A Novel Double Modulation Technique with High Spectrum Efficiency for TDCS

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Abstract. The modulation techniques in traditional transform domain communication system (TDCS) exist some drawbacks, such as low transmission rate and low spectrum efficiency. We propose a novel double modulation technique with high spectrum efficiency for TDCS in this paper. First, we divide the basis function averagely into several orthogonal modules, and conduct the CSK modulation. Then, the double modulation signal waveform can be obtained by employing bipolar modulation for different module combination. Furthermore, we propose two demodulation schemes for the proposed modulation technique, namely the cyclic shift keying (CSK)-bipolar and bipolar-CSK demodulation. We also derive the mathematical expressions of their bit error rate (BER) performance. Simulation results show that for different signal-to-noise ratio (SNR), the two demodulation schemes can both achieve reliable performance, satisfactory anti-interference capabilities and effectively improve spectrum efficiency. In addition, it can be verified that CSK-bipolar demodulation can achieve the same BER with less SNR compared with bipolar-CSK demodulation.

Keywords: TDCS · CSK · Bipolar modulation · Demodulation Spectrum efficiency

1 Introduction

Transform domain communication system (TDCS) was proposed by the U.S. Air Force Institute of Technology (AFIT) in 1990s. With its unique anti-interference theory, low probability intercept (LPI) and low probability detection (LPD) performance, TDCS has attracted widespread attention in many fields, such as in aeronautical communications and satellite communications [1, 2], etc. A huge number of researches have already been carried out in this field. For instance, the flexible spectrum access and multiple access of TDCS are analyzed in [3, 4] and [5], providing theoretical bases for applications. For the problem that the peak-to-average ratio of the basis function is

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large, schemes are proposed for improvement in [6] and [7], promoting the system LPI and LPD effectively. The accurate receiving strategy in TDCS which increases the bit error rate (BER) performance and reduces the system complexity is studied in [8].

With the development of research, traditional modulation and demodulation techniques with low spectrum efficiency can no longer meet the real-time requirement for information transmission in modern communication systems. Thus, it is increasingly urgent to design an efficient and reliable modulation technique. In TDCS, the basis function is used as the modulating waveform [9]. At present, the main modulation techniques in TDCS are bipolar modulation and cyclic shift keying (CSK). As a simple modulation scheme, bipolar modulation flips the basis function, and employs different code elements to represent positive and negative energy respectively. The technique has a simple demodulation procedure and good BER performance. However, in bipolar modulation every sending waveform can only transmit a bit of binary information, leading to extremely low transmission efficiency. CSK is developed from cyclic code shift keying (CCSK) [10]. Its sending waveform set is produced by different shifts of the basis function. It improves low spectrum efficiency to a certain extent, yet its information bits are exponential to demodulation complexity. Demodulation efficiency is getting lower with the increase in the amount of information.

For problems existing in bipolar modulation and CSK, some studies on modulation technique with high spectrum efficiency for TDCS have emerged recently. In [11], a sending waveform set including more waveforms is acquired through permutation and combination of the waveforms in the orthonormal waveform set of CSK. Although the spectrum efficiency is improved, it is difficult to be used in engineering due to huge demodulation cost. In [12], a modulation technique based on cluster is presented. After spectrum sensing, the entire unoccupied spectrum are averagely divided into several clusters, and orthogonal modulating waveforms are generated. The technique also improves spectrum efficiency, yet the allocation principle of random allocation modulation scheme is not described in detail, which makes it less applicable. The above techniques only detect maximum correlation value of real part in received waveform, and discard the imaginary part directly in demodulation. For this problem, a joint modulation method of real and imaginary part of the modulating waveform is proposed in [13]. Spectrum efficiency is doubled by the method, but it reduces the orthogonality of waveforms and leads to BER increase.

