the same time slot is discussed in [13–18]. Data rate and BER performance are increased, but schemes are complex and require additional synchronization circuits. Multicarrier modulation for DCSK (MC-DCSK) signal is explored in [13]. In spite of an efficient utilization of the transmitted energy, system implementation in (MC-DCSK) includes bank of narrow band modulator that needs a high degree of accuracy in the design to maintain subcarrier synchronization.

In this paper, we introduce new version of chaotic on-off scheme named (FCOOK). In FCOOK the stationary signal and its flipped version are added together within one bit duration to represent binary 1. for binary 0, no transmission takes place for the same bit duration. Based on the fact that the chaotic signal and its time flipped version are stationary, low cross correlation can be achieved [10]. This helps to design a new signal for the binary information transmission. The design allows the receiver to correlate each first half of incoming signal with the flipped version of the second half. Since both halves contain noncorrelated noise segments, this can be used to overcome the threshold shifting problem.

The remainder of this paper is organized as follows. Standard differentially coherent systems are described in Section 2. In Section 3, the transmitter and receiver models of FCOOK are described. Theoretical estimation of BER is derived in Section 4. Finally, simulation results are discussed in Section 5.

2. Chaos Based Systems: Revisited

2.1. DCSK. The transmitter structure of the DCSK is shown in Figure 1. Each information bit b, where $b \in \{1, -1\}$, is transmitted by sending two chaotic segments into successive identical time slots. Each slot is occupied by M samples, where $2M$ represent the spreading factor. First time slot contains a reference signal and second slot contains a delayed version of the reference signal multiplied by the information bit b. Therefore, the ith transmitted signal s_i for a single bit can be written as

$$s_i = \begin{cases} x_i, & 0 < i \le M, \\ bx_{i-M}, & M < i \le 2M. \end{cases} \tag{1}$$

Hence, average bit energy $E_b = 2MV(x_i)$, where $V(\cdot)$ is the variance operator and the expected value of $E(X) = 0$.

At the receiver, each received signal r_i is multiplied by its delayed version r_{i-M} and averaged over half bit duration. Assume that the channel is AWGN, and then the received

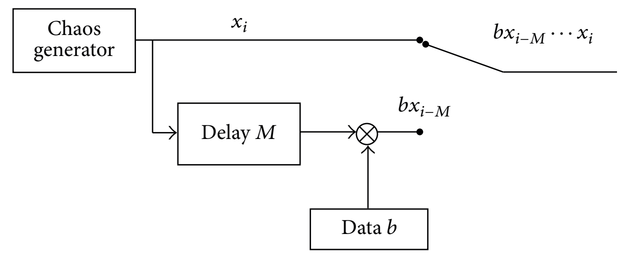

Figure 1: DCSK transmitter.

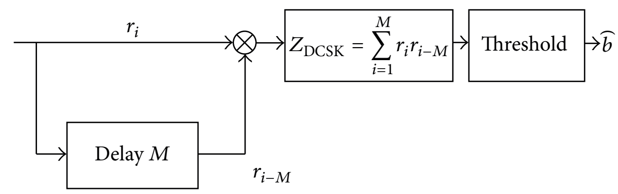

Figure 2: DCSK receiver.

signal $r_i = s_i + \zeta_i$, where ζ is stationary random process with $E(\zeta) = 0$ and the two-sided noise power spectral density is given by $V(\zeta) = N_o/2$. The correlator output Z_{DCSK} at the end of bit duration can be written as

$$\begin{aligned} Z_{\text{DCSK}} &= \sum_{i=1}^{M} r_i r_{i-M} = \sum_{i=1}^{M} (s_i + \zeta_i)(s_{i-M} + \zeta_{i-M}) \\ &= b\sum_{i=1}^{M} x_i^2 + \sum_{i=1}^{M} x_i (\zeta_{i-M} + b\zeta_i) + \sum_{i=1}^{M} \zeta_i \zeta_{i-M}. \end{aligned} \tag{2}$$

The DCSK receiver structure is shown in Figure 2. Information bit is decoded using the following rule:

$$\widetilde{b} = \begin{cases} 1, & Z_{\text{DCSK}} \ge 0, \\ -1, & Z_{\text{DCSK}} < 0. \end{cases} \tag{3}$$

