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Chaos-Based Communication Systems

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Abstract

The attractive properties of chaos signal that is generated from dynamic systems motivate the researchers to explore the advantage of using this signal type as a carrier in different communication systems. In this chapter, different types of digital chaos-based communication system are discussed; in particular, digital communications where reference signal and its modulated version are transmitted together. This type is called differential coherent systems. Brief surveys on the recently developed systems are presented.

Keywords: chaos, coherent systems, non-coherent systems, differentially coherent systems, DCSK, CDSK, HE-DCSK, TR-DCSK, EF-DCSK

1. Introduction

In digital communication systems, sinusoidal carriers with high frequency are used to carry information by modulation process where these carriers are deterministic with constant power over the time of transmission. Another proposed type of carriers is currently analyzed and is called chaotic. The chaotic signal is non-periodic, random-like, with low cross-correlation and impulse-like auto correlation. It is derived from dynamical systems, particularly from the independent state variables. The instantaneous value is often bounded between two constant peaks determined by the trajectory of the generated maps. To simplify the description of chaotic signal generation, let us consider the discrete time presentation for the iterative equation, that is, $x_n = f(x_{n-1}, u)$ where x_n is output vector of the state variable sampled at n th instant, $f(x_{n-1})$ is the iterative function determined by the map, finally μ is the parameter which controls the behavior of the chaotic function.

In chaos-based digital communications, bits are mapped to actual non-periodic output of chaotic circuits and the sample function for a given symbol is non-periodic and different from one bit to another [1]. Sample of chaos-based signal for symmetric tent map is shown in **Figure 1**.

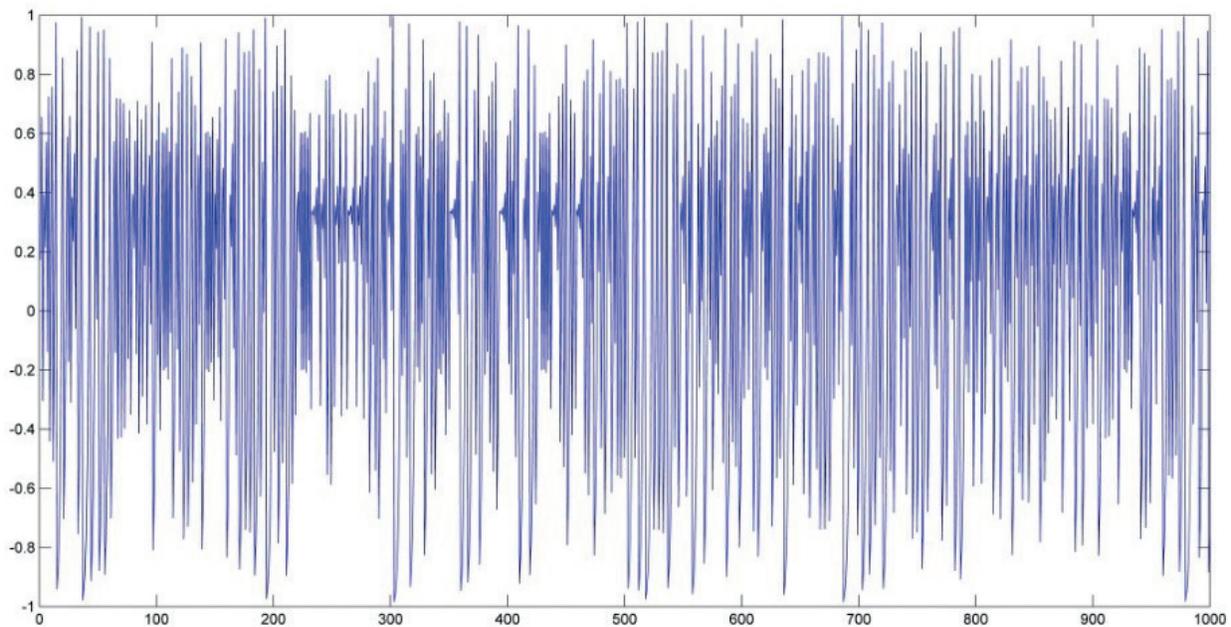


Figure 1. Chaotic signal generated by symmetric tent map.

Based on the previous discussion, receivers of digital chaotic communication systems can be broadly classified according to the receiver structures such as coherent, non-coherent and differentially coherent systems [2].

2. Types of chaos-based digital communication systems

2.1. Coherent systems

In coherent systems, a local synchronized copy of each sample function has to be produced at the receiver. When the transmitted signal is corrupted by the random noise, it will be challenging to synchronize the local generated carrier with that in the transmitters as in coherent shift keying (CSK) [1]. The idea of CSK is to map each information bit to chaos bases signal say f_1 and f_2 . If “+1” is to be sent, then chaos signal from generator f_1 is to be transmitted with one bit duration, and if “-1” is to be sent, chaos signal from generator f_2 is transmitted with same bit duration. The receiver should generate exact copy from f_1 and f_2 to recover the information. This is done by using dedicated synchronization circuits [3].

2.2. Non-coherent systems

This type of chaos receivers offers simple solution for synchronization problem by estimating one unique parameter such as power. This is achieved by multiplying and integrating the product of received sample signal with itself to estimate the signal energy. Chaos ON OFF keying (COOK) and non-coherent chaos shift keying are a practical implementation of this idea [4]. In COOK, the signal is transmitted within bit duration only if information “+1” is to be transmitted. Otherwise, no transmission is taken place at “-1” bit duration. A bit control

switch is used to control the emission of signal at the transmitter output. However, obtaining an optimum threshold to distinguish between signal sets does not depend only on signal power at the correlator output but also on the noise power estimation that is the major drawback of such systems [1].

2.3. Differentially coherent systems

Another scheme is developed where a reference signal is followed by another reference signal modulated by the information bit and called information carrying signal. This arrangement is known as differentially coherent systems. Here, every bit is presented by two sample functions. In the case of bit 1 transmission, the information is sent by transmitting two identical sample functions. For bit 0, the reference signal is transmitted and followed by an inverted copy of the sample function. General structure of the receiver is based on how to correlate the reference signal with information bearing signal.

Differentially coherent systems show better bit error rate (BER) performance among other existing chaos-based systems and in different channel conditions [5]. In spite of some structure complexity, hardware design is studied and tested.

In this chapter, standard differentially coherent schemes are described and tested by computer simulations, analytical expression to estimate BER in additive white Gaussian channel is obtained using Gaussian approximation method [6, 7]. A brief description of recently developed system is discussed.

3. Differential coherent systems

3.1. Differential chaos shift keying

Differential chaos shift keying (DCSK) transmitter structure is shown in **Figure 1**. Each information bit is represented by twin of successive chaotic signal slots with length of samples, where $2M$ represents the spreading factor. First time slot contains a reference signal and second slot contains the information bearing signal. That is simply a delayed version of the reference signal multiplied by the information bit. Thus, the instantaneous value of the transmitted signal at any instant can be written as

$$S_i = \begin{cases} x_i & 0 < i \leq M \\ b x_{i-M} & M < i \leq 2M \end{cases} \quad (1)$$

Average bit energy for a single bit can be given by:

$$E_b = 2MV(x_i) \quad (2)$$

where $V(\cdot)$ is the variance operator.

There are many chaotic maps which can be used as a signal source [1, 8]. However, symmetric tent map is selected to produce the chaotic signal due to its simplicity. Its discrete form is given

by the equation $x_{n+1} = 1 - 2|x_n|$ where x is uniformly distributed between 1 and -1 . It can be easily shown that $E(x) = 0$, $V(x) = \frac{1}{3}$ and $V(x^2) = \frac{4}{45}$ [1] where $E(\cdot)$ represents the average operator [6, 9, 10].