Due to the drawbacks exist in the above modulation and demodulation schemes, we are motivated to design a novel double modulation technique with high spectrum efficiency for TDCS. The double modulation technique includes two stages, namely the modular CSK and modular bipolar sequently. Furthermore, two demodulation methods are presented, and performance for the methods is simulated and analyzed under different signal-to-noise ratio (SNR) and interference-to-noise ratio (INR). Results verify the effectiveness and reliability of the modulation technique on information transmission with high spectrum efficiency. The contribution of the paper can be summarized as follows. On one hand, a novel double modulation technique with high spectrum efficiency for TDCS is proposed, and the principle and process of the technique is described in detail. On the other hand, two demodulation schemes for the proposed modulation technique are presented, and their BER performance is analyzed respectively.

The remaining of the paper is organized as the following. In Sect. 2, we give a review on the principle of TDCS. In Sect. 3, the double modulation technique is described in detail, and its spectrum efficiency is analyzed. In Sect. 4, we provide two corresponding demodulation methods. Simulations are performed to verify the effectiveness of the proposed method in Sect. 5. Finally, we conclude the paper in Sect. 6.

2 Review on TDCS

TDCS is a broadband communication system. Its principle can be summarized as: the interference spectrum is eliminated in the transform domain, and a noise-like basis function is generated and used to modulate the information bits in order to achieve the goals of anti-interference, LPI and LPD. The main principle of TDCS is shown in Fig. 1.

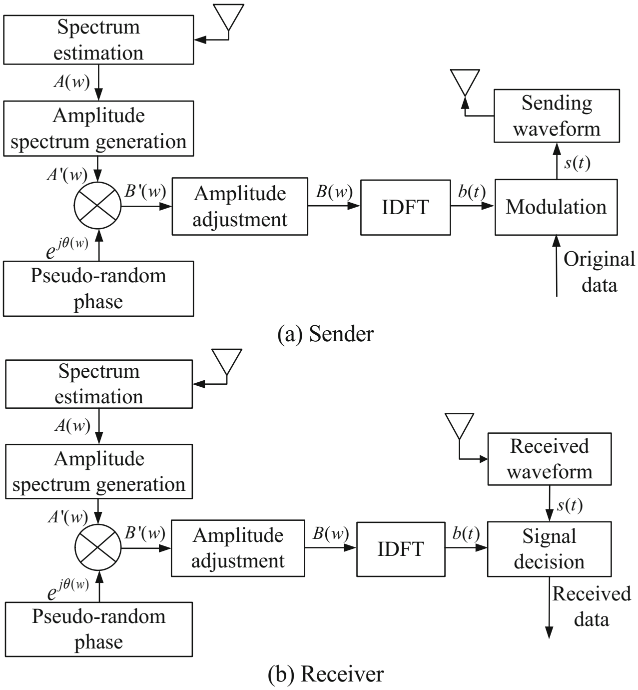


Fig. 1. Principle of TDCS.

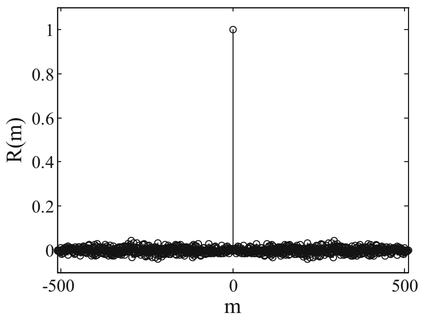
A basis function is employed to modulate information in TDCS. When subcarrier number is N, the discrete basis function in time domain can be expressed as

$$b(n) = \frac{1}{N}\sum_{k=1}^{N-1} CA_k\, e^{j\theta_k},\ e^{j2\pi kn/N} \qquad (1)$$

