A Multilevel Code Shifted Differential Chaos Shift Keying System With M-ary Modulation

Xiangming Cai, Weikai Xu, *Member, IEEE*, Rongfang Zhang, and Lin Wang, *Senior Member, IEEE*

***Abstract*—In this brief, a multilevel code shifted differential chaos shift keying system with M-ary modulation (MCS-MDCSK) is proposed, which is a hybrid of the M-ary modulation and multilevel code shifted differential chaos shift keying. In the proposed system, since the reference signal and a number of different information bearing signals which can carry M-ary constellation symbols are transmitted in the same slot, the spectral efficiency of MCS-MDCSK system is enhanced significantly. By combining with M-ary modulation, MCS-MDCSK system makes great progress in pursuit of higher data rate. Moreover, we derive the analytical bit-error-rate (BER) for the proposed system over the additive white Gaussian noise and multipath Rayleigh fading channels, and we verify our theoretical derivations by simulations. Finally, the BER performance of the proposed system is compared with other non-coherent chaotic modulation systems and MCS-MDCSK system is found to be superior and competitive.**

***Index Terms*—Chaotic modulation schemes, M-ary modulation, multilevel code shifted differential chaos shift keying (MCS-DCSK), high data rate.**

I. Introduction

IN THE past two decades, chaotic modulation schemes, using a wide-band non-periodic chaotic signal as their carriers [1], have drawn extensive attentions in wireless communication domain. The broadband aperiodic characteristic of chaotic signals makes them to be good candidates for spread spectrum communications [2]. Indeed, chaotic signal owns the superior properties of wide-band power spectral density, excellent auto-correlation and cross-correlation, which equip the chaotic communication systems with admirable robustness to mitigate degradation even in severe multipath environments [3], [4].

As a kind of non-coherent systems, the binary differential chaos shift keying (DCSK) shows excellent performance in multipath channels [5]. The low complexity transceiver and without the demand of chaotic synchronization make DCSK applied easily. As a transmitted-reference (TR) system, however, DCSK suffers from two dominant drawbacks. Firstly, the conventional DCSK has a relatively poor data rate, because half of the symbol period is used to transmit reference signal. Secondly, the long wide-band delay line creates obstacles to apply under the current background of CMOS technologies.

To refrain from the use of radio frequency (RF) delay circuit, code shifted differential chaos keying (CS-DCSK) is proposed in [6], where the reference signal and information bearing signal are overlapping in time domain, but orthogonal in code domain by using Walsh codes. Specially, the generalized code shifted differential chaos keying (GCS-DCSK) is proposed by the same authors [7], where the problem of delay line is avoided at receiver and the data rate can be improved by adding new information bearing signals in one symbol period. A multi-carrier DCSK (MC-DCSK) is proposed in [8], where the RF delay line problem is solved.

To ameliorate the data rate, quadrature chaos shift keying (QCSK) [9] is proposed and it can gain double data rate with the same bandwidth occupation and similar BER performance of DCSK. Then, a square-constellation-based M-ary DCSK is proposed in [10], which can further increase the data rate. As a binary modulation scheme, multilevel code shifted differential chaos shift keying (MCS-DCSK) [11] uses different Walsh codes to carry multiple bits, thus its data rate is improved, where the reference signal and information bearing signal are separated by Walsh codes instead of time delay multiplexing. Huang *et al.* [12] present an M-ary code shifted DCSK (GCS-MDCSK) which applies M-ary modulation to CS-DCSK to boost the data rate, but the utilization rate of Walsh codes is quite low. Recently, by combining MCS-DCSK with code index modulation, CIM-MCS-DCSK [13] has been proposed to achieve high data rate.