Under the standard assumptions that x is stationary and x_i is statistically independent from ζ_j at any (i, j), correlator output Z_{DCSK} tends to have Gaussian distribution at sufficient value of M [10]. Therefore, theoretical evaluation can be obtained by calculating the mean and variance of conditional Probability Density Function (PDF) of Z_{DCSK} at ± 1. If $\Pr(0) = \Pr(1) = 0.5$, then BER can be calculated as [10]

$$\text{BER}_{\text{DCSK}} = \frac{1}{2}\operatorname{erfc}\left(\sqrt{\frac{E_b}{4N_o}\left(1 + \frac{2}{5M}\frac{E_b}{N_o} + \frac{N_o}{2E_b}M\right)^{-1}}\right), \tag{4}$$

where

$$\operatorname{erfc}(y) = \frac{2}{\sqrt{\pi}} \int_y^{\infty} e^{-t^2/2} dt. \tag{5}$$

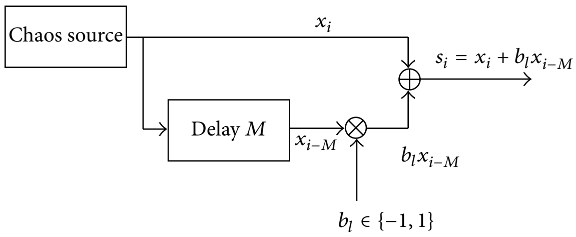

Figure 3: CDSK transmitter.

2.2. CDSK. Unlike DCSK, each information bit in CDSK is sent by transmitting a signal which is the sum of a chaotic sequence x_i and of the delayed chaotic sequence multiplied by the information signal $b_\ell x_{i-L}$, where ℓ is the bit counter. Thus, transmitted signal of CDSK at any instant i is given by

$$s_i = x_i + b_\ell x_{i-L}, \quad (\ell - 1) M < i \le \ell M, \tag{6}$$

where $L \ge M$ and $E_b = 2MV(x)$.

As shown in Figure 3, the CDSK transmitter differs from DCSK in that the switch in the transmitter is now replaced by an adder and the transmitted signal is never repeated. Therefore, data rate is doubled compared with that in DCSK [10]. Putting delay $L = M$, then the receiver of CDSK is similar to that of DCSK, and each segment is correlated with the previous one. Correlator output Z_{CDSK} can be calculated as

$$\begin{aligned} Z_{\text{CDSK}} &= \sum_{i=1}^{M} r_i r_{i-M} \\ &= \sum_{i=1}^{M} \left(x_i + b_\ell x_{i-M} + \zeta_i\right)\left(x_{i-M} + b_{\ell-M} x_{i-2M} + \zeta_{i-M}\right) \\ &= b_\ell \sum_{i=1}^{M} x_{i-M}^2 + \sum_{i=1}^{M} x_i x_{i-M} + b_{\ell-M} \sum_{i=1}^{M} x_i x_{i-2M} \\ &\quad + \sum_{i=1}^{M} x_i \zeta_{i-M} + b_\ell b_{\ell-M} \sum_{i=1}^{M} x_{i-M} x_{i-2M} \\ &\quad + b_\ell \sum_{i=1}^{M} x_{i-M} \zeta_{i-M} + \sum_{i=1}^{M} x_{i-M} \zeta_i + b_{\ell-M} \sum_{i=1}^{M} x_{i-2M} \zeta_i \\ &\quad + \sum_{i=1}^{M} \zeta_i \zeta_{i-M}. \end{aligned} \tag{7}$$

It can be clearly observed that the correlator output Z_{CDSK} contains more intrasignal and noise terms compared to DCSK. Thus, BER performance is decreased based on the previous assumptions in DCSK and given that $E(x_i x_{i+k}) = 0$, where k is an integer and $E(\cdot)$ is the average value. It can be easily shown that Z_{CDSK} has a Gaussian distribution and theoretical value of BER can be found by calculating the mean and variance of conditional PDF of Z_{CDSK} at +1 and −1

