Communication Model and Performance Analysis of Frequency Modulation-Correlation Delay-Orthogonal Chaotic Phase Shift Keying

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Abstract. In the Multi-ary chaos shift keying communication represented by CD-QCSK, each symbol carries multiple information bits, which can effectively improve the transmission rate. Since the bit energy of chaotic carrier is not constant, which may easily lead to misjudgment when receiving. Based on the feasibility study of combination in FM modulation and CD-QCSK communication, this article proposes a multi-ary FM-CD-QCSK communication model of frequency modulation-correlation delay-orthogonal chaos shift keying. By the FM modulator, The chaotic signal is changed into the carrier signal with constant envelope and random change of frequency within a certain range, so that each symbol has equal bit energy for transmission to improve the anti-interference and anti-noise ability of the system effectively. The simulation results show that, whatever the spreading spectrum factor changed, compared with existing Multi-ary chaos shift keying communication QCSK and CD-QCSK, the FM-CD-QCSK has better error performance and can better meet the requirements of high rate and communication quality under the same signal to noise ratio.

Keywords: Multi-ary · Chaos keying · FM modulation

1 Introduction

The chaotic signal takes advantage of the characteristics of aperiodic, high bandwidth, random-like and numerous, and is applied to spread spectrum and other wireless communication systems to act as carriers to achieve spectrum expansion while completing digital modulation. It has strong anti-noise, anti-interference, anti-multi-path fading and anti-parameter sensitivity [1, 2]. As the mainstream of binary chaotic keying communication technology, differential chaotic shift keying based on incoherent demodulation (Differential Chaos Shift Keying, DCSK) [3] does not need channel estimation and spread spectrum code synchronization, but it takes about half of the time to transmit power, use chaotic carriers that do not contain any data information as reference signals,

X. Jiang and P. Li (Eds.): GreeNets 2020, LNICST 333, pp. 233–242, 2020.
https://doi.org/10.1007/978-3-030-62483-5_25

which is difficult to meet the application requirements of high-speed, high-quality data transmission [4, 5]. Therefore, the Multi-ary chaotic keying communication with multiple information bits carried by each symbol has gradually become the focus of scholars at home and abroad [6].

In the article [7], a Multi-ary quadrature chaotic shift keying(QCSK) communication model is proposed based on DCSK. The model adopts four-phase orthogonal modulation and makes use of the zero correlation between the two orthogonal signals to increase its data transmission rate to twice as much as DCSK. In order to further improve the information transmission rate, the article [8], a Multi-ary correlation delay-quadrature chaotic shift keying (CD-QCSK) communication model is proposed by combining correlation delay shift keying (CDSK) [9] with QCSK. The model can have the advantages of high transmission rate of CDSK and QCSK at the same time, and its transmission rate can be 4 times of that of DCSK [10] and 2 times of that of QCSK. However, due to the aperiodic characteristics of chaotic signal, the bit energy will change with time after CD-QCSK modulation, which leads to the increase of bit error rate (BER) caused by decision problem.

Based on the above analysis, this paper proposes a combination of frequency modulation (FM) [11] and CD-QCSK communication, and proposes a Multi-ary frequency modulation-correlation delay-quadrature chaos shift keying (FM-CD-QCSK) communication model. At the transmitter, the chaotic signal is transformed into a carrier whose envelope is constant and the frequency varies randomly in a certain range by FM modulation, so that each symbol has the same bit energy and reduces the bit error rate (BER). At the receiving end, the reference signal and its orthogonal signal are divided into two ways to correlate with the carrier signal. As well as the information transmitted by each symbol can be doubled without FM resolution, and the system can improve the information transmission rate while reducing the bit error rate. The communication performance of FM-CD-QCSK system in Gaussian white noise channel and Riley channel is simulated and analyzed, and compared with the Multi-ary chaotic keying communication system QCSK and CD-QCSK. The results show that the FM-CD-QCSK system can effectively combine the error performance with the transmission rate, and will have a certain application prospect in the field of high-speed wireless communication.