Motivated by the works of [10]–[12], we propose a multilevel code shifted differential chaos shift keying system with M-ary modulation, namely MCS-MDCSK. In the proposed system, we use the orthogonal Walsh code sequences to carry the in-phase component and quadrature component of the M-ary constellation symbol which is different from the design of conventional MCS-DCSK system. Since the reference signal and numerous M-ary information bearing signals are transmitted in the same slot, the spectral efficiency of the proposed system is enhanced significantly. Compared with the previously suggested DCSK systems [7], [11], [12], the proposed system can increase the data rate in a linear fashion by combining with M-ary modulation. Then, the theoretical BER expressions of MCS-MDCSK system over AWGN and multipath Rayleigh fading channels are derived and the simulation results validate our derivations. Finally,

Manuscript received November 19, 2018; accepted December 6, 2018. Date of publication December 12, 2018; date of current version July 30, 2019. This work was supported by the National Natural Science Foundation of China under Grant 61671395 and Grant 61871337. This brief was recommended by Associate Editor Y. Xia. *(Corresponding author: Weikai Xu.)*

The authors are with the Department of Communication Engineering, Xiamen University, Xiamen 361005, China (e-mail: samson0102@qq.com; xweikai@xmu.edu.cn; zrofmoyi@foxmail.comm; wanglin@xmu.edu.cn).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TCSII.2018.2886377

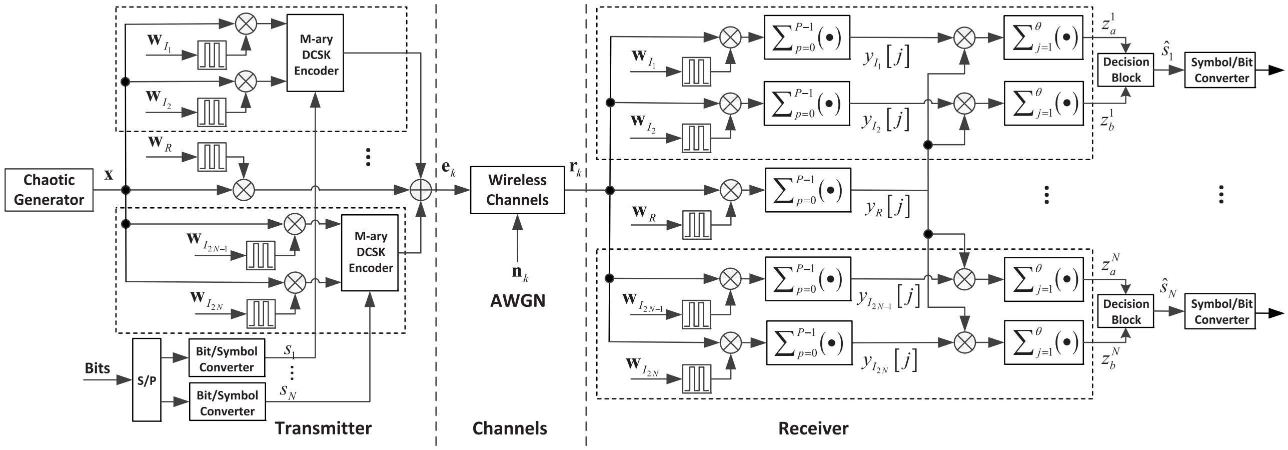

Fig. 1. The block diagram of MCS-MDCSK system.

the BER performance of the proposed MCS-MDCSK system is compared with other non-coherent chaotic modulation systems and the results show MCS-MDCSK system can achieve satisfactory BER performance in contrast to its rivals.

The remainder of this brief is organized as follows. Section II presents MCS-MDCSK system. Performance analysis is provided in Section III. In Section IV, the simulation results are given. Finally, Section V concludes this brief.

II. MCS-MDCSK SYSTEM

A. The Transmitter

The block diagram of MCS-MDCSK system is shown in Fig. 1. At the transmitter, the overall transmitted signals are the sum of the reference signal and numerous M-ary information bearing signals. Therefore, the k^{th} baseband discrete MCS-MDCSK symbol $\mathbf{e}_k$ can be expressed in a vector form as

$$\mathbf{e}_k = \mathbf{w}_R \otimes \mathbf{x} + \sum_{n=1}^{N} \left(a_n \mathbf{w}_{I_{2n-1}} \otimes \mathbf{x} + b_n \mathbf{w}_{I_{2n}} \otimes \mathbf{x}\right), \tag{1}$$