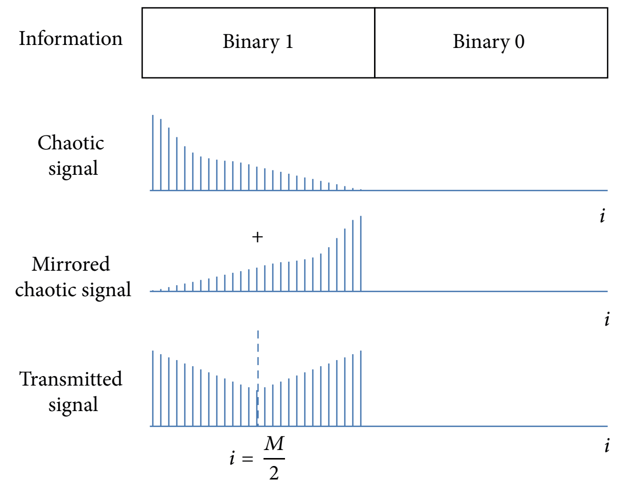

Figure 4: Flipped Chaotic On-Off Keying signal format for binary 1 and binary 0.

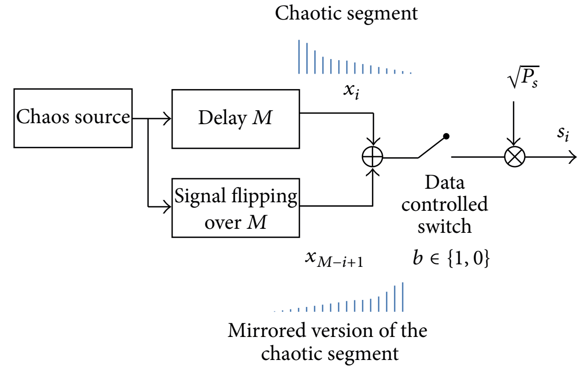

Figure 5: Flipped COOK transmitter.

transmission. Decoding is performed according to the same rule in (3). Thus, BER is given by [10]

$$\text{BER}_{\text{CDSK}} = \frac{1}{2}\operatorname{erfc}\left(\sqrt{\frac{E_b}{8N_o}\left(1 + \frac{19}{20M}\frac{E_b}{N_o} + \frac{N_o}{4E_b}M\right)^{-1}}\right). \tag{8}$$

3. Proposed Scheme: Flipped Chaotic On-Off Keying (FCOOK)

3.1. Signal Format. In our scheme, binary 1 is transmitted by sending the sum of adding identical, mirrored chaotic segments with length of M. Thereby, the resultant signal for binary 1 will be symmetric around $i = M/2$ as shown in Figure 4. On the other hand, the receiver keeps silence for binary 0 duration and no signal will be transmitted.

3.2. Transmitter Description. In order to generate the FCOOK signal in Figure 4, the FCOOK transmitter setup is proposed as shown in Figure 5. A flipped signal x_{M-i+1} is generated by receiving a copy of M samples and flipping them over one bit duration. This process requires the forward signal to be delayed for one bit duration till the end of one segment generation. To achieve time synchronization between the emitted segment and its flipped version, a delay element is inserted before the adder. However, this has no effect on system notation or analysis because we assume that both segments are ready to be added at any instant i. Then, the symmetric transmitted signal for single bit duration can be written as

$$s_i = b\sqrt{P_s}\left(x_i + x_{M-i+1}\right), \quad 0 < i \le M, \tag{9}$$

where $\sqrt{P_s}$ is signal level and $b \in \{1, 0\}$. Compared with (3), the FCOOK system transmits all the signal components only within M samples. This offers double bit rate compared with DCSK system.

3.3. Receiver Description. At the receiver, each incoming signal, r_i, is multiplied with its mirrored version r_{M-i+1} over duration of $M/2$ only to avoid having duplicated terms in the correlator output. Signal is mirrored by sampling and reverting the received signal over one bit duration as shown in Figure 6. The delay element is added to compensate the delay incurred in the time reversal of the received signal.

Assume that both transmitter and receiver are fully synchronized and the channel is AWGN; then the correlator output Z at the end of single bit duration can be given as