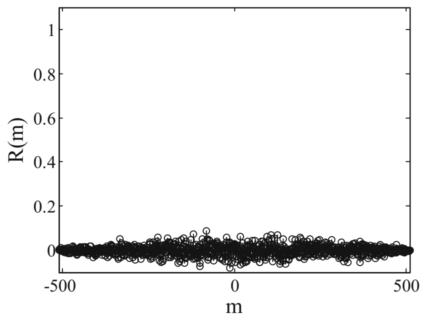
Where C is the adjusting factor of amplitude, A_k is the amplitude spectrum vector, $e^{j\theta_k}$ is the pseudo-random phase, and $e^{j2\pi kn/N}$ is the coefficient of inverse discrete Fourier transform (IDFT). The basis function in frequency domain is derived through the tagged amplitudes in frequency domain mapping to random phases distributed averagely on $[0, 2\pi]$. And the basis function in time domain is the inverse transform of that in frequency domain. Thus, it can be regarded as a noise-like sequence with N points, and has a good correlation performance. Its correlation function can be expressed as

$$\begin{aligned} R(m) &= \sum_{m=-(N-1)}^{N-1} b(n+m)b^*(n) \\ &= \sum_{m=-(N-1)}^{N-1} \frac{C^2}{N^2} \sum_{k=1}^{N-1} A_k^2 e^{j(\theta_k - \theta_k')} e^{j\left(\frac{2\pi kn}{N} - \frac{2\pi k(n+m)}{N}\right)} \end{aligned} \tag{2}$$

When $m = 0$, the auto-correlation function reaches the maximum value. When $N = 512$, the correlation performance of the basis function is shown in Fig. 2.



(a) Auto-correlation performance



(b) Cross-correlation performance

Fig. 2. Correlation performance of the basis function in TDCS.

3 Double Modulation Technique

3.1 Modular CSK

Since the basis function has a good correlation property, its waveforms through different time shifts have strict orthogonality. M-CSK is the cyclic shift of the basis function with the same step-length, and can be represented as

$$\begin{aligned} s_i(n) &= b(n - \frac{(i-1)T}{M})_T \quad , \ i \in (1, M) \\ &= \frac{1}{N} \sum_{k=1}^{N-1} C A_k e^{j\theta_k} e^{j2\pi kn/N} e^{-\frac{j\pi S_i k}{M}} \end{aligned} \tag{3}$$

From another point of view, the basis function with length N can be divided averagely into M modules before modulation, denoted as b_1, b_2,…, b_M respectively. The length of every module is N/M. The same waveform set as that in M-CSK can be derived by the cyclic shifts of the M modules in sequence. At this time every waveform can represent k bits information ($M = 2^k$). The process of the modular CSK is shown in Fig. 3.

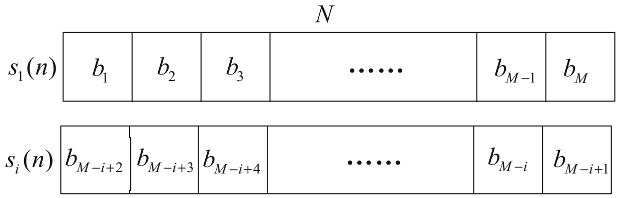


Fig. 3. Process of the modular CSK.

After the cyclic shift, the waveforms are mutually orthogonal in the waveform set. If the energy of the sending waveform is $\sqrt{\varepsilon}$, the energy distance between different waveforms is $\sqrt{2\varepsilon}$. Let ε_1, ε_2,…, $\varepsilon_M$denote the energy of every module respectively, and the set of modular CSK waveforms can be represented as

$$\begin{array}{lclcl} s_1 & = & \overbrace{(\sqrt{\varepsilon}, 0, \cdots, 0)}^{N} & = & \overbrace{(\varepsilon_1, \varepsilon_2, \cdots, \varepsilon_M)}^{N} \\ s_2 & = & (0, \sqrt{\varepsilon}, \cdots, 0) & = & (\varepsilon_M, \varepsilon_1, \cdots, \varepsilon_{M-1}) \\ & & \vdots & & \vdots \\ s_M & = & (0, \cdots, 0, \sqrt{\varepsilon}) & = & (\varepsilon_2, \cdots, \varepsilon_M, \varepsilon_1) \end{array}, \tag{4}$$

3.2 Modular Bipolar Modulation

From (4), in the waveform set derived from the modular CSK, modules corresponding to any two waveforms are all mutually orthogonal. Hence, we can take full use of the orthogonality to achieve the second modulation. Every successive ξ modules in M modules of the CSK waveform are recombined to derive γ new modules. Thus, $\gamma = M/\xi$. Let $s_{i1}(n)$, $s_{i2}(n)$,…, $s_{i\gamma}(n)$ denote the new modules respectively. The length of every new module is $N\xi/M$, and any two modules are mutually orthogonal. When $\xi = 2$, the new modules are shown in Fig. 4.