where $\mathbf{x}$ denotes a θ-length chaotic signal generated by the logistic map $x_{j+1} = 1 - 2x_j^2$. $\mathbf{w}_R = [w_{R,1}, w_{R,2}, \ldots, w_{R,P}]$ is a P-length Walsh code sequence used to carry the reference signal. Then, $\mathbf{w}_{I_{2n-1}} = [I_{2n-1},1, w_{I_{2n-1},2}, \ldots, w_{I_{2n-1},P}]$ and $\mathbf{w}_{I_{2n}} = [w_{I_{2n},1}, w_{I_{2n},2}, \ldots, w_{I_{2n},P}]$ are another two Walsh code sequences for information bearing signals. $\otimes$ denotes Kronecker product and N represents the number of M-ary constellation symbols transmitted in a symbol duration and its maximum value is $N_{\max} = \frac{P-2}{2}$. In addition, a_n and b_n are the real part and imaginary part of the n^{th} M-ary constellation symbol. $s_n = a_n + ib_n$, where $i = \sqrt{-1}$ is imaginary part unit, is encoded by M-ary DCSK encoder in the M-ary constellation. In this brief, we define the spreading factor of MCS-MDCSK system as $\beta = P\theta$.

B. The Receiver

Assuming that the transmitted signal is contaminated by the multipath fading and additive white Gaussian noise, the received baseband discrete signal can be given as

$$\mathbf{r}_k = \sum_{l=1}^{L} \alpha_{k,l} \mathbf{e}_{k-\tau_{k,l}} + \mathbf{n}_k, \tag{2}$$

where L is the number of path, then $\alpha_{k,l}$ and $\tau_{k,l}$ are the channel propagation coefficient and the appropriate time delay of the l^{th} path, respectively. $\mathbf{n}_k$ is additive white Gaussian noise vector with zero mean and covariance $\frac{N_0}{2}\mathbf{I}$, where $\mathbf{I}$ denotes the identity matrix. Particularly, for $L = 1$, $\alpha_1 = 1$ and $\tau_1 = 0$, the channel degrades into AWGN channel.

The receiver structure of the proposed system is shown in Fig. 1. Firstly, considering the n^{th} symbol, we extract the reference signal $y_R[j]$ and information bearing signals $y_{I_{2n-1}}[j]$, $y_{I_{2n}}[j]$ from the receiver signal by different Walsh code sequences. Then, the signal $y_R[j]$ is correlated to $y_{I_{2n-1}}[j]$ and $y_{I_{2n}}[j]$, respectively. Thus, two decision variables z_a^n and z_b^n are obtained. Finally, the minimum distance decision criterion is applied to get the estimated n^{th} information symbol $\hat{s}_n$ as

$$\hat{s}_n = \arg\min_{s \in S}\left(|[z_a^n + \sqrt{-1}z_b^n] - s|^2\right), \tag{3}$$

where S denotes the M-ary constellation point sets. Thus the original transmitted bits can be recovered by converting $\hat{s}_n$ from constellation symbols to bits.

C. Data Rate Analysis and Comparison

In this subsection, we analyse the data rate of the proposed MCS-MDCSK system and make a comparison with other chaotic communication systems. For the sake of fairness, we define the number of total transmitted bits per symbol duration as the data rate R. According to [7], [11], and [12], for a given P-order Walsh code matrix, the maximum available data rate of GCS-DCSK, MCS-DCSK and GCS-MDCSK are calculated as $R_{1,\max} = \frac{P}{2}$, $R_{2,\max} = P - 2$ and $R_{3,\max} = \frac{P}{4}\log_2 M$, respectively. As for CIM-MCS-DCSK system, the maximum available data rate depends on P and the number of modulated bits U_t, namely $R_{4,\max} = \lfloor \log_2[C(P-1, U_t)] \rfloor + U_t$ [13]. Then, the maximum available data rate of the proposed MCS-MDCSK system can be obtained as $R_{5,\max} = \frac{P-2}{2}\log_2 M$.