2 FM-CD-QCSK Communication Model

2.1 Emission Model

Figure 1 shows emission model of FM-CD-QCSK. If high-frequency carrier $c(t) = A_c \cos \omega_c t$ is assumed, the chaotic signal $x(t)$ with random amplitude variation can be output after frequency modulation as follows:

$$x'(t) = A_c \cos(\omega_c t + k_f \int_0^t x(\tau) d\tau) = A_c \cos \varphi(t) \tag{1}$$

In the formula (1), A_c is the carrier amplitude, k_f is the frequency modulation coefficient, and $x'(t)$ is the chaotic frequency modulation signal with constant amplitude and random frequency variation.

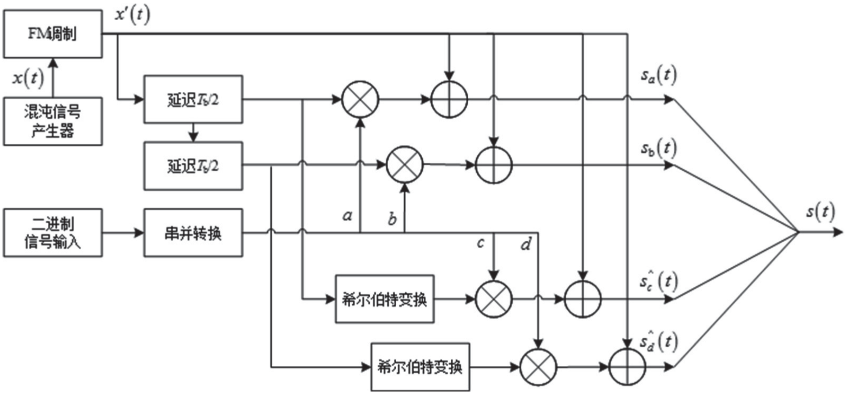


Fig. 1. Emission model of FM-CD-QCSK

In view of the shortage of transmitting reference signal in half of each symbol period of QCSK, FM-CD-QCSK uses the communication principle of CDSK chaotic keying for reference, converts binary information sequence into information signal as a, b, c, d, modulates four information signals at the same time by using chaotic signal of delay $T_{\mathrm{b}}/2$, T_{b} and its orthogonal signal, and then transmits it after superposition with chaotic frequency modulation signal $x'(t)$.

In the l symbol period, the output signal of the FM-CD-QCSK transmitter, as follows.

$$s(t)=\begin{cases} s_a(t)=x'(t)+ax'(t-T_{\mathrm{b}}/2), & (l-1)T_{\mathrm{b}}\le t<(l-3/4)T_{\mathrm{b}} \\ s_b(t)=x'(t)+bx'(t-T_{\mathrm{b}}), & (l-3/4)T_{\mathrm{b}}\le t<(l-2/4)T_{\mathrm{b}} \\ s_{\hat{c}}(t)=x'(t)+c\hat{x}'(t-T_{\mathrm{b}}/2), & (l-2/4)T_{\mathrm{b}}\le t<(l-1/4)T_{\mathrm{b}} \\ s_{\hat{d}}(t)=x'(t)+d\hat{x}'(t-T_{\mathrm{b}}), & (l-1/4)T_{\mathrm{b}}\le t<lT_{\mathrm{b}} \end{cases} \tag{2}$$

In the formula (2), $\hat{x}'(t)$ is a chaotic signal with which $x'(t)$ is orthogonal by Herbert transform. After the information sequence is transformed by bipolar transformation, a, c is modulated with the chaotic frequency modulation signal $x'(t-T_{\mathrm{b}}/2)$ of delay $T_{\mathrm{b}}/2$ and its orthogonal chaotic frequency modulation signal $\hat{x}'(t-T_{\mathrm{b}}/2)$, and b, d is modulated with the chaotic frequency modulation signal $x'(t-T_{\mathrm{b}})$ and its orthogonal chaotic frequency modulation signal $\hat{x}'(t-T_{\mathrm{b}})$ with a delay of T_{b}, respectively. If the information signal is "+1", the information signal is the same as the reference signal; if the information signal is "−1", the information signal is opposite to the reference signal. Therefore, the transmitted information signal is included in the correlation value of symbol sample values of two adjacent symbol.