Received signal sample $r_i = s_i + \zeta_i$ is received via noisy channel characterized by Gaussian distribution where noise sample ζ_i is stationary random process with $E(\zeta) = 0$ and its power spectral density given by $V(\zeta) = \frac{N_0}{2}$. The received sample is multiplied by its delayed version r_{i-M} and the multiplication output is integrated over half bit duration M . Assuming that synchronization is achieved perfectly at the DCSK receiver shown in **Figure 3**. Then, the correlator output Z_{DCSK} at the end of bit duration can be described.

$$\begin{aligned} Z_{DCSK} &= \sum_{i=1}^M r_i r_{i-M} = \sum_{i=1}^M (S_i + \zeta_i)(S_{i-M} + \zeta_{i-M}) \\ &= b \sum_{i=1}^M x_i^2 + \sum_{i=1}^M x_i(\zeta_{i-M} + b\zeta_i) + \sum_{i=1}^M \zeta_i \zeta_{i-M} \end{aligned} \quad (3)$$

Average value of the correlator output can be determined by the value of information bit in the first term, while other terms will have mean value of zero due to their statistical independence [1, 6, 9, 11]. The correlator output is passed to the detector with zero threshold value to minimize BER as described in (4).

$$\tilde{b} = \begin{cases} 1 & Z_{DCSK} \geq 0 \\ -1 & Z_{DCSK} < 0 \end{cases} \quad (4)$$

As the chaotic signal 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 . Therefore, BER analytical evaluation of DCSK is obtained by calculating the means and variances of conditional probability of $P(Z_{DCSK} | b = 1)$ and $P(Z_{DCSK} | b = -1)$, respectively; then theoretical estimate of BER can be calculated as (5)

$$BER_{DCSK} = \frac{1}{2} \operatorname{erfc} \left(\sqrt{\frac{E_b}{4N_0} \left(1 + \frac{2 E_b}{5M N_0} + \frac{N_0}{2E_b} M \right)^{-1}} \right) \quad (5)$$

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

Two major drawbacks of DCSK systems are as follows: (1) data rate is reduced by half because of the need of separate reference signal and (2) a technical issue can be generated from continuous change of switch position in **Figure 2**.

3.2. CDSK

Sending reference signal and information bearing signals in separate time slot will result in data rate reduction by half. Instead, orthogonality between each chaotic signal and its delayed

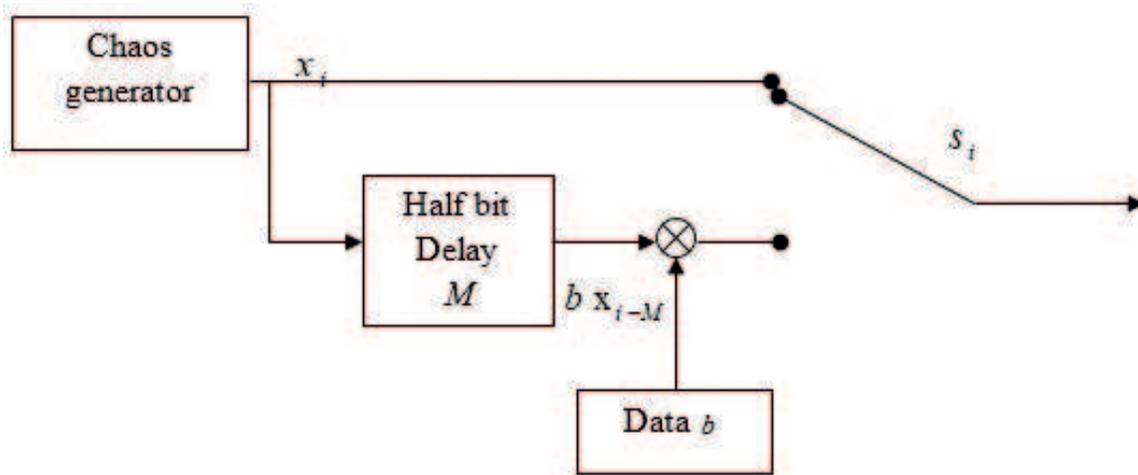


Figure 2. DCSK transmitter.

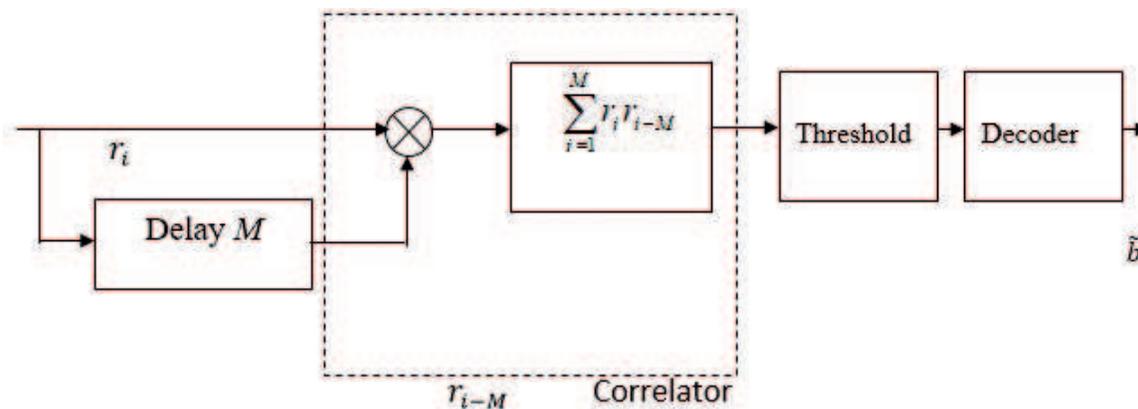


Figure 3. DCSK receiver.

version can be utilized efficiently by adding the generated chaotic signal with the modulated version of the previous signal. This scheme is known as correlation delay shift keying (CDSK) [6]. Information bit is sent by transmitting a signal as the sum of a chaotic sequence x_i and of the delayed chaotic sequence multiplied by the information signal $b_l x_{i-L}$ where l is the bit counter and L is the amount of sequence to be delayed. Hence, the transmitted signal of CDSK at any instant i is given by

$$s_i = x_i + b_l x_{i-L} \quad (l-1)M < i \leq lM \quad (6)$$

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

Compared with structure of DCSK, structure of CDSK transmitter is characterized by replacing the switch by an adder as illustrated in Figure 4. Data rate is doubled when compared with DCSK because of reference time slot utilization [6]. Putting delay $L=M$, then the receiver of CDSK is similar to that DCSK and each received sample r_i segment is correlated with the previous one r_{i-M} . Hence, correlator output Z_{CDSK} can be computed as

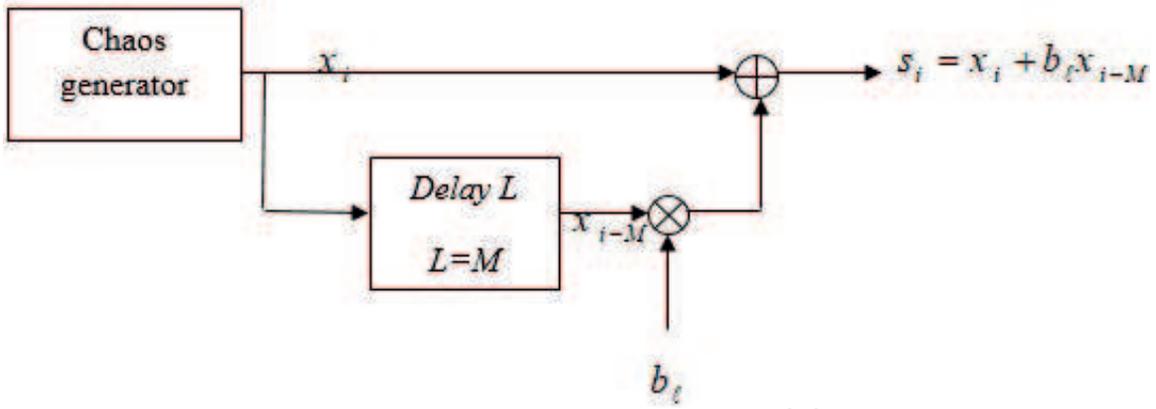


Figure 4. CDSK transmitter.