The comparison of the maximum attainable data rate is shown in Table I. Apparently, the data rate of MCS-MDCSK

TABLE I
COMPARISONS OF MAXIMUM AVAILABLE DATA RATE BETWEEN MCS-MDCSK SCHEME AND OTHER NON-COHERENT CHAOTIC COMMUNICATION SCHEMES

Modulation Scheme	Data Rate
GCS-DCSK ($R_{1,\max}$)	$\frac{P}{2}$
MCS-DCSK ($R_{2,\max}$)	$P-2$
GCS-MDCSK ($R_{3,\max}$)	$\frac{P}{4}\log_2 M$
CIM-MCS-DCSK ($R_{4,\max}$)	$\lfloor \log_2 [C(P-1,U_t)] \rfloor + U_t$
MCS-MDCSK ($R_{5,\max}$)	$\frac{P-2}{2}\log_2 M$

can be increased in a linear fashion with P and in a logarithmic way with the modulation order M. MCS-MDCSK has greater maximum achievable data rate compared with GCS-MDCSK for the given M when $P \geq 8$. Additionally, while the maximum available data rate of MCS-MDCSK is enlarging with the increasing of M for the constant P, the maximum data rate of MCS-DCSK remains invariable when M augments.

III. PERFORMANCE ANALYSIS

Since all N branches for different symbols are independent of each other, we only need to evaluate the error probability of one of them. Apparently, the reference signal can be obtained as (4), as shown at the bottom of this page. Similarly, the information bearing signals of the n^{th} in-phase branch and quadrature branch can be stated as

$$y_{I_{2n-1}}[j] = \sum_{l=1}^{L} \alpha_l P a_n x_{j-\tau_l} + \sum_{p=0}^{P-1} w_{I_{2n-1},p+1} n_{p\theta+j}, \tag{5}$$

$$y_{I_{2n}}[j] = \sum_{l=1}^{L} \alpha_l P b_n x_{j-\tau_l} + \sum_{p=0}^{P-1} w_{I_{2n},p+1} n_{p\theta+j}, \tag{6}$$

where $1 \leq j \leq \theta$. According to the receiver, the decision variable z_a^n can be calculated as (7), as shown at the bottom of this page. Since the signal components of (7) are independent of each other, the means and variances of A, B, C and D are independent as well. Similar derivation processes can be found in [11], thus the mean and variance of z_a^n can be derived as

$$\begin{aligned}\mathrm{E}\left[z_a^n\right] &= \mathrm{E}[A] + \mathrm{E}[B] + \mathrm{E}[C] + \mathrm{E}[D] \\ &= \sum_{l=1}^{L} \alpha_l^2 P^2 \theta a_n \mathrm{E}\left[x_{j-\tau_l}^2\right] = \sum_{l=1}^{L} \alpha_l^2 \frac{P a_n E_s}{1+N},\end{aligned} \tag{8}$$

$$\begin{aligned}\mathrm{Var}\left[z_a^n\right] &= \mathrm{Var}[A] + \mathrm{Var}[B] + \mathrm{Var}[C] + \mathrm{Var}[D] \\ &= \left(1 + a_n^2\right) \sum_{l=1}^{L} \alpha_l^2 P^3 \theta \mathrm{E}\left[x_{j-\tau_l}^2\right] \frac{N_0}{2} + P^2 \theta \frac{N_0^2}{4} \\ &= \left(1 + a_n^2\right) \sum_{l=1}^{L} \alpha_l^2 \frac{P^2 E_s N_0}{2(1+N)} + P^2 \theta \frac{N_0^2}{4},\end{aligned} \tag{9}$$

where E_s denotes the symbol energy of MCS-MDCSK system, which can be expressed by $E_s = (1+N)P\theta \mathrm{E}[x_{j-\tau_l}^2]$. Similarly, the mean and variance of z_b^n can be given as

$$\mathrm{E}\left[z_b^n\right] = \sum_{l=1}^{L} \alpha_l^2 \frac{P b_n E_s}{1+N}, \tag{10}$$

$$\begin{aligned} y_R[j] &= \sum_{p=0}^{P-1} w_{R,p+1} \left\{ \sum_{l=1}^{L} \alpha_l \left[w_{R,p+1} x_{p\theta+j-\tau_l} + \sum_{n=1}^{N} \left(a_n w_{I_{2n-1,p+1}} x_{p\theta+j-\tau_l} + b_n w_{I_{2n,p+1}} x_{p\theta+j-\tau_l} \right) \right] + n_{p\theta+j} \right\} \\ &= \sum_{l=1}^{L} \sum_{p=0}^{P-1} \alpha_l w_{R,p+1}^2 x_{p\theta+j-\tau_l} + \sum_{l=1}^{L} \alpha_l \sum_{n=1}^{N} a_n \underbrace{\left(\sum_{p=0}^{P-1} w_{R,p+1} w_{I_{2n-1,p+1}} x_{p\theta+j-\tau_l} \right)}_{=0} \\ &\quad + \sum_{l=1}^{L} \alpha_l \sum_{n=1}^{N} b_n \underbrace{\left(\sum_{p=0}^{P-1} w_{R,p+1} w_{I_{2n,p+1}} x_{p\theta+j-\tau_l} \right)}_{=0} + \sum_{p=0}^{P-1} w_{R,p+1} n_{p\theta+j} \\ &= \sum_{l=1}^{L} \alpha_l P x_{j-\tau_l} + \sum_{p=0}^{P-1} w_{R,p+1} n_{p\theta+j}. \end{aligned} \tag{4}$$