$$\begin{aligned} Z &= \sum_{i=1}^{M/2} r_i r_{M-i+1} = \left(b\sqrt{P_s}\left(x_i + x_{M-i+1}\right) + \zeta_i\right)\left(b\sqrt{P_s}\left(x_{M-i+1} + x_i\right) + \zeta_{M-i+1}\right) \\ &= \underbrace{bP_s \sum_{i=1}^{M/2}\left(x_i^2 + x_{M-i+1}^2\right)}_{A} + \underbrace{2bP_s \sum_{i=1}^{M/2}\left(x_i \cdot x_{M-i+1}\right)}_{B} + \underbrace{b\sqrt{P_s}\sum_{i=1}^{M/2}\left(x_i \cdot \zeta_{M-i+1}\right) + b\sqrt{P_s}\sum_{i=1}^{M/2}\left(x_{M-i+1} \cdot \zeta_M\right)}_{C} \\ &\quad + \underbrace{b\sqrt{P_s}\sum_{i=1}^{M/2}\left(x_i \cdot \zeta_i\right) + b\sqrt{P_s}\sum_{i=1}^{M/2}\left(x_{M-i+1} \cdot \zeta_{M-i+1}\right)}_{D} \underbrace{\sum_{i=1}^{M/2}\left(\zeta_i \cdot \zeta_{M-i+1}\right)}_{E}. \end{aligned} \tag{10}$$

Detector input Z consists of the required signal (A), intrasignal (B) term, signal-noise terms (C, D), and noise-noise term (E); all these terms are contributed only if binary 1 is transmitted. In binary 0 transmission, except for (E), all the terms are disappeared because $b = 0$ in (10).

For the sake of simplicity, we set the threshold α_{th} value at the middle between signal elements $(0, E_b)$. Thus, the received signal is decoded according to the following rule:

$$\tilde{b} = \begin{cases} 1, & Z \ge \alpha_{\text{th}}, \\ 0, & Z < \alpha_{\text{th}}. \end{cases} \tag{11}$$

4. Performance Evaluation

A baseband model is used to evaluate the BER performance of FCOOK. Our performance computation is based on Gaussian approximation method that provides good estimation of BER at large spreading factor [10, 15]. For small spreading factor values, bit energy distribution is required [19, 20]. We start our evaluation by revisiting some properties of chaotic signals and few standard assumptions.

Symmetric Tent Map, defined by the equation $x_{n+1} = 1 - 2|x_n|$, is applied to generate the discrete chaotic signal. Signal is stationary and is uniformly distributed between $(-1, 1)$ with zero mean and computed variances $V(x) = 1/3$ and $V(x^2) = 4/45 = 4/5 * V^2(x)$ [6].

Recall that a chaotic signal, as any spreading spectrum signals, has an impulse like autocorrelation value such that

$$E\left(x_i x_j\right) = \begin{cases} V\left(x_i\right), & i = j, \\ 0, & i \ne j. \end{cases} \tag{12}$$

Therefore, it is easy to show that, for sufficient value of M, $E(x_k x_{M-i+1}) = 0$, where $i \le M/2$ and

$$\begin{aligned} V\left(x_i x_{M-i+1}\right) &= V\left(x_i\right) + V\left(x_{M-i+1}\right) \\ &\quad - 2\operatorname{cov}\left(x_i x_{M-i+1}\right) \\ &\approx V\left(x_k\right) + V\left(x_{M-k+1}\right). \end{aligned} \tag{13}$$

It is logically to assume that ζ_i is statistically independent from x_i at any (i, j) and ζ_j for any $i \ne j$. Based on the central limit theorem and with previous assumptions, correlator output in (10) can be regarded as a Gaussian distributed [10]; thereby the performance can be fully characterized by calculating the mean and variances for the PDF of Z at binary 1 and 0 transmission. Hence,

$$\begin{aligned} E(Z \mid b = 1) &= E(A) + E(B) + E(C) + E(D) \\ &\quad + E(F) = P_s \sum_{i=1}^{M/2} E\left(x_i^2 + x_{M-i+1}^2\right) \\ &= P_s M V(x) = E_b, \end{aligned}$$

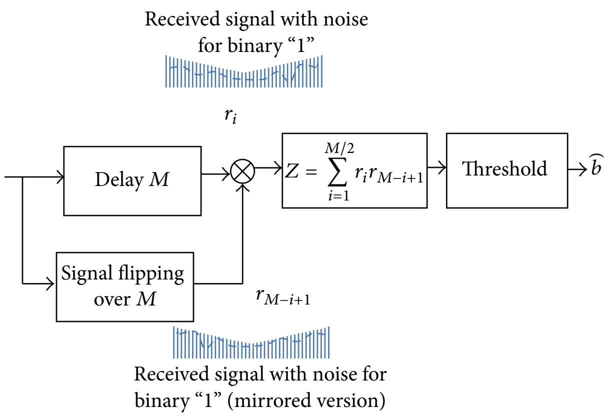

Figure 6: Flipped COOK receiver.