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

It can be clearly observed that the correlator output Z_{CDSK} contains more intra-signal and noise terms compared to DCSK. Hence, BER performance is expected to be lower. The cross terms in (7) is statistically independent and Z_{CDSK} tends to have Gaussian distribution at sufficient value of M . Theoretical value of BER can be found by calculating the mean and variance of Z_{CDSK} when the transmitted bit is $+1$ and -1 , respectively. Decoding is performed according to the same rule in (4) and BER is given by [6].

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

3.3. High efficiency-differential chaos shift keying (HE-DCSK)

To enhance the bandwidth efficiency of DCSK and CDSK, a pair of information bits can be modulated using same reference signal by reusing each reference signal twice [9]. First, reference signal is modulated with information bit after delay of M sequence as a standard DCSK. Second, information bit is modulated after the delay of $3M$. Both modulated segments are added together in the second time slot. The scheme is illustrated in Figure 5. Thus, transmitted signal which is emitted from HE-DCSK transmitter can be written as:

$$S_i = \begin{cases} x_i & 2kM < i \leq (2k+1)M \\ b_{2k} x_{i-M} + b_{2k-1} x_{i-3M} & (2K+1)M < i \leq (2K+1)M \end{cases} \tag{9}$$

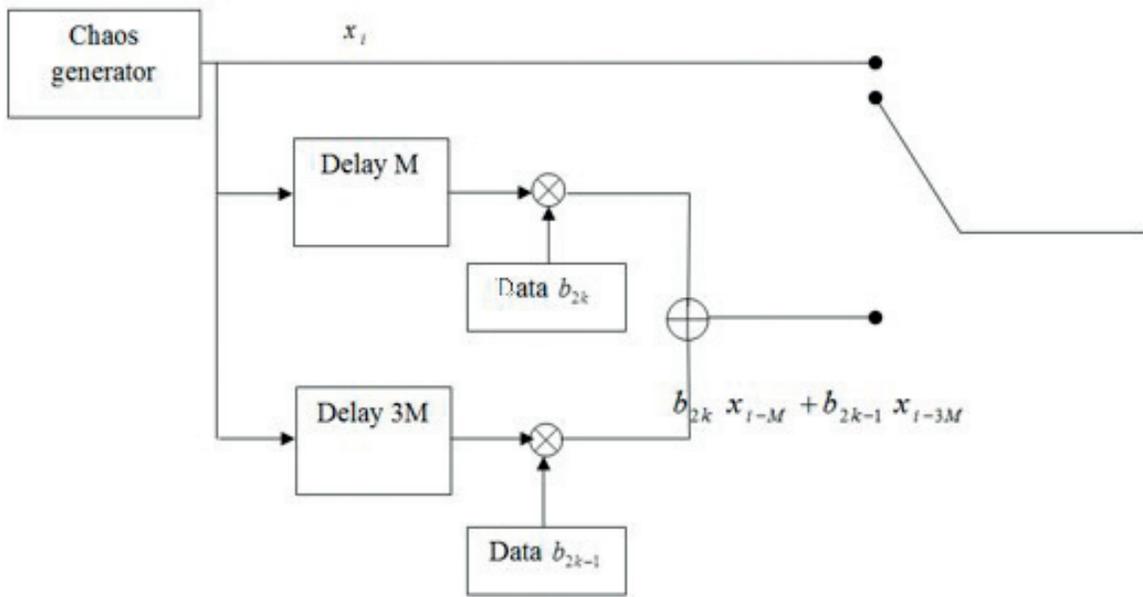


Figure 5. HE-DCSK transmitter diagram.

where k is the pair sequence number. Signal is received through AWGN where each received signal is delayed and correlated twice, first, after M samples delay and second, after $3M$ as shown in Figure 6. The scheme represents an extended version of DCSK receiver, therefore the output of first modulator Z_i can be given by:

$$\begin{aligned}
 Z_1 &= \sum_{i=1}^M r_i r_{i-M} = \sum_{i=1}^M (S_i + \zeta_i)(S_{i-M} + \zeta_{i-M}) = \sum_{i=1}^M (x_{i-M} + \zeta_i)(b_{2k}x_{i-M} + b_{2k-1}x_{i-3M} + \zeta_i) \\
 &= b_{2k} \sum_{i=1}^M x_{i-M}^2 + b_{2k-1} \sum_{i=1}^M x_{i-M}x_{i-3M} + b_{2k} \sum_{i=1}^M x_{i-M}\zeta_{i-M} + b_{2k-1} \sum_{i=1}^M x_{i-3M}\zeta_{i-M} + \sum_{i=1}^M x_{i-M}\zeta_i + \sum_{i=1}^M \zeta_i\zeta_{i-M}
 \end{aligned} \tag{10}$$

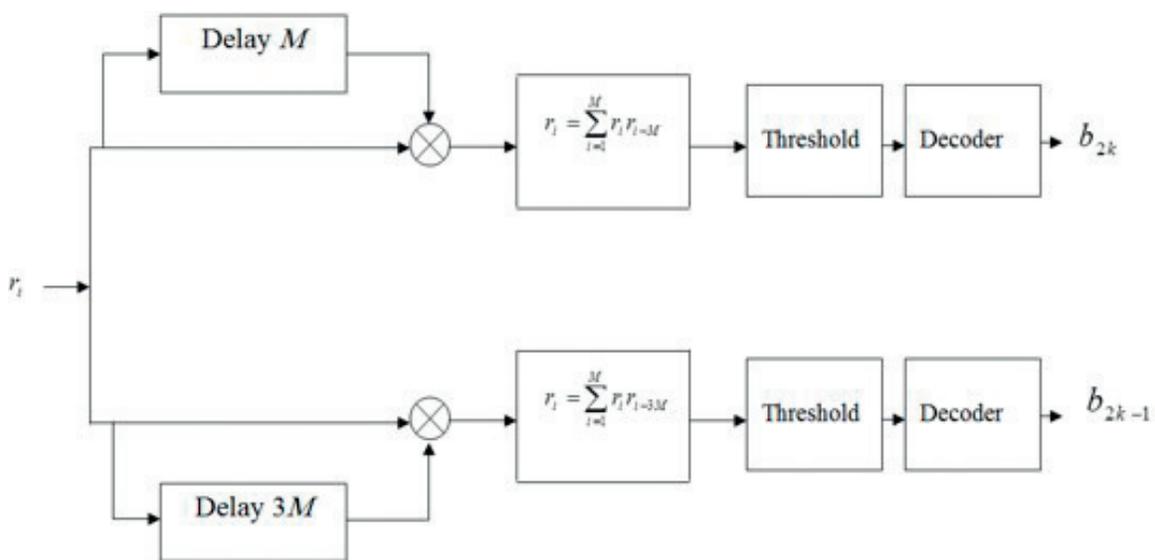


Figure 6. HE-DCSK receiver diagram.