$$\begin{aligned} z_a^n &= \sum_{j=1}^{\theta} \left[\left(\sum_{l=1}^{L} \alpha_l P x_{j-\tau_l} + \sum_{p=0}^{P-1} w_{R,p+1} n_{p\theta+j} \right) \left(\sum_{l=1}^{L} \alpha_l P a_n x_{j-\tau_l} + \sum_{p=0}^{P-1} w_{I_{2n-1},p+1} n_{p\theta+j} \right) \right] \\ &= \underbrace{\sum_{j=1}^{\theta} \sum_{l=1}^{L} \alpha_l^2 P^2 a_n x_{j-\tau_l}^2}_{A} + \underbrace{\sum_{j=1}^{\theta} \sum_{l=1}^{L} \alpha_l P x_{j-\tau_l} \left(\sum_{p=0}^{P-1} w_{I_{2n-1},p+1} n_{p\theta+j} \right)}_{B} + \underbrace{\sum_{j=1}^{\theta} \sum_{l=1}^{L} \alpha_l P a_n x_{j-\tau_l} \left(\sum_{p=0}^{P-1} w_{R,p+1} n_{p\theta+j} \right)}_{C} \\ &\quad + \underbrace{\sum_{j=1}^{\theta} \left(\sum_{p=0}^{P-1} w_{R,p+1} n_{p\theta+j} \right) \left(\sum_{p=0}^{P-1} w_{I_{2n-1},p+1} n_{p\theta+j} \right)}_{D}. \end{aligned} \tag{7}$$

$$\mathrm{Var}\left[z_b^n\right] = \left(1+b_n^2\right)\sum_{l=1}^{L}\alpha_l^2\frac{P^2E_sN_0}{2(1+N)} + P^2\theta\frac{N_0^2}{4}. \quad (11)$$

It is clearly observed that the decision variables z_a^n and z_b^n are independent Gaussian variables with means $m_1 = a_nE_m$ and $m_2 = b_nE_m$, respectively, where $E_m = \sum_{l=1}^{L}\alpha_l^2\frac{PE_s}{1+N}$. According to (9) and (11), in addition, the variances of z_a^n and z_b^n can be rewritten as $\sigma_1^2 = (1+a_n^2)\sum_{l=1}^{L}\alpha_l^2\frac{P^2E_sN_0}{2(1+N)} + P^2\theta\frac{N_0^2}{4}$ and $\sigma_2^2 = (1+b_n^2)\sum_{l=1}^{L}\alpha_l^2\frac{P^2E_sN_0}{2(1+N)} + P^2\theta\frac{N_0^2}{4}$, respectively.

Particularly, when $M \geq 4$, the value of $1+a_n^2$ and $1+b_n^2$ are both approximately equal to 1. Thus, in this case, both variances of z_a^n and z_b^n are approximately expressed as $\sigma^2 \approx \sum_{l=1}^{L}\alpha_l^2\frac{P^2E_sN_0}{2(1+N)} + P^2\theta\frac{N_0^2}{4}$. The derivation of BER expression for MCS-MDCSK system is similar to the counterpart of M-ary DCSK, which can be deduced from [10] as

$$P_{\mathrm{e}} \approx \frac{1}{\log_2 M}\left[1 - \int_{-\frac{\pi}{M}}^{\frac{\pi}{M}}\frac{1}{2\pi}\exp\left(-\frac{\rho^2}{2}\right) + \exp\left(-\frac{\rho^2\sin^2\varphi}{2}\right)\frac{\rho\cos\varphi}{\sqrt{2\pi}}Q(-\rho\cos\varphi)\mathrm{d}\varphi\right], \quad (12)$$

where

$$\rho = \frac{E_m}{\sigma} = \frac{2\gamma_s}{\sqrt{2\gamma_s(1+N)+(1+N)^2\theta}},\quad M \geq 4, \quad (13)$$