2.2 Receiving Model

Figure 2 shows receiving model of FM-CD-QCSK. It is assumed that the transmitted signal is interfered by additive white Gaussian noise $n(t)$ in the transmission process, the received signal is correlated with its delay $T_{\mathrm{b}}/2$, T_{b} signal respectively. For example $r_a(t)$, $r_{\hat{c}}(t)$, the output $y_a(t)$, $y_c(t)$ through the correlator are

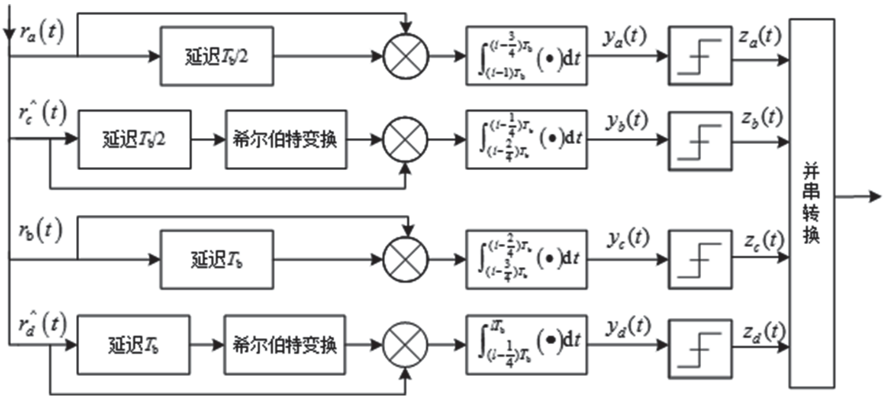


Fig. 2. Receiving model of FM-CD-QCSK

$$\begin{aligned}
y_a(t) &= \int_{(l-1)T_\mathrm{b}}^{(l-\frac{3}{4})T_\mathrm{b}} r_a(t) r_a(t - T_\mathrm{b}/2)\mathrm{d}t \\
&= \int_{(l-1)T_\mathrm{b}}^{(l-\frac{3}{4})T_\mathrm{b}} [sa(t) + n(t)][sa(t - T_\mathrm{b}/2) + n(t - T_\mathrm{b}/2)]\mathrm{d}t \\
&= \int_{(l-1)T_\mathrm{b}}^{(l-\frac{3}{4})T_\mathrm{b}} [sa(t)sa(t - T_\mathrm{b}/2)]\mathrm{d}t + \int_{(l-1)T_\mathrm{b}}^{(l-\frac{3}{4})T_\mathrm{b}} [sa(t)n(t - T_\mathrm{b}/2)]\mathrm{d}t \\
&+ \int_{(l-1)T_\mathrm{b}}^{(l-\frac{3}{4})T_\mathrm{b}} [sa(t - T_\mathrm{b}/2)n(t)]\mathrm{d}t + \int_{(l-1)T_\mathrm{b}}^{(l-\frac{3}{4})T_\mathrm{b}} [n(t)n(t - T_\mathrm{b}/2)]\mathrm{d}t \\
&= \int_{(l-1)T_\mathrm{b}}^{(l-\frac{3}{4})T_\mathrm{b}} [sa(t)sa(t - T_\mathrm{b}/2)]\mathrm{d}t
\end{aligned} \tag{3}$$

$$\begin{aligned}
y_c(t) &= \int_{(l-\frac{2}{4})T_\mathrm{b}}^{(l-\frac{1}{4})T_\mathrm{b}} r_c^{\wedge}(t) r_c^{\wedge}(t - T_\mathrm{b}/2)\mathrm{d}t \\
&= \int_{(l-\frac{2}{4})T_\mathrm{b}}^{(l-\frac{1}{4})T_\mathrm{b}} [s_c^{\wedge}(t) + n(t)][s_c^{\wedge}(t - T_\mathrm{b}/2) + n(t - T_\mathrm{b}/2)]\mathrm{d}t \\
&= \int_{(l-\frac{2}{4})T_\mathrm{b}}^{(l-\frac{1}{4})T_\mathrm{b}} [s_c^{\wedge}(t)s_c^{\wedge}(t - T_\mathrm{b}/2)]\mathrm{d}t + \int_{(l-\frac{2}{4})Tb}^{(l-\frac{1}{4})Tb} [s_c^{\wedge}(t)n(t - T_\mathrm{b}/2)]\mathrm{d}t \\
&+ \int_{(l-\frac{2}{4})T_\mathrm{b}}^{(l-\frac{1}{4})T_\mathrm{b}} [s_c^{\wedge}(t - T_\mathrm{b}/2)n(t)]\mathrm{d}t + \int_{(l-\frac{2}{4})Tb}^{(l-\frac{1}{4})Tb} [n(t)n(t - T_\mathrm{b}/2)]\mathrm{d}t \\
&= \int_{(l-\frac{2}{4})T_\mathrm{b}}^{(l-\frac{1}{4})T_\mathrm{b}} [s_c^{\wedge}(t)s_c^{\wedge}(t - T_\mathrm{b}/2)]\mathrm{d}t
\end{aligned} \tag{4}$$