$$\begin{aligned}
V(Z \mid b=1) &= V(A) + V(B) + V(C) + V(D) \\
&\quad + V(E), \\
V(A) &= \sum_{i=1}^{M/2} V\left(P_s x_i^2 + P_s x_{M-i+1}^2\right) \\
&= \frac{4}{5} P_s^2 M V(x) V(x) = \frac{4}{5}\frac{E_b^2}{M}, \\
V(B) &= V\left(2\sum_{i=1}^{M/2} P_s x_i x_{M-i+1}\right) \\
&= 4P_s^2 V\left(\sum_{i=1}^{M/2} x_i x_{M-i+1}\right) = 2\frac{E_b^2}{M}, \\
V(C) &= V\left(\sqrt{P_s}\sum_{i=1}^{M/2}\left(x_i \cdot \zeta_{M-i+1}\right)\right) \\
&\quad + V\left(\sqrt{P_s}\sum_{i=1}^{M/2}\left(x_{M-i+1} \cdot \zeta_{M}\right)\right) \\
&= MP_s V(x) V(\zeta) = \frac{E_b N_o}{2}.
\end{aligned} \tag{14}$$

Similarly $V(D) = E_b N_o/2$. Consider

$$\begin{aligned}
V(E) &= V\left(\sum_{i=1}^{M/2} \zeta_i \zeta_{M-i+1}\right) = \sum_{i=1}^{M/2} V\left(\zeta_i \zeta_{M-i+1}\right) \\
&= \frac{MN_o^2}{8}, \\
V(Z \mid b=1) &= \frac{4}{5}\frac{E_b^2}{M} + 2\frac{E_b^2}{M} + E_b N_o + \frac{MN_o^2}{8} \\
&= \frac{14}{5}\frac{E_b^2}{M} + E_b N_o + \frac{MN_o^2}{8}, \\
E(Z \mid b=0) &- 0, \\
V(Z \mid b=0) &= V(E) = \frac{MN_o^2}{8}.
\end{aligned} \tag{15}$$

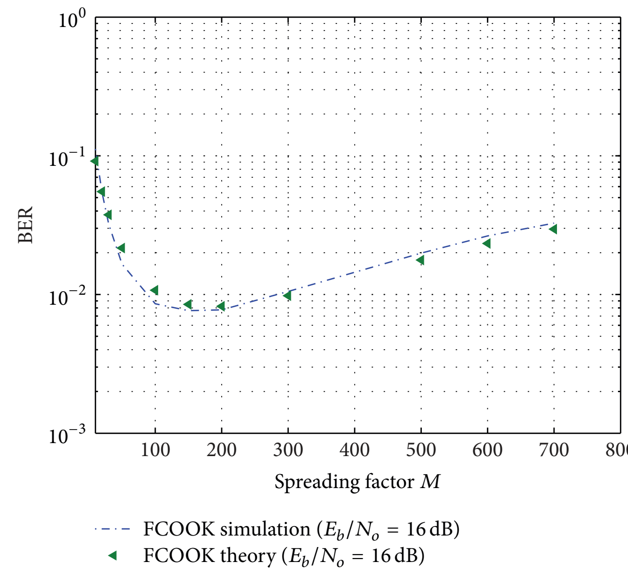

Figure 7: BER performance versus spreading factor M.

If the input to the decision device is less than the threshold α_{th}, a received bit 1 can be detected as bit 0, while bit 0 can be detected as bit 1 if the metric is more than the threshold and assumes that $P_r(0) = P_r(1) = 0.5$.