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{+\infty}\exp(-\frac{t^2}{2})\mathrm{d}t,\quad x \geq 0, \quad (14)$$

where $\gamma_s = \frac{E_s}{N_0}\sum_{l=1}^{L}\alpha_l^2$ is the instantaneous symbol signal-to-noise ratio (SNR).

When $M = 2$, the MCS-MDCSK system degrades into conventional MCS-DCSK system. In this case, the mean and variance of the MCS-DCSK system can be expressed as $\mu_t = \sum_{l=1}^{L}\alpha_l^2\frac{PE_s}{1+N}$ and $\sigma_t^2 = \sum_{l=1}^{L}\alpha_l^2\frac{P^2E_sN_0}{1+N} + P^2\theta\frac{N_0^2}{4}$, respectively. Thus, the bit error probability of MCS-DCSK system can be calculated as

$$P_e = \frac{1}{2}\mathrm{erfc}\left[\left(\frac{2(1+N)}{\gamma_s} + \frac{\theta(1+N)^2}{2\gamma_s^2}\right)^{-\frac{1}{2}}\right], \quad (15)$$

where $\mathrm{erfc}(x) = \frac{2}{\sqrt{\pi}}\int_x^{\infty}e^{-t^2}dt$ is the complementary error function. Clearly, the above BER expression is the same as the counterpart in [11], which verifies our analysis and derivation.

Considering the L independent and identically-distributed (i.i.d) Rayleigh-fading channels, the probability density function of instantaneous symbol-SNR can be written as [8], [10]

$$f(\gamma_s) = \frac{\gamma_s^{L-1}}{(L-1)!\bar{\gamma}_c^L}\exp\left(-\frac{\gamma_s}{\bar{\gamma}_c}\right), \quad (16)$$

where $\bar{\gamma}_c = \frac{E_s}{N_0}\mathrm{E}[\alpha_j^2] = \frac{E_s}{N_0}\mathrm{E}[\alpha_l^2]$, $j \neq l$ is the average symbol-SNR per channel and γ_s meets $\sum_{l=1}^{L}\mathrm{E}[\alpha_l^2] = 1$. Finally, the BER expression of MCS-MDCSK system over multipath Rayleigh fading channel is given by

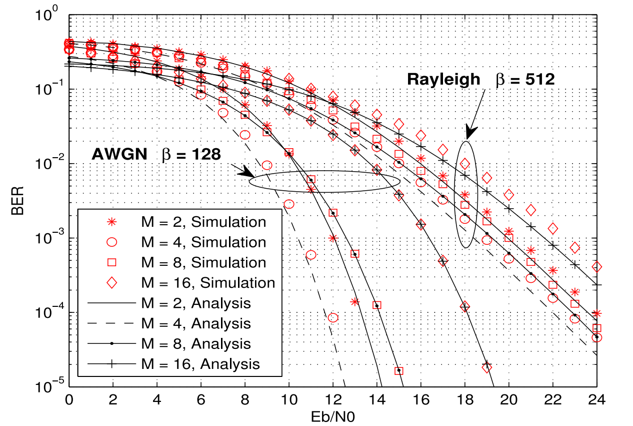

Fig. 2. Comparisons of the simulated results and theoretical results over AWGN and multipath Rayleigh fading channels with $P = 8$, $N = 2$ and $M = 2, 4, 8, 16$.

$$P_{\mathrm{fading}} = \int_0^{+\infty}P_{\mathrm{e}}\cdot f(\gamma_s)\mathrm{d}\gamma_s, \quad (17)$$

where the integral above can be evaluated numerically.