In the formula (3) and (4), due to the good auto-correlation of chaotic signals, the correlation values of the other three terms are all zero except that the first term is a useful term carrying information. When the threshold value of the decision circuit is set to zero, the FM modulation will make the signal energy tend to be constant. When $y_a(t)$, $y_c(t) > 0$, the value of the decision output is "+1", and when $y_a(t)$, $y_c(t) < 0$ the value of the decision output is "−1".

3 FM-CD-QCSK Simulation Analysis

In order to study the communication performance of FM-CD-QCSK, the FM-CD-QCSK communication model based on Gaussian (AWNG) channel and Riley (Rayleigh) channel is simulated and analyzed, and the influence of the system parameters on the communication performance is obtained, and compared with other similar chaotic keying communication models.

Figure 3 shows the variation of error performance of FM-CD-QCSK with spread spectrum factor in AWNG channel. The simulation time is T = 2000 s and the spread spectrum factor is m = 8, 16, 32. It can be seen from the simulation diagram that when $E_b/N_0 < 4$ dB, the error performance of the FM-CD-QCSK system at different m values is comparable, which indicates that the influence of the spreading factor on the system performance is not obvious in this range. When the signal-to-noise ratio (SNR) is larger than 4 dB, the spread spectrum factor increases, which leads to the deterioration of the error performance of the system. This is because the noise interference term of the receiver correlator demodulation is proportional to the spread spectrum factor. With the increase of the spread spectrum factor, the introduced noise component will increase, which will lead to the deterioration of the error code performance of the system. Therefore, there is an optimal m value parameter setting.

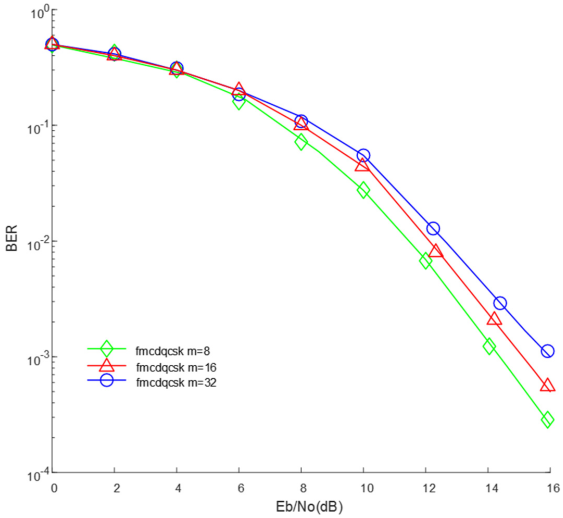


Fig. 3. BER performance of FM-CD-QCSK under different spreading factors of AWNG channel

Figure 4 shows the variation of error performance of FM-CD-QCSK system with signal-to-noise ratio (SNR) in AWNG channel. The simulation time is T = 2000 s, and the signal-to-noise ratio is $E_b/N_0 = 4, 10, 16$ respectively. The simulation results show that the bit error rate (BER) decreases with the increase of SNR. At the same time, when $E_b/N_0 = 4$ dB, the BER curve is almost a straight line, which shows that the influence of spread spectrum factor on BER is not obvious at low SNR. When $E_b/N_0 = 10, 16$ dB, it can be found that when $0 < \mathrm{m} < 8$, as the spreading factor increases, the bit error rate gradually decreases, but when the spread spectrum factor increases to the critical value $\mathrm{m} = 8$, the bit error rate increases with the increase of spread spectrum factor. This is due to the increase of the noise component introduced in the receiver correlator with the increase of the spread spectrum factor, which leads to the increase of the bit error rate (BER) of the system. Therefore, under the condition of certain signal-to-noise ratio (SNR), the optimal error performance of FM-CD-QCSK system will be obtained by properly selecting the spread spectrum factor $\mathrm{m} = 8$.