Then the average probability of error, P_e, can be expressed as

$$\begin{aligned}
P_e = \frac{1}{2}\Bigg(&\frac{1}{\sqrt{2\pi V(Z \mid b=1)}}\int_{-\infty}^{\alpha_{\text{th}}} e^{-(Z-E_b)^2/2V(Z|b=1)} dZ \\
&+ \frac{1}{\sqrt{2\pi V(Z \mid b=0)}}\int_{\alpha_{\text{th}}}^{\infty} e^{-Z^2/2V(Z|b=0)} dZ\Bigg),
\end{aligned} \tag{16}$$

$$\begin{aligned}
P_e = \frac{1}{2}\Bigg(&Q\left(\sqrt{\frac{E_b}{N_o}\left(\frac{14E_b}{MN_o} + 1 + \frac{M}{8}\frac{N_o}{E_b}\right)^{-1}}\right) \\
&+ Q\left(\frac{E_b}{N_o}\sqrt{\frac{2}{M}}\right)\Bigg).
\end{aligned} \tag{17}$$

5. Simulation Results and Discussion

In this section, the BER performance of DCSK, CDSK, and FCOOK is tested with the wide range of spreading factors M values and at various E_b/N_o levels. To have fair comparison, signal level in the proposed scheme is set to $\sqrt{2}$. Hence average energy E_b for each bit is given, $(4MV(x) + 0)/2 = 2MV(x)$. This is exactly equal to the average bit energy used in DCSK and CDSK [10].

Apparently, small disagreement between theoretical estimation and simulation results appears at relatively small M in Figure 7. This is one of Gaussian approximation method drawback as mentioned in Section 4. However, clear agreement between analytical estimate and the simulation results can be observed at $M > 100$, which positively supports our closed form expression in (17). Additionally, the suboptimum

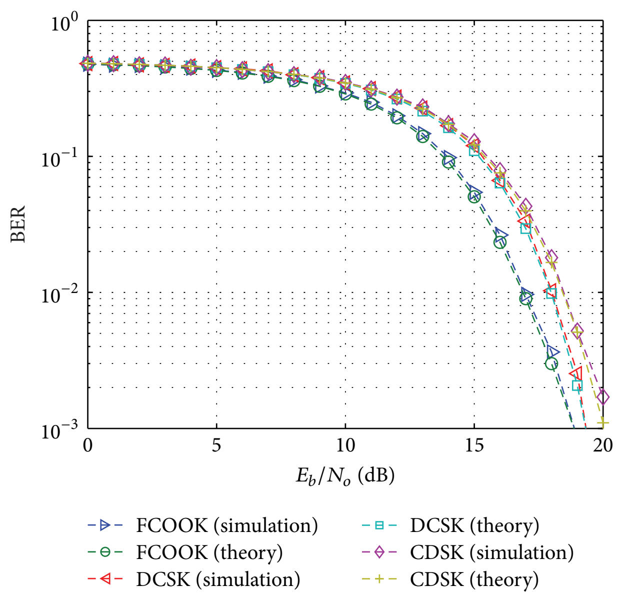

FIGURE 8: Relation between BER and E_b/N_o for DCSK, CDSK, and FCOOK by simulations and theoretical estimation at $M = 100$.

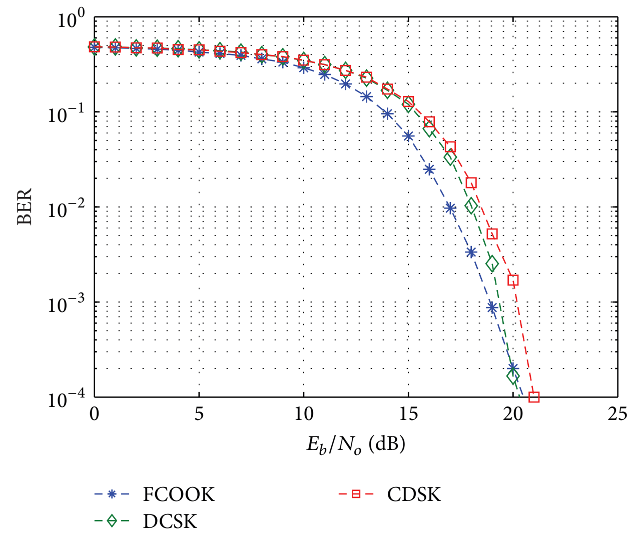

FIGURE 10: Simulated BERs versus E_b/N_o for FCOOK, DCSK, and CDSK at $M = 600$.