IV. Numerical Results

This section evaluates the performance of the proposed MCS-MDCSK system over AWGN and multipath Rayleigh fading channels. In order to avoid the intersymbol interference (ISI) in our simulation, the largest multipath time delay must be much shorter than the symbol duration $0 < \tau_{\max} << \beta T_c$, where T_c is the interval of chaotic samples. Useless otherwise stated, we use the three paths Rayleigh channel as fading channel. The relevant parameters of the fading channel are set to equal average power gain $\mathrm{E}(\alpha_1^2) = \mathrm{E}(\alpha_2^2) = \mathrm{E}(\alpha_3^2) = 1/3$ and the time delay $\tau_1 = 0$, $\tau_2 = T_c$, $\tau_3 = 5T_c$.

To confirm our theoretical derivations in previous section, the analytical results are compared with the corresponding simulation results, over AWGN and multipath Rayleigh fading channels, as shown in Fig. 2. Clearly, the simulation results almost match the theoretical ones for both channels. Note that a major disagreement appears when the SNR is small. This is caused by the approximation made in (12). In AWGN channel, when $M = 4$, MCS-MDCSK system achieves better BER performance than $M = 2$. This is due to the fact that the proposed system with 4-ary modulation can be considered as a combination of two 2-ary modulation (i.e., DCSK). However, unlike the case of DCSK, there is only one reference signal to be transmitted for two information bearing signals in the proposed system [9]. From the viewpoint of bit energy, the overhead per transmitted bit is reduced. Therefore, the BER performance is enhanced. Whereas, the BER performance of MCS-MDCSK system, except the above special case, worsens when M increases. The main reason lies in that the decision boundaries of M-ary constellation are decreasing when M increases. Additionally, the preferable performance over multipath Rayleigh fading channel occurs in medium modulation orders (i.e., $M = 4$ or 8).

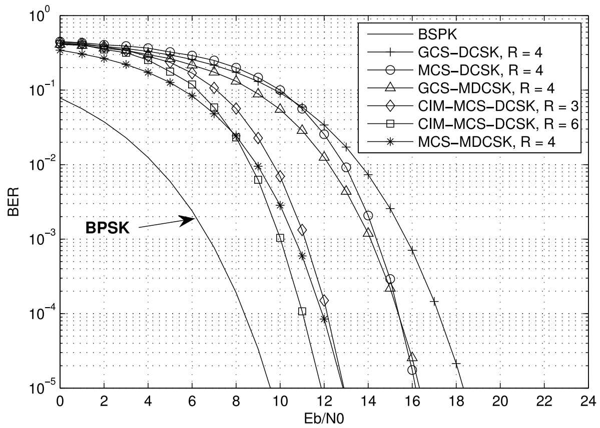

Fig. 3. Comparisons of BER performance between MCS-MDCSK and other non-coherent chaotic communication systems over AWGN channel with $\beta = 128$.

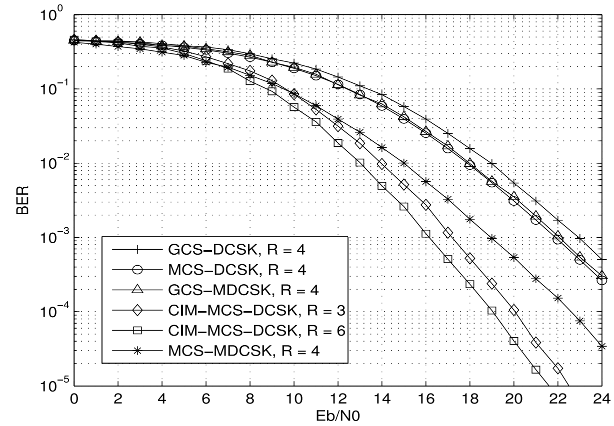

Fig. 4. Comparisons of BER performance between MCS-MDCSK and other non-coherent chaotic communication systems over multipath Rayleigh fading channel with $\beta = 512$.

In Fig. 3 and Fig. 4, we make a performance comparison between MCS-MDCSK and other non-coherent chaotic communication systems over AWGN and multipath Rayleigh fading channels. The BER performance of BPSK is listed as a reference to fundamental BER limits. The simulation parameters are set as follows: $P = 8$ for all the systems, $M = 4$ for MCS-MDCSK and GCS-MDCSK system and $U_t = 1$ or $U_t = 2$ are used for CIM-MCS-DCSK. Clearly, the MCS-MDCSK system shows preferable performance compared to GCS-DCSK, MCS-DCSK and GCS-MDCSK over both AWGN and multipath Rayleigh fading channels. For example, in AWGN channel, while the performance gain of MCS-MDCSK over MCS-DCSK is almost 3dB at BER level 10^{-5}, the performance improvement for MCS-MDCSK system over GCS-DCSK system is greater than 5dB at the same BER level above. In the case of multipath Rayleigh fading channel, the performance gain between MCS-MDCSK and GCS-MDCSK is about 3dB at BER level 10^{-3}. Since CIM-MCS-MDCSK system possesses the benefits of code index modulation, which comes up with new dimensions for conveying bits, the CIM-MCS-DCSK system can achieve superior BER performance.