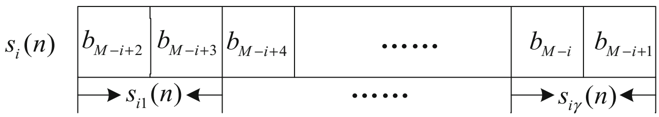


Fig.4 Combination of modules when $\xi = 2$.

We modulate every new module with bipolar modulation, and denote different information bits by its positive and negative energy, namely,

$$s_{ij}(n) = \begin{cases} s_{ij}(n), \text{if information is } 0 \\ -s_{ij}(n), \text{if information is } 1 \end{cases}, \tag{5}$$

Through the modular bipolar modulation, the sending waveform set can be expressed as

$$\begin{aligned} s_1 &= \overbrace{((-1)^{s^1}(\varepsilon_1+\varepsilon_2),(-1)^{s^2}(\varepsilon_3+\varepsilon_4),\cdots,(-1)^{s^j}(\varepsilon_{M-1}+\varepsilon_M))}^{N} \\ s_2 &= ((-1)^{s^1}(\varepsilon_M+\varepsilon_1),(-1)^{s^2}(\varepsilon_2+\varepsilon_3),\cdots,(-1)^{s^j}(\varepsilon_{M-2}+\varepsilon_{M-1})) \\ &\vdots \\ s_M &= ((-1)^{s^1}(\varepsilon_2+\varepsilon_3),\cdots,(-1)^{s^{j-1}}(\varepsilon_{M-2}+\varepsilon_{M-1}),(-1)^{s^j}(\varepsilon_M+\varepsilon_1)) \end{aligned}, \tag{6}$$

Where s^1, s^2,…, s^j denote the information bit 0 or 1 after the modular bipolar modulation of the sending waveform. 0 represents the positive energy of the module, and 1 represents the negative energy of the module. $\varepsilon_1+\varepsilon_2$, $\varepsilon_2+\varepsilon_3$,… denote the energy of every module through recombination, and its energy is $1/\gamma$ of the waveform energy.

3.3 Spectrum Efficiency

For the modular CSK, every waveform can denote k bits information. For the communication system with symbol rate R_s, the bit transmission rate is

$$R_b = R_s \log_2 M = \frac{\log_2 M}{T_s}, \tag{7}$$

Where T_s is the symbol period. Then, γ bits information is modulated with bipolar modulation with γ modules. After modulation, the bit transmission rate can be expressed as

$$R_b = R_s(\log_2 M + \gamma) = \frac{\log_2 M + \gamma}{T_s}, \tag{8}$$

The symbol period is $T_s = 1/\Delta f$, and K_{used} is the number of available subcarrier. Thus, the signal bandwidth is

$$W_{used} = K_{used} \cdot \Delta f, \tag{9}$$

According to the definition in 9, the spectrum efficiency of the modulation in this paper can be expressed as

$$\eta = \frac{R_b}{W_{used}} = \frac{R_s \cdot (\log_2 M + \gamma)}{K_{used} \cdot \Delta f} = \frac{\log_2 M + \gamma}{K_{used}}, \tag{10}$$

Therefore, compared with CSK, the spectrum efficiency has been improved $\frac{\gamma}{K_{used}}$.

4 Double Modulation Technique

Through two times modulations, the shift property and local turnover property of the modulating waveform have both been changed. For the demodulation of the sending waveform, both of the properties have interacted with each other. The turnover property is based on the shift property, and the shift property can be extracted simultaneously when the local turnover is exact. In this section, we proposed two demodulation schemes, and analyze their BER performance.

4.1 Csk-Bipolar Demodulation

Double modulating waveform is the combination of modular cyclic shift of the basis function and bipolar modulation. Firstly the order of the cyclic shift is demodulated, and then the sending information is recovered through modular bipolar demodulation. The demodulation flow is shown in Fig. 5.