Similarly, Z_2 can be calculated by $Z_2 = \sum_{i=1}^M r_i r_{i-3M}$. Average value of the first term in (10) contains the useful signal energy while the remaining terms are having zero mean. Information recovery is performed by comparing Z_1 and Z_2 with zero-based threshold defined by the following equation.

$$\tilde{b}_{2k} = \begin{cases} 1 & Z_1 \geq 0 \\ -1 & Z_1 < 0 \end{cases} \tag{11}$$

$$\tilde{b}_{2k-1} = \begin{cases} 1 & Z_2 \geq 0 \\ -1 & Z_2 < 0 \end{cases} \tag{12}$$

Both correlator output Z_1 and Z_2 exhibit Gaussian distribution. BER of any correlator can be given as [9]

$$BER_{HE-DCSK} = \frac{1}{2} \operatorname{erfc} \left(\sqrt{\frac{E_b}{4N_o} \left(\frac{9}{8} + \frac{9}{10M} \frac{E_b}{N_o} + \frac{9}{32} \frac{N_o}{2E_b} M \right)^{-1}} \right) \tag{13}$$

3.4. Time reversal-differential chaos shift keying (TR-DCSK)

The system is initially proposed [12] and developed by Albassam [13]. In this scheme, reference signal is generated and added to its time-reversed version. Hence, no separate time slot for reference signal is needed. This will generate a symmetric signal around the middle of bit duration. First half is transmitted directly and the second half is modulated with information bit. Provided that M is spreading factor, transmitted signal can be given by

$$S_i = \begin{cases} x_i + x_{M-i+1} & 0 < i \leq \frac{M}{2} \\ b(x_i + x_{M-i+1}) & \frac{M}{2} < i \leq M \end{cases} \tag{14}$$

Transmitter block diagram is illustrated in **Figure 7**.

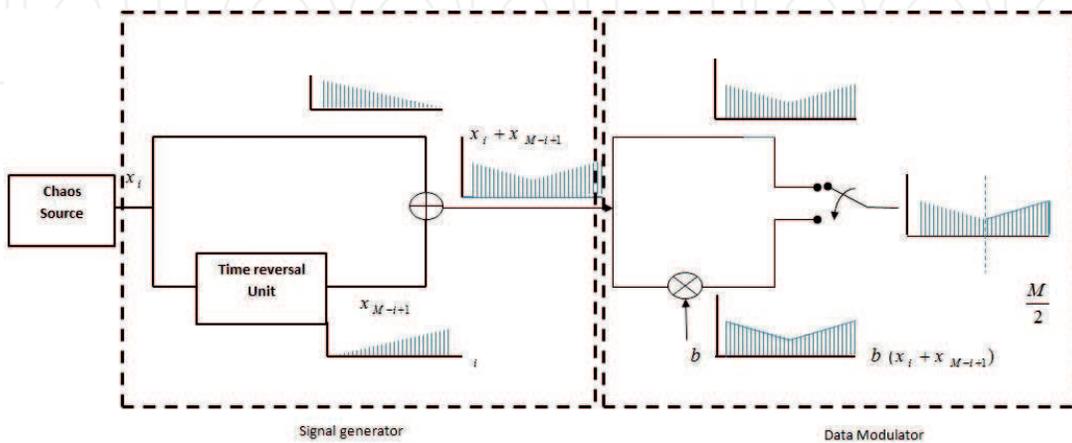


Figure 7. Time reversal DCSK transmitter.

Channel under investigation is AWGN and the received signal can be written as

$$r_i = \begin{cases} x_i + x_{M-i+1} + \zeta_i & 0 < i \leq \frac{M}{2} \\ b(x_i + x_{M-i+1}) + \zeta_i & \frac{M}{2} < i \leq M \end{cases} \quad (15)$$

At the receiver, each incoming noisy segment undergoes time reversal process. Hence, the output after the time reversal unit r'_i can be given as

$$r'_i = \begin{cases} b(x_{M-i+1} + x_i) + \zeta_{M-i+1} & 0 < i \leq \frac{M}{2} \\ (x_i + x_{M-i+1}) + \zeta_{M-i+1} & \frac{M}{2} < i \leq M \end{cases} \quad (16)$$

Perfect bit synchronization is assumed where each incoming signal r_i is correlated with time-reversed version r'_i . Due to signal symmetry, correlator output is integrated over the duration of $\frac{M}{2}$, which is twice as in DCSK and CDSK. This is to avoid the effect of redundant signal components in the second half (i.e., $> \frac{M}{2}$). The correlator output Z at the end of first bit duration can be given as

$$\begin{aligned} Z &= \sum_{i=1}^{\frac{M}{2}} r_i r'_i = \sum_{i=1}^{\frac{M}{2}} (x_i + x_{M-i+1} + \zeta_i) b(x_{M-i+1} + x_i + \zeta_{M-i+1}) \\ Z &= b \sum_{i=1}^{\frac{M}{2}} x_i^2 + b \sum_{i=1}^{\frac{M}{2}} x_{M-i+1}^2 + 2b \sum_{i=1}^{\frac{M}{2}} x_i x_{M-i+1} + b \sum_{i=1}^{\frac{M}{2}} x_i \zeta_i + b \sum_{i=1}^{\frac{M}{2}} x_{M-i+1} \zeta_{M-i+1} + \sum_{i=1}^{\frac{M}{2}} x_i \zeta_{M-i+1} \\ &\quad + b \sum_{i=1}^{\frac{M}{2}} x_{M-i+1} \zeta_i + b \sum_{i=1}^{\frac{M}{2}} \zeta_{M-i+1} \zeta_i \end{aligned} \quad (17)$$

Similarly, BER rate can be readily shown to have

$$BER_{TRDCSK} = \text{erfc} \left(\sqrt{\frac{E_b}{4N_o} \left(\frac{14 E_b}{10 N_o} + 1 + \frac{M N_o}{4 E_b} \right)^{-1}} \right) \quad (18)$$

3.5. Energy efficient-differential chaos shift keying (EF-DCSK)

In all previous systems, each transmitted signal is composed of two separate segments such as reference signal and information bearing signal. A simplified system with minimum energy requirement is proposed in Ref. [14]. Simply, a chaos source generates a signal for one bit to be sent as a reference. Then, the transmitter will decide to send either same reference signal or newly generated one using a bit controlled switch as shown in **Figure 9**. For example, if information bit 1 is transmitted, delayed version of the reference signal is transmitted. Otherwise, the transmitter will generate a new signal. Therefore, each segment will play a dual role; one as information bearing signal at the time of bit generation and as a reference signal for the next bit duration. This eliminates the need for sending reference separately. Without loss of

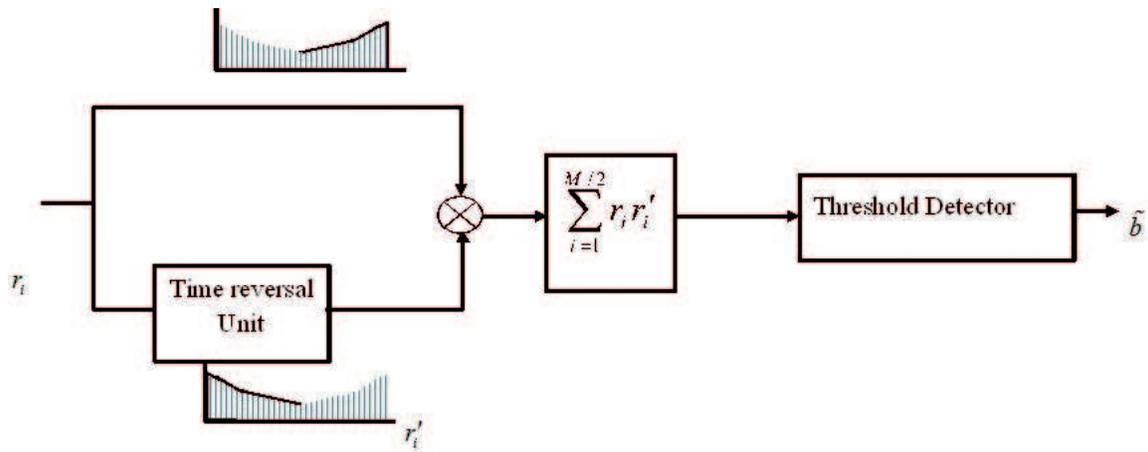


Figure 8. Time reversal DCSK receiver diagram.