V. Conclusion

A multilevel code shifted differential chaos shift keying system with M-ary modulation has been proposed in this brief. The analytical BER expressions have also been derived for the proposed MCS-MDCSK system over both AWGN and multipath Rayleigh fading channels. Then the validity of the theoretical expressions has been verified by our simulation results. Comparing to GCS-DCSK, MCS-DCSK and GCS-MDCSK, the proposed MCS-MDCSK system with reasonable parameters has higher data rate for the same transmission resource. Meantime, for the fixed data rate, the proposed system achieves lower BER level for the given SNR. Therefore, the proposed system not only improves the data rate to a great extent, but also has preferable BER performance in contrast to its rivals. Considering the demand of higher data rate and the rugged environment of future wireless communication, the proposed MCS-MDCSK system is up-and-coming.

References

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

[2] L. Ye, G. Chen, and L. Wang, "Essence and advantages of FM-DCSK versus conventional spread-spectrum communication methods," *Circuits Syst. Signal Process.*, vol. 24, no. 5, pp. 657–673, Oct. 2005.

[3] R. Vali, S. Berber, and S. K. Nguang, "Accurate derivation of chaos-based acquisition performance in a fading channel," *IEEE Trans. Wireless Commun.*, vol. 11, no. 2, pp. 722–731, Feb. 2012.

[4] M. Dawa, G. Kaddoum, and Z. Sattar, "A generalized lower bound on the bit error rate of DCSK systems over multi-path Rayleigh fading channels," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 65, no. 3, pp. 321–325, Mar. 2018.

[5] G. Kolumbán *et al.*, "Differential chaos shift keying: A robust coding for chaos communications," in *Proc. NDES*, Seville, Spain, Jun. 1996, pp. 87–92.

[6] W. Xu, L. Wang, and G. Kolumbán, "A novel differential chaos shift keying modulation scheme," *Int. J. Bifurcation Chaos*, vol. 21, no. 3, pp. 799–814, Mar. 2011.

[7] W. K. Xu, L. Wang, and G. Kolumbán, "A new data rate adaption communications scheme for code-shifted differential chaos shift keying modulation," *Int. J. Bifurcation Chaos*, vol. 22, no. 8, pp. 1–8, Aug. 2012.

[8] G. Kaddoum, F. Richardson, and F. Gagnon, "Design and analysis of a multicarrier differential chaos shift keying communication system," *IEEE Trans. Commun.*, vol. 61, no. 8, pp. 3281–3291, Aug. 2013.

[9] Z. Galias and G. M. Maggio, "Quadrature chaos-shift keying: Theory and performance analysis," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 48, no. 12, pp. 1510–1519, Dec. 2001.

[10] L. Wang, G. Cai, and G. Chen, "Design and performance analysis of a new multiresolution M-ary differential chaos shift keying communication system," *IEEE Trans. Wireless Commun.*, vol. 14, no. 9, pp. 5197–5208, Sep. 2015.

[11] T. Huang, L. Wang, W. Xu, and F. C. M. Lau, "Multilevel code-shifted differential-chaos-shift-keying system," *IET Commun.*, vol. 10, no. 10, pp. 1189–1195, Jul. 2016.

[12] Y. Tan, W. Xu, and S. Hong, "An M-ary code shifted differential chaos shift keying scheme," in *Proc. 23rd Asia–Pac. Conf. Commun. (APCC)*, Perth, WA, Australia, 2017, pp. 1–6.

[13] Y. Tan, W. Xu, T. Huang, and L. Wang, "A multilevel code shifted differential chaos shift keying scheme with code index modulation," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 65, no. 11, pp. 1743–1747, Nov. 2018.