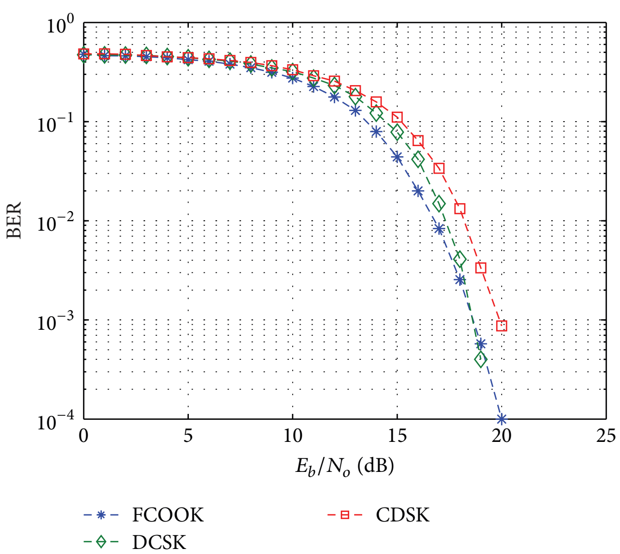

FIGURE 9: Simulated BERs versus E_b/N_o for FCOOK, DCSK, and CDSK at $M = 500$.

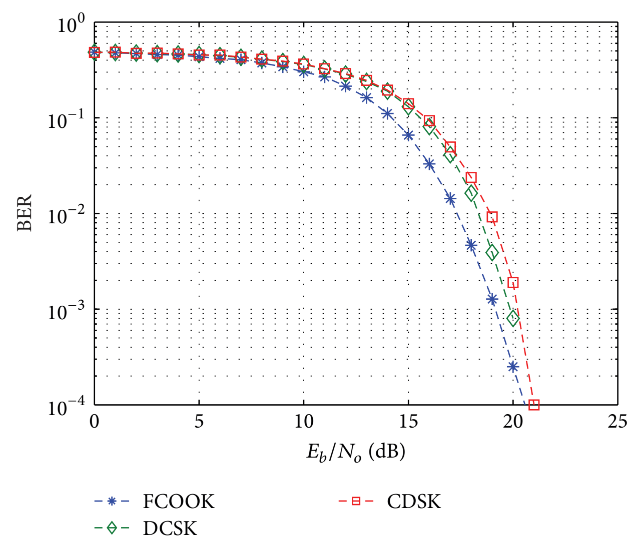

FIGURE 11: Simulated BERs versus E_b/N_o for FCOOK, DCSK, and CDSK at $M = 700$.

performance for our prosed system can be noticed between $M = 100$ and $M = 200$, but this decreases after $M = 200$. The reason behind this performance is that when M increases, the noise-noise contribution grows faster than the signal energy in (10).

The theoretical estimations for BER, which are obtained by Gaussian approximation method in [10, 15], and simulation results for DCSK and CDSK are compared with FCOOK at $M = 100$ as shown in Figure 8. In addition to the matching between theoretical estimation and simulation results, FCOOK can always pass the performance of CDSK and outperform DCSK in considerable range of E_b/N_o.

Furthermore, CDSK seems always to be 2 dB worse than FCOOK in Figures 9, 10, and 11, respectively; the reason of which is that there are much more intrasignal interference and noise interference components in the correlator output of CDSK. The proposed system performs almost 1 dB better than DCSK with $M = 600$ and 700 at E_b/N_o less than 18 dB. This can be explained by the fact that, compared to DCSK, the contribution of noise terms in (2) is halved. This contribution is the reason of nonlinearity at large value of M which causes all the systems to have low BER performances at very large spreading factors.

6. Conclusion

A new chaotic communication scheme named FCOOK is developed for binary transmission. The system makes an advantage of the low correlation between the chaotic segments and its mirrored twin. The BER performance of the system is derived analytically using Gaussian approximation method. Simulation results illustrate the capability of the expression to predict BER at different spreading factor. Moreover, performance of the proposed scheme is compared with DCSK and CDSK systems by plotting BER with E_b/N_o at the same spreading factor. Results show that FCOOK has advantage of 2 dB compared with CDSK and 1 dB compared with the DCSK.

Competing Interests

The authors declare that they have no competing interests.

References

[1] G. Kolumban, M. P. Kennedy, and L. O. Chua, "The role of synchronization in digital communications using chaos. II. Chaotic modulation and chaotic synchronization," *IEEE Transactions on Circuits and Systems. I. Fundamental Theory and Applications*, vol. 45, no. 11, pp. 1129–1140, 1998.

[2] A. Gholipour, B. N. Araabi, and C. Lucas, "Predicting Chaotic time series using neural and neurofuzzy models: a comparative study," *Neural Processing Letters*, vol. 24, no. 3, pp. 217–239, 2006.