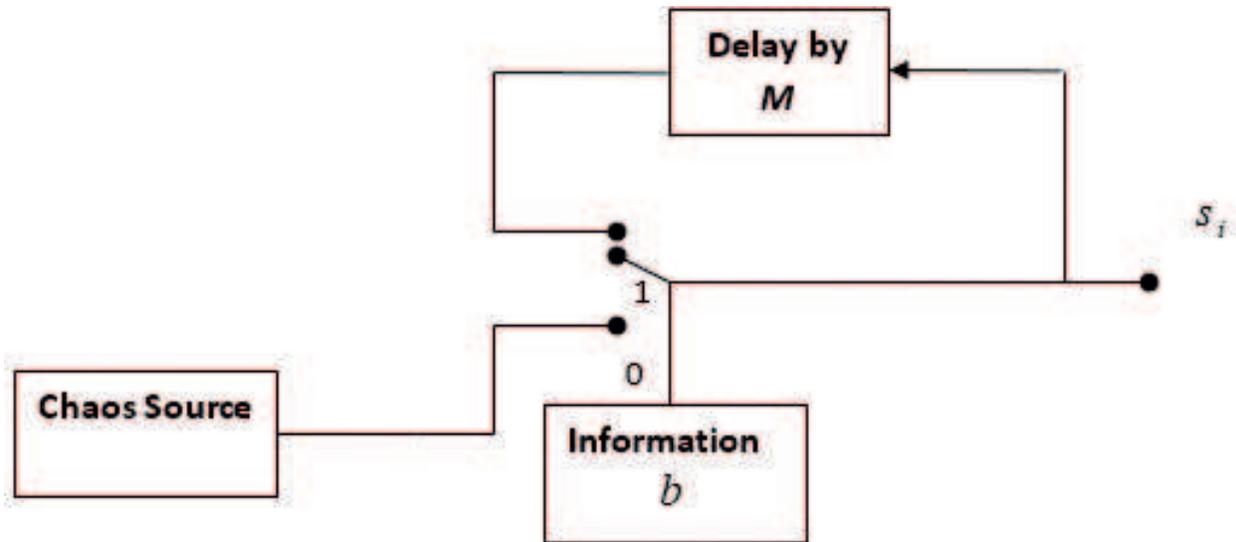


Figure 9. Energy efficient DCSK transmitter diagram.

generality, we will consider the analysis for the first bit b where $b \in \{1, 0\}$ and the transmitted signal S_i at the i th instant can be represented as

$$S_i = x_{i-bM} \tag{19}$$

The source emits M samples for each information bit in addition to the initial reference signal. Thus, the average bit energy transmitted can be found as.

$$E_b = \frac{l+1}{l} MVar(x^2) \approx MVar(x^2) \tag{20}$$

Information decoding is performed by correlating each incoming signal r_i with its delayed version and the correlation product is averaged over M . Information bit \tilde{b} can be extracted by comparing correlator output with the predefined threshold as shown in **Figure 10**.

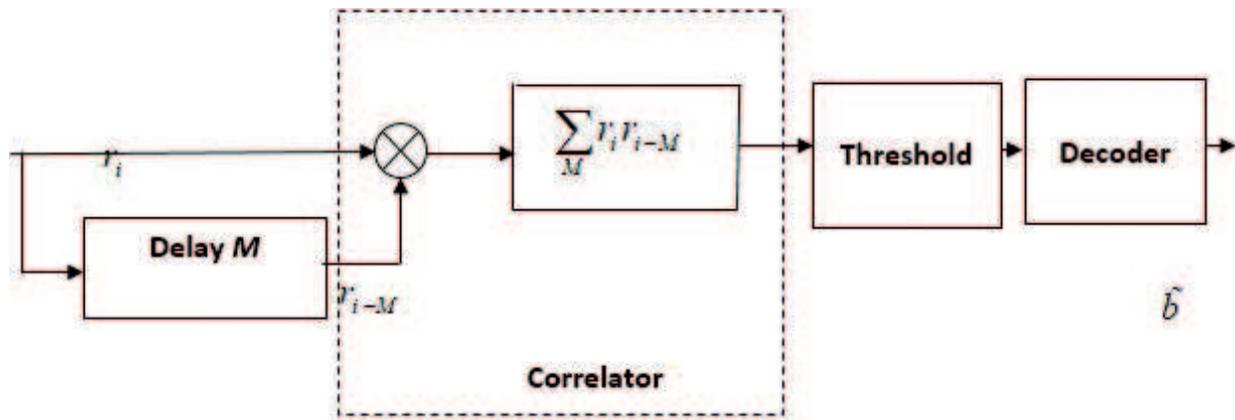


Figure 10. EF-CDSK receiver.

The received signal r_i can be described as $r_i = s_i + \zeta_i$ and the correlator output Z_{ef} can be formulated as

$$\begin{aligned}
 Z &= \sum_{i=1}^M r_i r_{i-M} = \sum_{i=1}^M (x_{i-bM} + \zeta_i)(x_{i-M} \zeta_{i-M}) \\
 &= \sum_{i=1}^M (x_{i-bM} x_{i-M}) + \sum_{i=1}^M (x_{i-bM} \zeta_{i-M}) + \sum_{i=1}^M (x_{i-M} \zeta_i) + \sum_{i=1}^M (\zeta_i \zeta_{i-M})
 \end{aligned} \tag{21}$$

Signal energy estimation can be obtained only by taking the mean value of first term in (7). Ideally, this will be either zero or $V_{ar(x)}$, all other terms are the zero mean. Obviously, it can be observed that the number of cross-terms of EF-CDSK correlator is less to that in CDSK. However, the distance between signal elements (average value of the correlator for each transmitted bit) is half compared to that in DCSK. Despite all that, the information can be decoded according to the following rule

$$\tilde{b} = \begin{cases} 1 & Z \geq \alpha_{th} \\ 0 & Z < \alpha_{th} \end{cases} \tag{22}$$

where α_{th} is the decoding threshold and it is given by $E_b/2$.