For the sending waveform s_i, the demodulation model of the modular CSK order for the received waveform r can be expressed as

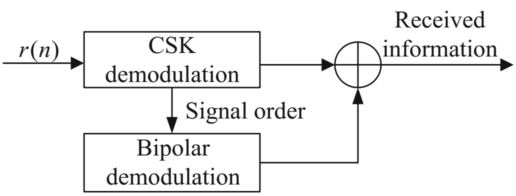


Fig. 5. Flow of CSK-bipolar demodulation.

$$a = \max\left\{ r \cdot \begin{bmatrix} s_{1,1}^* & s_{1,2}^* & \cdots & s_{1,2^\gamma}^* \\ s_{2,1}^* & \ddots & & s_{2,2^\gamma}^* \\ \vdots & & \ddots & \vdots \\ s_{M,1}^* & s_{M,2}^* & \cdots & s_{M,2^\gamma}^* \end{bmatrix} \right\}, \tag{11}$$

Where $a$is the order when the correlation demodulation of every waveform in the waveform set is maximum. The row number of the matrix represents the dimension $M$of the modular CSK orthogonal waveform set, and the column number of the matrix represents 2^γ kinds of waveform when the energy of γ modules are positive or negative values respectively in the same modulating waveform. When the received waveform is demodulated using (11), every waveform needs $M \cdot 2^{\gamma}$ times waveform correlation operations. The computing costs too much for engineering applications.

From (6), we can observe that modular bipolar modulation of the sending waveform does not change the orthogonality between each module. Thus, in the modular CSK demodulation of signal, positive or negative state of every module can be ignored. Thereby, the demodulation of the sending waveform can be simplified to a pure CSK demodulation. Assuming the sending signal is s_1, the received signal can be expressed as

$$r = (\sqrt{\varepsilon} + n_1, n_2, \cdots, n_M), \tag{12}$$

Where n_1, n_2,..., n_M are Gaussian white noise with mean value 0 and variance $\frac{N_0}{2}$. (11) can be simplified as in [14]

$$\begin{aligned} a = \max(r \cdot s_i^*) &= \max\left\{ r \cdot \begin{bmatrix} \sqrt{\varepsilon}, 0, \cdots, 0 \\ 0, \sqrt{\varepsilon}, \cdots, 0 \\ \vdots \\ 0, \cdots, 0, \sqrt{\varepsilon} \end{bmatrix} \right\}, \\ &= \sum \max \left\{ \begin{matrix} \varepsilon + \sqrt{\varepsilon} n_1 \\ \cdots \\ \sqrt{\varepsilon} \cdot n_M \end{matrix} \right\} \end{aligned} \tag{13}$$

Let $z_i = r \cdot s_i^*$, and the probability that the waveform is received correctly can be expressed as in [14]

$$\begin{aligned} P_a &= P(z_1 > z_2, z_1 > z_3, \cdots, z_1 > z_M | s_1 send) \\ &= P(\sqrt{\varepsilon} + n_1 > n_2, \sqrt{\varepsilon} + n_1 > n_3, \cdots, \sqrt{\varepsilon} + n_1 > n_M | s_1 send) \\ &= P(\sqrt{\varepsilon} + n > n_2, \sqrt{\varepsilon} + n > n_3, \cdots, \sqrt{\varepsilon} + n > n_M | s_1 send, n_1 = n), \\ &= \int_{-\infty}^{\infty} (P(\sqrt{\varepsilon} + n > n_2 | s_1 send, n_1 = n))^{M-1} \cdot p_{n_1}(n) \mathrm{d}n \end{aligned} \tag{14}$$

Where $P(\sqrt{\varepsilon} + n > n_2 | s_1 send, n_1 = n) = 1 - Q(\frac{n + \sqrt{\varepsilon}}{\sqrt{N_0/2}})$, and $p_{n_1}(n) = \frac{1}{\sqrt{\pi N_0}} e^{-\frac{n^2}{N_0}}$.