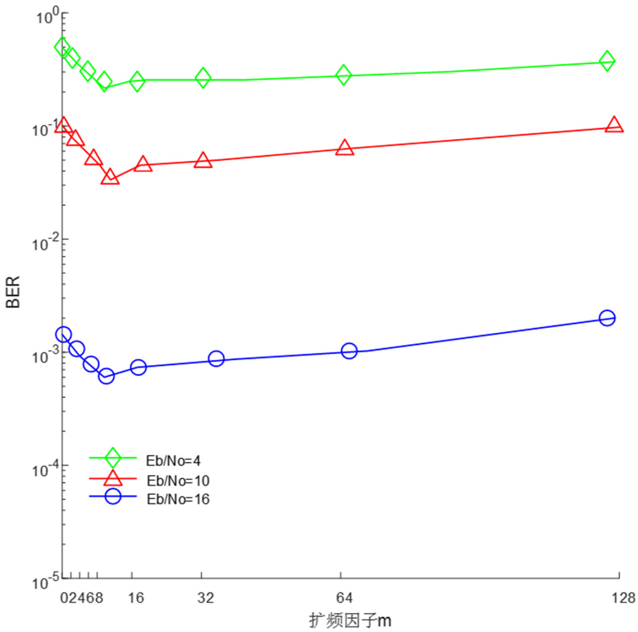
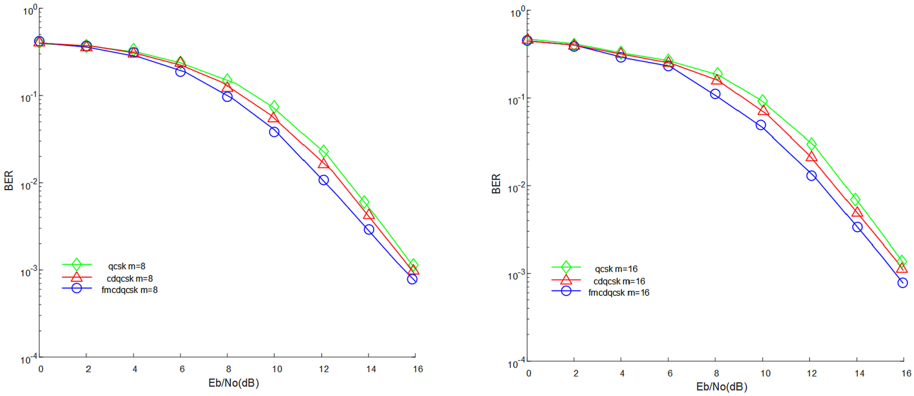


Fig. 4. BER performance of FM-CD-QCSK under different signal-to-noise ratios in AWNG channel

Figure 5 shows the simulation results for all systems (including FM-CD-QCSK 、CD-QCSK and QCSK) with different values of M for BER performance comparison. The simulation time is $\mathrm{T} = 2000$ s, and the spread spectrum factor is $\mathrm{m} = 8, 16$ respectively. By comparing diagram (a), diagram(b), it can be found that when $0 < E_b/N_0 < 16$, the bit error rate (BER) of FM-CD-QCSK system is better than that of QCSK and CD-QCSK at different m values. When the bit error rate is the same, the signal-to-noise ratio (SNR) of FM-CD-QCSK is about 1 dB higher than that of CD-QCSK and 2 dB higher than that of QCSK. Thus it can be seen that by introducing FM modulation into CD-QCSK, FM-CD-QCSK can achieve better communication performance.