BER expression can be found by calculating mean and variance of the Gaussian distribution function of $P(Z | b = 1)$ and $P(Z | b = -1)$ and can be formulated as

$$\begin{aligned}
 BER_{EFCDK} &= \frac{1}{2} \operatorname{erfc} \left(\frac{E_b}{2\sqrt{2} \sqrt{\left(\frac{E_b^2}{M} + E_b N_o + \frac{MN_o^2}{4}\right)}} \right) \\
 &= \frac{1}{2} \operatorname{erfc} \left(\sqrt{\frac{E_b}{8N_o}} \left(1 + \frac{1}{M} \frac{E_b}{N_o} + \frac{M}{4} \frac{N_o}{E_b} \right) \right)
 \end{aligned} \tag{23}$$

4. Performance evaluation

A simulation result of BER for DCSK, CDSK, HE-DCSK and TR-DCSK schemes BER versus $\frac{E_b}{N_o}$ is presented in **Figures 11–14** with typical values of M , respectively. For all the systems, it can be clearly observed that BER performance is decreased by increment of spreading factor M . This is due to the nonlinear contribution of the last term in (3), (7), (10), and (17) with respect to other terms which exhibit linear contribution with respect to M .

In **Figure 15**, an overall comparison between an optimum differentially coherent systems performance is shown. With respect to DCSK, CDSK system has degradation in performance by 2–3 dB. This is due to two fundamental reasons: (1) number of cross terms in CDSK correlator is more than in DCSK and (2) incomplete orthogonality between intra-signal terms [1, 6, 9], which can affect the correlator output negatively. Additionally, HE-DCSK outperform DCSK at $M = 100$ and when $\frac{E_b}{N_o}$ is below 17 dB. The fact behind this is the reduction in average bit from $2MVar(x)$ to $3\frac{M}{2}Var(x)$ which result in improvement by 1.25 dB. However, this improvement is vanished due to signal to signal contribution. TR-DCSK always shows better performance against DCSK, CDSK and HE-DCSK by an average of 2 dB.

In **Figure 14**, theoretical estimation of BER for all the above mentioned systems in (5), (8), (13) and (18) is plotted against simulation result. Clearly, there is an acceptable matching between theoretical expression and simulated version. However, these expressions are derived based on GA approximation method, which is suitable for the system operating in large spreading factor. To have more accurate derivation, it is preferred to implement integration method [15].

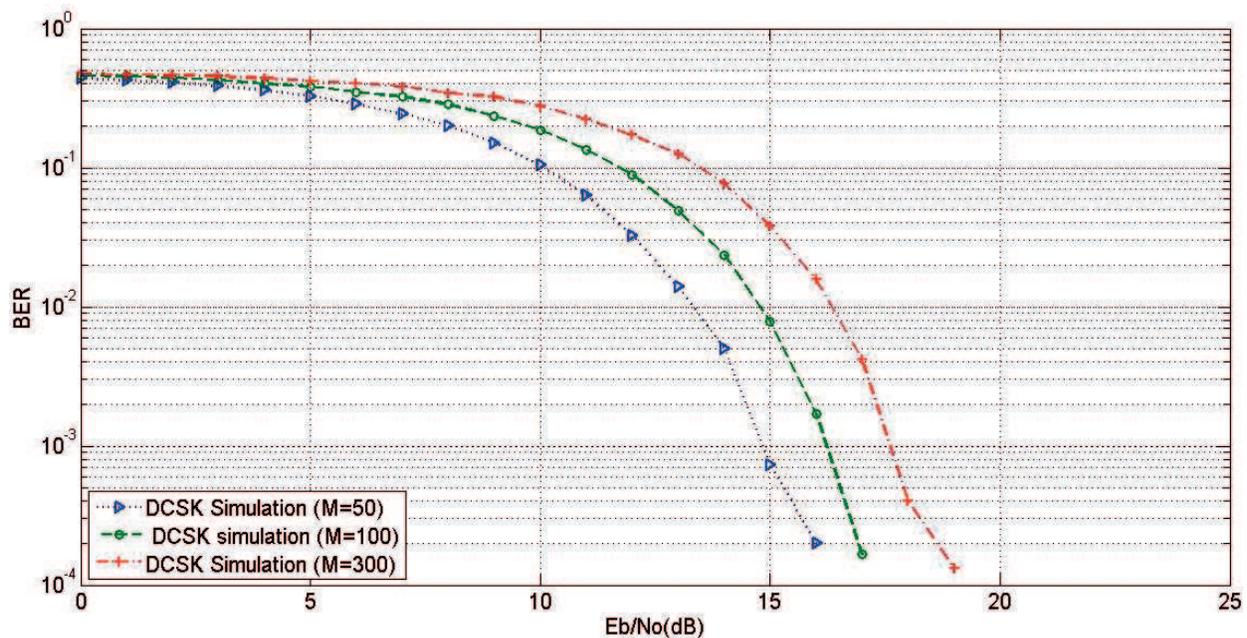


Figure 11. BER vs. E_b/N for DCSK system at $M = 50, 100$ and 300 .

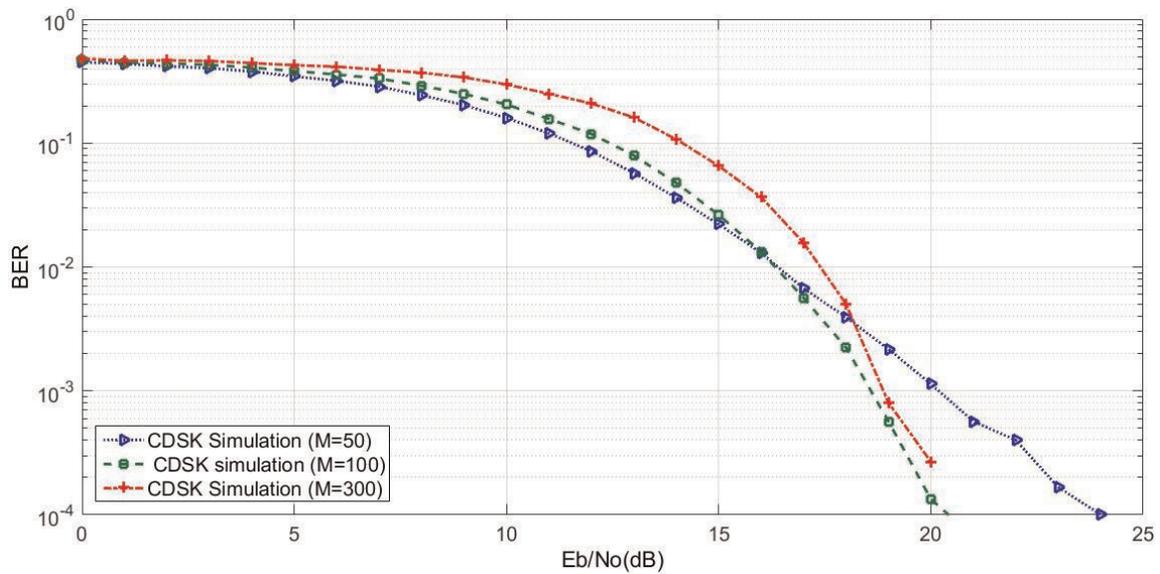


Figure 12. BER vs. E_b/N for CDSK system at $M = 50, 100$ and 300 .