[3] B. R. Andrievsky and A. L. Fradkov, "Adaptive-based methods for information transmission by means of chaotic signal source modulation," *Automation and Remote Control*, vol. 72, no. 9, pp. 1967–1980, 2011.

[4] S. Arai and Y. Nishio, "Noncoherent correlation-based communication systems choosing different chaotic maps," in *Proceedings of the IEEE International Symposium on Circuits and Systems (ISCAS '07)*, pp. 1433–1436, May 2007.

[5] T.-I. Chien, Y.-C. Hung, and T.-L. Liao, "A non-correlator-based digital communication system using interleaved chaotic differential peaks keying (I-CDPK) modulation and chaotic synchronization," *Chaos, Solitons and Fractals*, vol. 29, no. 4, pp. 965–977, 2006.

[6] F. C. M. Lau and C. K. Tse, *Chaos-Based Digital Communication Systems: Operating Principles, Analysis Methods, and Performance Evaluation*, Springer, Berlin, Germany, 2003.

[7] G. Kis, Z. Jako, M. P. Kennedy, and G. Kolumban, "Chaotic communications without synchronization," in *Proceedings of the 6th IEE Conference on Telecommunications*, pp. 49–53, IEE, April 1998.

[8] G. Kolumbán, M. P. Kennedy, Z. Jákó, and G. Kis, "Chaotic communications with correlator receivers: theory and performance limits," *Proceedings of the IEEE*, vol. 90, no. 5, pp. 711–732, 2002.

[9] M. Long, Y. Chen, and F. Peng, "Bit error rate improvement for chaos shift keying chaotic communication systems," *IET Communications*, vol. 6, no. 16, pp. 2639–2644, 2012.

[10] M. Sushchik, L. S. Tsimring, and A. R. Volkovskii, "Performance analysis of correlation-based communication schemes utilizing chaos," *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*, vol. 47, no. 12, pp. 1684–1691, 2000.

[11] G. Kolumban, Z. Jako, and M. P. Kennedy, "Enhanced versions of DCSK and FM-DCSK data transmission systems," in *Proceedings of the IEEE International Symposium on Circuits and Systems (ISCAS '99)*, vol. 4, pp. 475–478, IEEE, Orlando, Fla, USA, June 1999.

[12] W. N. Tam, F. C. M. Lau, and C. K. Tse, "Generalized correlation-delay-shift-keying scheme for noncoherent chaos-based communication systems," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 53, no. 3, pp. 712–721, 2006.

[13] G. Kaddoum, F.-D. Richardson, and F. Gagnon, "Design and analysis of a multi-carrier differential chaos shift keying communication system," *IEEE Transactions on Communications*, vol. 61, no. 8, pp. 3281–3291, 2013.

[14] P. Chen, L. Wang, and F. C. M. Lau, "One analog STBC-DCSK transmission scheme not requiring channel state information," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 60, no. 4, pp. 1027–1037, 2013.

[15] H. Yang and G.-P. Jiang, "High-efficiency differential-chaos-shift-keying scheme for chaos-based noncoherent communication," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 59, no. 5, pp. 312–316, 2012.

[16] H. Yang and G.-P. Jiang, "Reference-modulated DCSK: a novel chaotic communication scheme," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 60, no. 4, pp. 232–236, 2013.

[17] W. Xu, L. Wang, and G. Chen, "Performance analysis of the CS-DCSK/BPSK communication system," *IEEE Transactions on Circuits and Systems I*, vol. 61, no. 9, pp. 2624–2633, 2014.

[18] H. Yang, G.-P. Jiang, and J. Duan, "Phase-separated DCSK: a simple delay-component-free solution for chaotic communications," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 61, no. 12, pp. 967–971, 2014.

[19] G. Kaddoum, P. Chargé, D. Roviras, and D. Fournier-Prunaret, "A methodology for bit error rate prediction in chaos-based communication systems," *Circuits, Systems, and Signal Processing*, vol. 28, no. 6, pp. 925–944, 2009.

[20] G. Kaddoum, P. Chargé, and D. Roviras, "A generalized methodology for bit-error-rate prediction in correlation-based communication schemes using chaos," *IEEE Communications Letters*, vol. 13, no. 8, pp. 567–569, 2009.