(a) m=8 (b) m=16

Fig. 5. Comparison of BER performance between FM-CD-QCSK,CD-QCSK and QCSK in AWNG channel

Figure 6 shows the variation of BER performance of FM-CD-QCSK with spread spectrum factor in Rayleigh channel. The simulation time is T = 2000 s, and the spread spectrum factor is m = 8, 16, 32 respectively. The maximum Doppler translation of channel parameters is 1 Hz, and the M-path parameter is L = 3. The simulation results show that when $E_b/N_0 < 4$ dB, FM-CD-QCSK has similar bit error performance under different spread spectrum factors, which shows that the spread spectrum factor has little effect on the bit error rate at low signal-to-noise ratio (SNR) of Riley channel. When the signal-to-noise ratio (SNR) is larger than 4 dB, the error performance of the system is improved with the increase of spread spectrum factor. By comparing with Fig. 5, it can be found that the optimal value of spread spectrum factor of FM-CD-QCSK system in Rayleigh channel is larger than that in Gaussian channel, which is due to the fact that multipath delay will increase the decision energy, thus offsetting the partial correlation noise interference caused by the increase of spread spectrum factor.

Figure 7 shows the BER performance simulation curve of FM-CD-QCSK in AWNG channel and Rayleigh. channel. The simulation time is T = 2000 s, the spread spectrum factor is m = 8, the maximum Doppler translation of channel parameters is 1 Hz, and the multipath channel parameters are L = 2 and L = 3 respectively. When $0 < E_b/N_0 < 18$, the bit error rate (BER) of FM-CD-QCSK in Gaussian channel is close to 0, and the bit error rate (BER) of FM-CD-QCSK in Rayleigh fading channel is higher than that in Gaussian channel, and the attenuation is slower. It is shown that the effect of multipath delay effect on signal transmission in Riley channel model is more serious than that in AWGN channel, so the error performance of the system in Gaussian channel is obviously better. In Riley channel, when $E_b/N_0 < 10$ dB, the bit error rate (BER) of FM-CD-QCSK under different multipath channel parameters is approximately the same, which indicates that the multipath channel parameters have little effect on the system performance in this range. When the signal-to-noise ratio (SNR) is larger than 10 dB, the difference between L = 3 and L = 2 is gradually obvious. When BER = 10^{-2}, the signal-to-noise ratio (SNR) of the system with multipath parameter L = 3 is about 2 dB higher than that

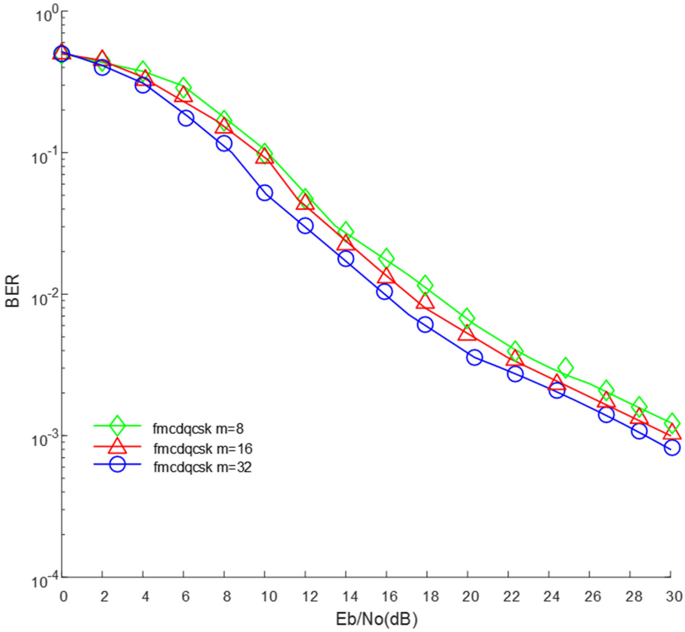


Fig. 6. BER performance of FM-CD-QCSK under different spread spectrum factors in rayleigh channel

of L = 2, which is due to the increase of signal energy in the decision variable due to the superposition of signal energy in each path channel, which makes it easier for the decision valve to judge the correct value.

Figure 8 shows the BER performance simulation curves of FM-CD-QCSK, CD-QCSK and QCSK over Rayleigh channel. The simulation time is T = 2000 s, the spreading factor is m = 16, the maximum Doppler shift of the channel parameters is 1 Hz, and the multipath channel parameters are L = 2 and L = 3, respectively. Compared with diagram (a), diagram (b), the BER values of the three systems are very similar when $0 < E_b/N_0 < 10$. It is shown that the error performance of the three systems is approximately the same when the signal-to-noise ratio (SNR) of the three systems is low. When $10 < E_b/N_0 < 30$, with the increase of signal-to-noise ratio (SNR), the bit error rate (BER) of FM-CD-QCSK decays faster, and the advantages of BER are more and more obvious. In the case of $E_b/N_0 = 30$, the bit error rate (BER) of FM-CD-QCSK approaches zero. It can be concluded that the error performance of FM-CD-QCSK system in Riley channel is better than that of CD-QCSK and QCSK.