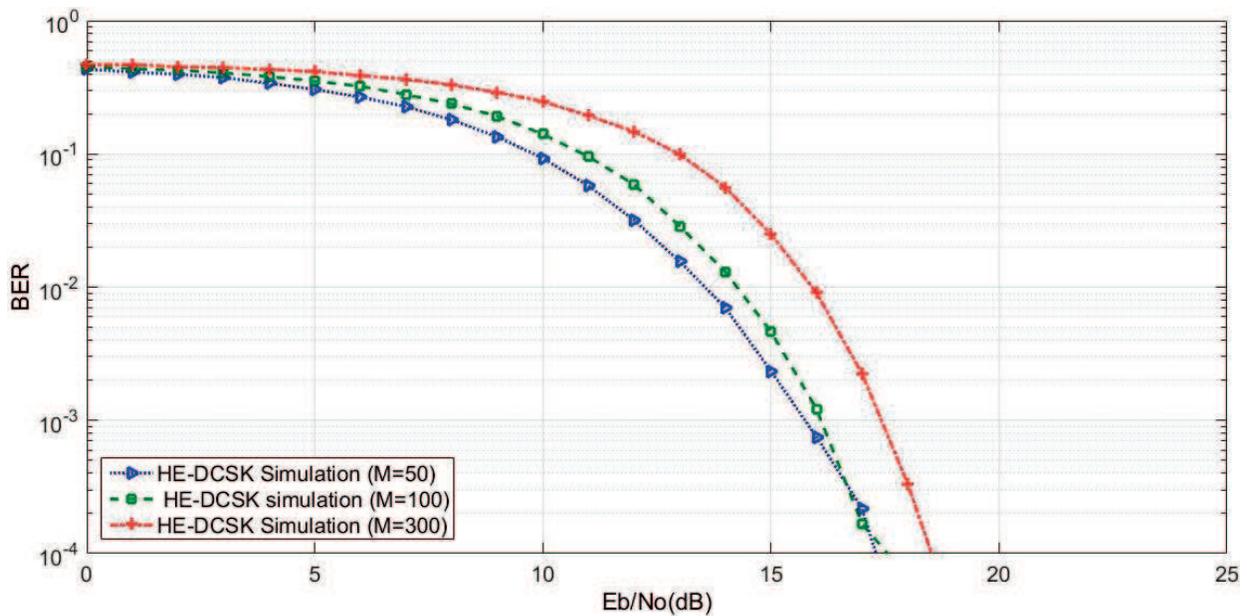


Figure 13. BER vs. E_b/N for HE-DCSK system at $M = 50, 100$ and 300 .

5. Other differential coherent systems

Many chaotic systems have been suggested to enhance BER and bandwidth efficiency of DCSK. Single reference segment is used as a reference to modulate and demodulate multiple successive bits in Ref. [16]. Average bit energy is reduced with bit error rate enhancement. However, the system is not suitable for secure communications due to easy spectrum prediction

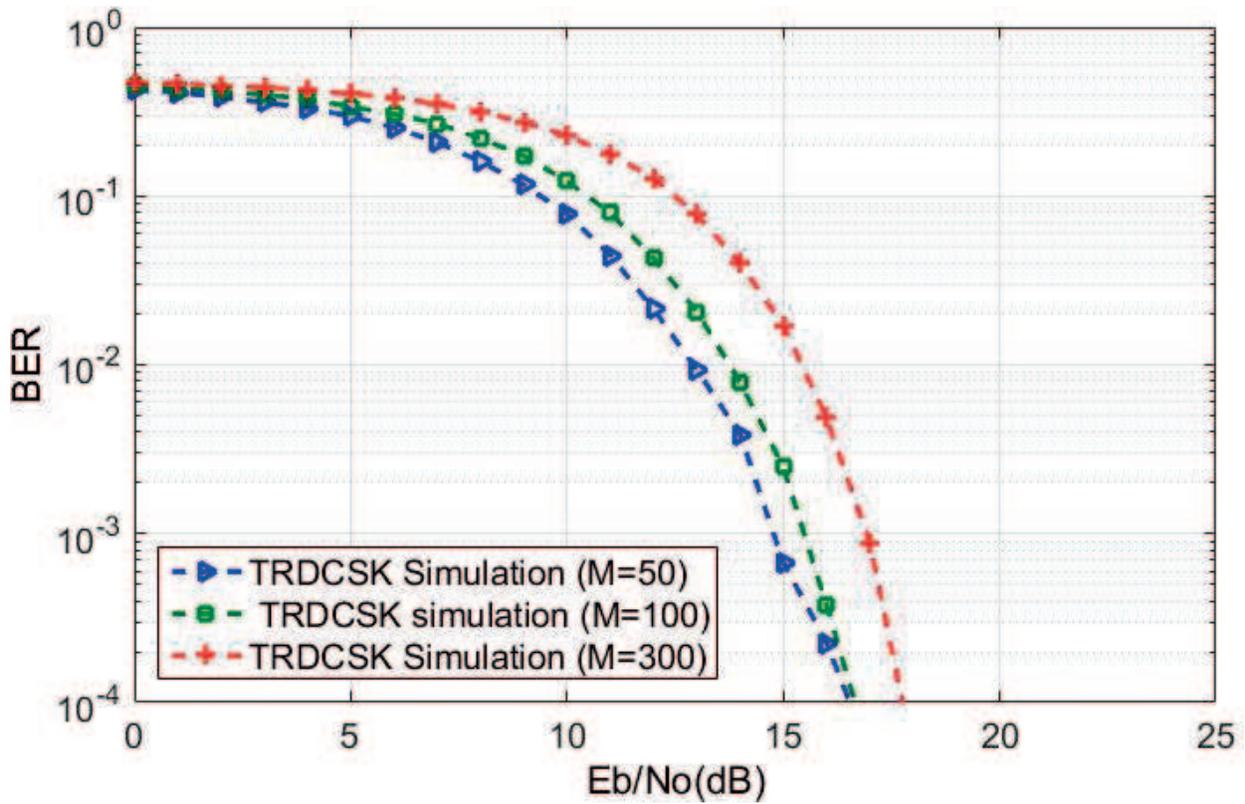


Figure 14. BER vs. Eb/N for TR-DCSK system at $M = 50, 100$ and 300 .

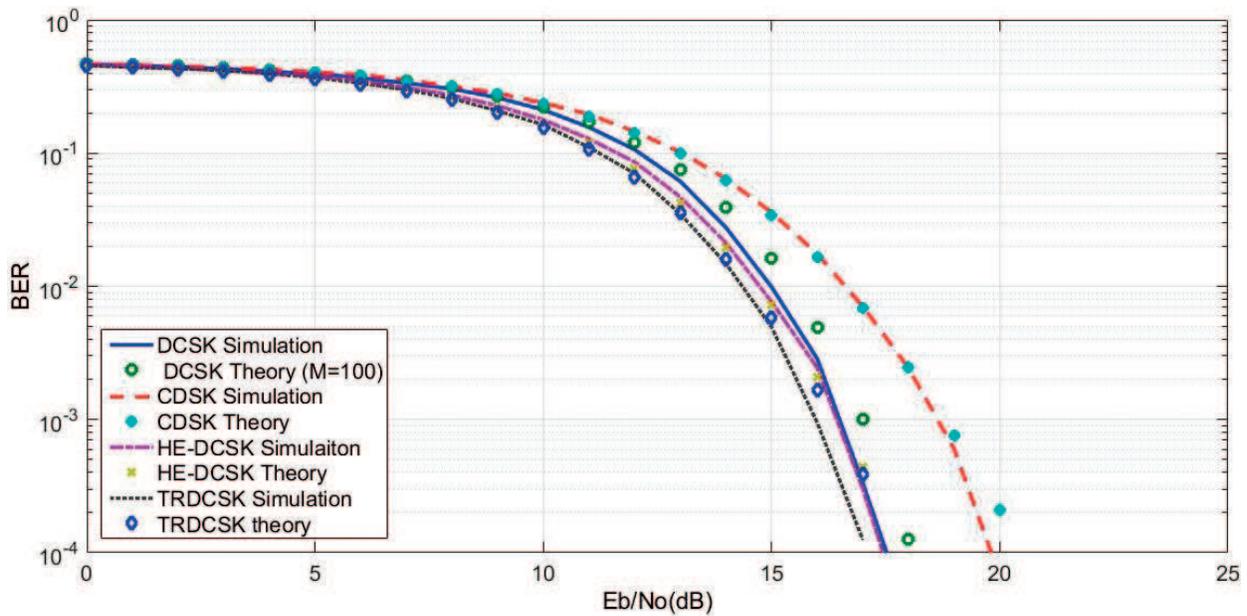


Figure 15. Simulation result and theoretical evaluation for DCSK, CDSK, HE-DCSK and TR-DCSK at $M = 500$.

in addition to the need for multiple delay elements in both transmitter and receiver which increase the system complexity. Chaotic signals have fluctuated energy due to randomness nature of the signal. To have fixed energy, FM-DCSK is proposed in Ref. [17] as a possible

solution. Permutation between chaotic samples is implemented to destroy the similarity between the reference signal and information signal in DCSK. Moreover, permutation is used to reduce the interference between different users in multiple access-DCSK (MA-DCSK).