Assuming through the modular bipolar modulation the probability of information bit 0 is equal to that of 1, the decision threshold in bipolar demodulation can be set to 0. The probability of a correct decision in a module can be expressed as

$$P_b = 1 - Q\left(\sqrt{2\sqrt{\varepsilon}/\gamma N_0}\right), \tag{15}$$

Therefore, the probability that the sending waveform is correctly received absolutely is

$$P = \frac{k}{k+\gamma} P_a + \frac{\gamma}{k+\gamma} P_a \cdot (P_b)^{\gamma}, \tag{16}$$

4.2 Bipolar-CSK Demodulation

For the sending waveform s_i, if every module s_{ij} can be received correctly, s_i will also inevitably be received correctly. Therefore, firstly the γ modules in the received waveform can be bipolar-based demodulated respectively, and count the modulation order of every module simultaneously. The maximum order in statistic result will be regarded as modular CSK order. The demodulation flow is shown in Fig. 6.

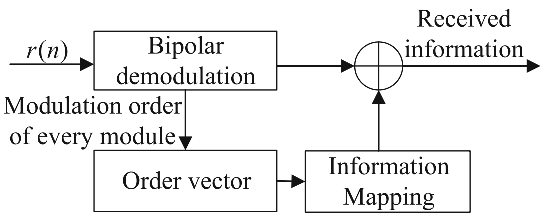


Fig. 6. Flow of bipolar-CSK demodulation.

In the modular bipolar demodulation of any received waveform r, every module is demodulated by the correlation demodulation of the corresponding module in M waveforms. Let r_1 denote the first module of the received waveform, and the demodulation model can be expressed as

$$[a, b] = \max\left\{ r_1 \cdot \begin{bmatrix} s_{1,1}^* & -s_{1,1}^* \\ s_{2,1}^* & -s_{2,1}^* \\ \vdots & \vdots \\ s_{M,1}^* & -s_{M,1}^* \end{bmatrix} \right\}, \tag{17}$$

Where $a \in (1, 2, \cdots, M)$ and $b \in (1, 2)$ represent the maximum dimension number and column number of the demodulation matrix, respectively. $s_{i,1}^*$ is the conjugate of the first module in the sending waveform set. As only the maximum real parts of the correlation receiver are detected in demodulation, and the real parts of $r_1 s_{i1}^*$ and $-r_1 s_{i1}^*$ are the opposite of each other, (17) can be expressed as

$$\begin{aligned} a &= \max\left[\left|\left|r_1 s_{1,1}^*\right| \quad \left|r_1 s_{2,1}^*\right| \quad \cdots \quad \left|r_1 s_{M,1}^*\right|\right|\right]^T \bigcap b \\ &= \max\left[(r_1 s_{1,1}^*) > (-r_1 s_{1,1}^*)\right] \end{aligned}, \tag{18}$$

Only when a and b are both solved correctly, the first module of the received waveform will be demodulated correctly. From (6), we can get that $s_{1,1}^*$, $s_{2,1}^*$, …, $s_{M,1}^*$are M orthogonal waveform vectors. Therefore, the model for solving a can be changed to

$$a = \max\left[r_1 \cdot \begin{pmatrix} \sqrt{\varepsilon}/\gamma, 0, \cdots, 0 \\ 0, \sqrt{\varepsilon}/\gamma, \cdots, 0 \\ \vdots \\ 0, \cdots, 0, \sqrt{\varepsilon}/\gamma \end{pmatrix}\right], \tag{19}$$

Where $\sqrt{\varepsilon}/\gamma$ is the energy of every module. Thus, the probability that a is judged correctly is

$$P_a = \int_{-\infty}^{\infty} \frac{1}{\sqrt{\pi N_0}} \left[1 - Q\left(\frac{\gamma n + \sqrt{\varepsilon}}{\gamma\sqrt{N_0/2}}\right)\right]^{M-1} e^{-\frac{n^2}{N_0}} dn, \tag{20}$$