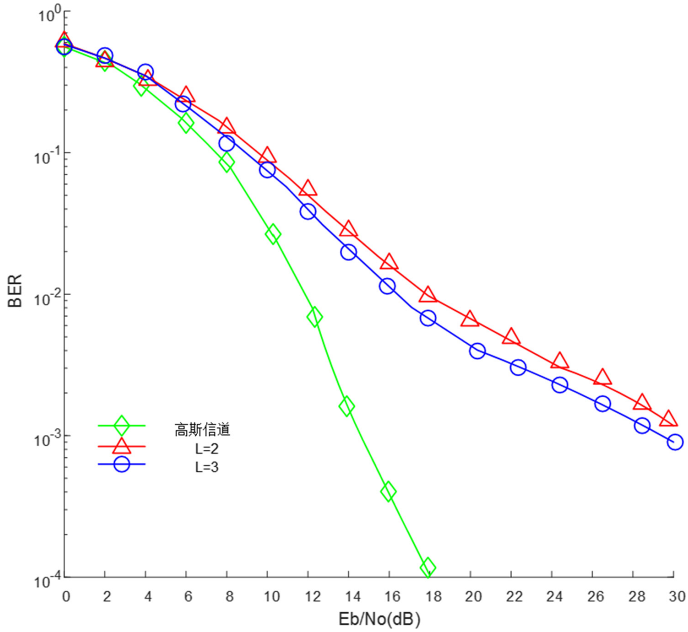
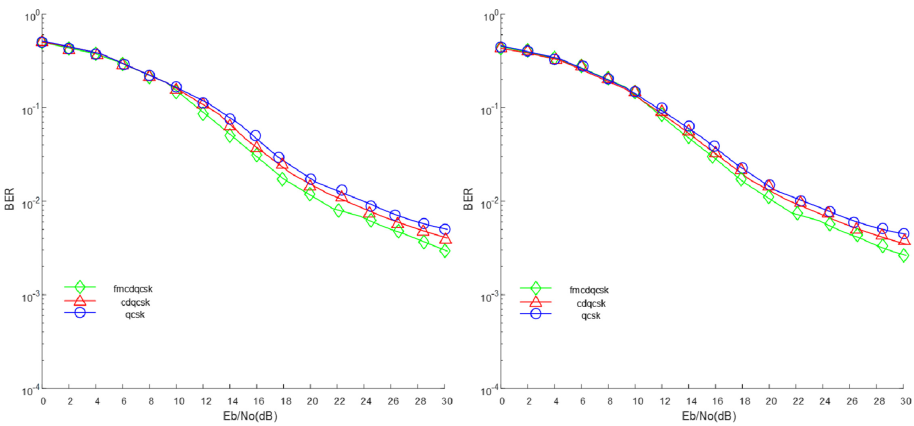


Fig. 7. Comparison of BER performance of FM-CD-QCSK in AWNG channel and rayleigh channel



(a) L=2 (b) L=3

Fig. 8. Comparison of BER performance between FM-CD-QCSK,CD-QCSK and QCSK in rayleigh channel

4 Conclusion

In order to further improve the anti-interference and anti-noise ability of Multi-ary chaotic keying communication represented by CD-QCSK, a new type of FM-CD-QCSK Multi-ary chaotic keying communication model is proposed by combining it with FM modulation. The system makes each symbol have equal bit energy by FM modulation, and can ensure high-speed transmission of information while reducing the bit error rate. The communication performance of FM-CD-QCSK in AWNG and Rayleigh channels are simulated and compared with CD-QCSK and QCSK. It is concluded that FM-CD-QCSK has better communication performance and can better meet the high quality and high speed application requirements of wireless communication.

Funding. This work was supported by Heilongjiang Fundamental Research Foundation for the Local Universities in 2018 (2018KYYWF1189) and Science and Technology Innovation Foundation of Harbin (2017RAQXJ082).

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