Sending both reference and information bearing signal in separate time slot causes a reduction in bandwidth efficiency of differential coherent systems such as DCSK. Hence, many systems have been designed to combine both reference signal and information bearing signal in one time slot. Xu and Wang proposed a code-shifted DCSK (CS-DCSK) system [18]. System is based on using Walsh code to combine reference signal and information bearing signal in single time slot rather than sending them separately. An extend version of CS-DCSK which sent multiple bits using single reference is named as (high data rate-DCSK) [19]. Another scheme which is based on mapping series of bits into two channels and each encoded output is consider as an initial condition value for the sequence generator pairs and their outputs are added and up converted [20]. Implementation of delay diversity scheme as a basic building block for space time block coder (STBC) is suggested in ref. [21]. Here, bits stream is converted from series to parallel; an each bit in parallel channel is modulated by DCSK modulators and followed by analogue space time block coder (STBC). This arrangement gains advantage of transmission by 5 dB at BER of 1×10^{-4} compared with the single input-single output DCSK.

Efficiency of multicarrier modulation has been used to send multiple bits of modulating each information bits with subcarrier using multicarrier modulation-DCSK. The system provides a considerable saving in bandwidth [22]. However, the cost which needs to pay is the complexity of having multiple carrier multipliers in the transmitter side and bank of matched filter on the receiver side.

Transmitting reference signal followed by information bearing signal is the common signal format for most of the differential coherent spread spectrum systems which can be affected by fast fading channel. A suggested scheme to send only one sample form reference signal followed directly by one sample from information bearing signal is analyzed and tested in Ref. [23]. The system provides immunity against fading in continuous mobility environment. System block diagram is almost similar to standard DCSK except for switching timing.

Major drawback of DCSK system is the addition of channel random noise in both signal segments reference and information bearing signal. Therefore, a noise reduction technique has been introduced to reduce the noise variance by sending a repeated subsegment of samples inside one bit duration rather than sending continuous stream of samples. At the receiver, averaging operation is performed over the repeated segment before the standard correlation procedure [24]. This enhances the BER performance over other newly developed segments.

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References

- [1] Lau FCM, Tse CK. Chaos-Based Digital Communication Systems: Operating Principles, Analysis Methods, and Performance Evaluation. Berlin, Germany: Springer; 2003
- [2] Kolumban G, Kennedy MP, Chua LO. 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*. November 1998;**45**(11): 1129-1140
- [3] Lau F, Tse C. Optimum Correlator-type receiver design for CSK communication systems. *International Journal of Bifurcation and Chaos*. 2002;**12**:1029-1038
- [4] Kis G, Jako Z, Kennedy MP, Kolumban G. Chaotic communications without synchronization. In: *Proceedings of the 6th IEE Conference on Telecommunications*. IEE; April 1998. p. 49-53
- [5] Sushchik M, Tsimring LS, Volkovskii AR. Performance analysis of correlation-based communication schemes utilizing chaos. *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*. 2000;**47**(12):1684-1691
- [6] Kolumbán G, Kennedy MP, Jákó Z, Kis G. Chaotic communications with correlator receivers: Theory and performance limits. *Proceedings of the IEEE*. 2002;**90**(5):711-732
- [7] <https://link.springer.com/article/10.1007/BF01200500>
- [8] Larson LE, Tsimring LS, Liu J-M. *Digital Communications Using Chaos and Nonlinear Dynamics*. New York, NY: Springer; 2006
- [9] Yang H, Jiang G-P. High-efficiency differential-chaos-shift-keying scheme for chaos-based noncoherent communication. *IEEE Transactions on Circuits and Systems II: Express Briefs*. 2012;**59**(5):312-316
- [10] Yang H, Jiang G-P. Reference-modulated DCSK: A novel chaotic communication scheme. *IEEE Transactions on Circuits and Systems II: Express Briefs*. 2013;**60**(4):232-236
- [11] Chernov NI. Limit theorems and Markov approximations for chaotic dynamical systems. *Probability Theory and Related Fields*. Sep. 1995;**101**(3):321-362
- [12] Albassam Nizar N. Reference flipped-differential chaos shift keying scheme for chaos-based communications. *International Journal of Engineering & Technology*. April 2015;**4**(2):320-326
- [13] Albassam N. Design of DCSK based on modified time reversal technique. *Cogent Engineering*, **4**(1):1365576. <https://doi.org/10.1080/23311916.2017.1365576>
- [14] Albassam. Energy efficient scheme for differential coherent chaos based communication system. In: *International Conference on Control, Decision and Information Technologies 34 (CoDIT2017)*, Spain; 2017
- [15] Kaddoum G, Chargé P, Roviras D. A generalized methodology for bit-error-rate prediction in correlation-based communication schemes using chaos. *IEEE Communications Letters*. 2009;**13**(8):567-569

- [16] Kolumban G, Jako Z, Kennedy MP. 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. Orlando, FL, USA: IEEE; June 1999. p. 475-478
- [17] Lau FCM, Cheong KY, Tse CK. Permutation-based DCSK and multiple-access DCSK systems. *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*. June 2003;**50**(6):733-742
- [18] Xu WK, Wang L, Kolumbán G. A novel differential chaos shift keying modulation scheme. *International Journal of Bifurcation and Chaos*. 2011;**21**(03):799-814
- [19] Xu W, Wang L, Chen G. Performance analysis of the CS-DCSK/BPSK communication system. *IEEE Transactions on Circuits and Systems I*. 2014;**61**(9):2624-2633
- [20] Xu M, Leung H. A novel high data rate modulation scheme based on chaotic signal separation. *IEEE Transactions on Communications*. October 2010;**58**(10):2855-2860
- [21] Chen P, Wang L, Lau FCM. One analog STBC-DCSK transmission scheme not requiring channel state information. *IEEE Transactions on Circuits and Systems I: Regular Papers*. 2013;**60**(4):1027-1037
- [22] Kaddoum G, Richardson F-D, Gagnon F. Design and analysis of a multi-carrier differential chaos shift keying communication system. *IEEE Transactions on Communications*. 2013;**61**(8):3281-3291
- [23] Escribano FJ, Kaddoum G, Wagemakers A, Giard P. Design of a new differential chaos-shift-keying system for continuous mobility. *IEEE Transactions on Communications*. May 2016;**64**(5):2066-2078
- [24] Kaddoum G, Soujeri E. NR-DCSK: A noise reduction differential chaos shift keying system. *IEEE Transactions on Circuits and Systems II: Express Briefs*. July 2016;**63**(7):648-652