Assuming through the modular bipolar modulation the probability of information bit 0 is equal to that of 1, the decision threshold for solving b can be set to 0. The probability for correct decision is

$$P_b = 1 - Q\left(\sqrt{2\sqrt{\varepsilon}/\gamma N_0}\right), \tag{21}$$

The demodulation of every module in the same received waveform is independent. The probability for correct decision on the bipolar modulation of any module is

$$P_{one} = P_a P_b, \tag{22}$$

For the sending waveform s_1, the order decision result of any module is $a \in (1, 2, \cdots, M)$. For a single module, the probability of correct decision on orders is P_a. The possibility number of error decision is $M - 1$, and thus the probability that the order is misjudged as i can be expressed as $\frac{1-P_a}{M-1}$. The decisions on the CSK order are statistics of the decision on each module order, and the decisions of different modules are independent and have equal probability. When the correct decision probability P_a of a single module order is larger than any error decision probability $\frac{1-P_a}{M-1}$, the decision on CSK order is correct, namely

$$P_{csk} = P\left(P_a > \frac{1 - P_a}{M - 1}\right), \tag{23}$$

In summary, the probability that the sending waveform is received completely correctly is

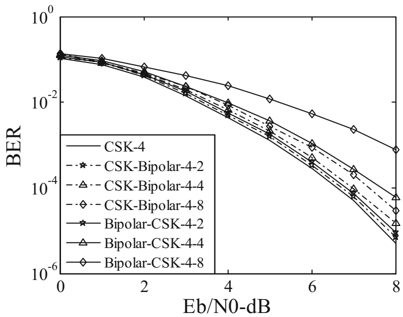
$$P = \frac{k}{k+\gamma} P_{csk} + \frac{\gamma}{k+\gamma} (P_a P_b)^{\gamma}, \tag{24}$$

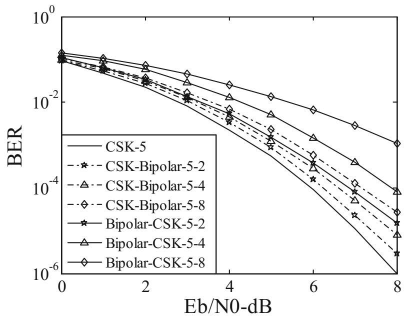
5 Simulations

In simulations, the system bandwidth is 10MHz, the subcarrier number is 512, and the amount of information is 10^8 bits.

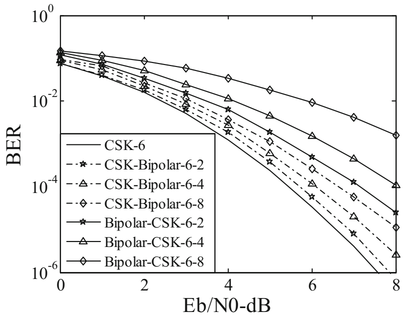
5.1 BER

We denote the CSK with $k = 4$ as CSK-4, where k represents the admissible number of information bits in CSK, and $M = 2^k$. The CSK-bipolar demodulation with $k = 4$ and $\gamma = 2$, and the bipolar-CSK demodulation with $k = 4$ and $\gamma = 2$, are represented by CSK-bipolar-4-2 and bipolar-CSK-4-2, respectively. When k is 4, 5, 6, γ is 2, 4, 8, and





(a) BER performance when $k = 4$ and different values of γ (b) BER performance when $k = 5$ and different values of γ



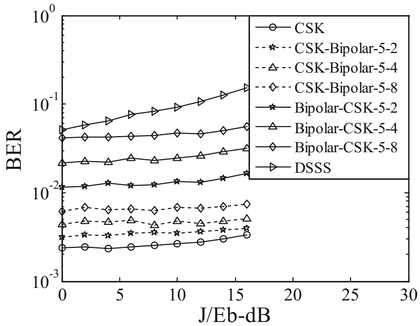
(c) BER performance when $k = 5$ and different values of γ

Fig. 7. BER under different SNR.

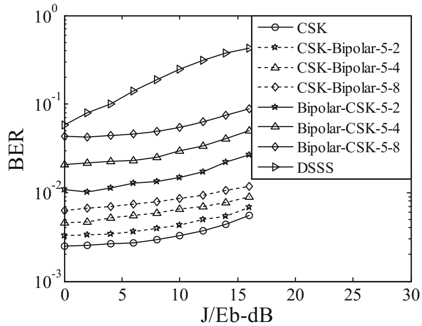
the jamming-to-signal power ratio (JSR) is 5 dB, the BER performance under different SNR is shown in Fig. 7.

From Fig. 7, we can acquire that when the received waveform is CSK-bipolar based demodulated, the BER decreases with the increase of k, and increases with the increase of γ. The reason lies in the error accumulation of different modules in the modular bipolar demodulation. Compared with CSK-bipolar demodulation, the BER in bipolar-CSK demodulation is higher, and its growth rate increases with the increase of γ. Since the demodulation of received waveform order is based on the correct decision on every module order, BER rises with the increase of k. Compared with CSK of the same k, BER performance for both of the two demodulation schemes decrease with the increase of γ.

When $k = 5$, γ is 2, 4, and 8 respectively, and SNR is 5 dB, BER with different JSR is shown in Fig. 8.



(a) Single-tone interference



(b) Single-tone LFM interference

Fig. 8. BER under different JSR

From Fig. 8, it can be observed that with the increase of JSR, BER for direct sequence spread spectrum (DSSS) system decreases sharply. Nevertheless, TDCS eliminates interference spectrum in transform domain, and thus has a good anti-interference ability. Its BER increases slowly with the increase of JSR. Under the same simulation conditions, the ability of rejecting single-tone interference is better than that of rejecting LFM interference.

5.2 Spectrum Efficiency

We estimate the spectrum of single-tone interference by FFT, and its normalized power spectrum density (PSD) is shown in Fig. 9.

When the threshold is set to the peak value of 40%, the number of available subcarrier is 511, and the BER is 10^{-4}, the spectrum efficiency and required SNR is shown in Fig. 10.

From Fig. 10, we can know that compared to CSK, the spectrum efficiency of the double modulation technique is increasing continuously with the increase of γ. Using

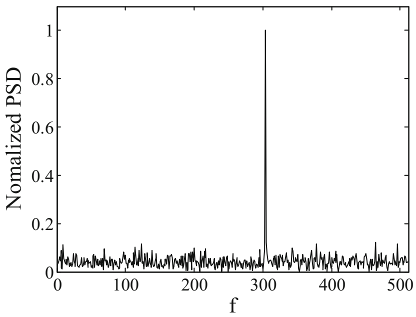


Fig. 9. Normalized PSD of the single-tone interference

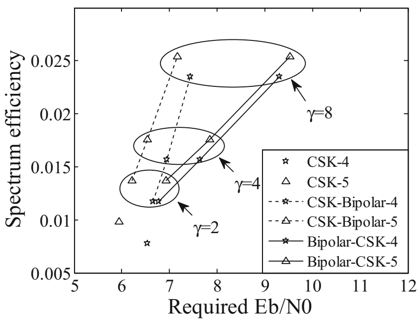


Fig. 10. Distribution of spectrum efficiency

the CSK-bipolar demodulation can bring a great improvement to spectrum efficiency at the cost of a little SNR performance. When adopting the bipolar-CSK demodulation, the improvement of spectrum efficiency costs more SNR.

6 Conclusions

In this paper, we proposed a novel double modulation technique with high spectrum efficiency for TDCS. We firstly analyzed the performance of the modulating waveform, and described the modulation flow in detail. Then we proposed two demodulation techniques for this modulation, and derived its mathematical expressions for its performance. Finally, we simulated the technique and analyzed its BER performance and spectrum efficiency with different SNR and JSR, verifying the reliability of information transmission when the two demodulation techniques cope with noises and interferences. Results show that CSK-bipolar demodulation can improve spectrum efficiency greatly at the cost of only a little SNR, while the same spectrum efficiency can be achieved at the cost of more SNR in bipolar-CSK demodulation.

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