

# DDCSK-Walsh Coding: A Reliable Chaotic Modulation-Based Transmission Technique

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**Abstract**—To overcome the performance loss of noncoherent detectors of differential chaos-shift keying (DCSK), some improved versions of DCSK have been proposed. However, little has been done to improve the multiuser DCSK system based on Walsh codes (WCs), i.e., referred to as DCSK-WC, although it is considered more feasible in practice among the existing multiuser DCSK systems. This brief introduces a novel differentially DCSK (DDCSK) technique into such a multiuser system so as to build the desirable DDCSK-WC, obtaining significant performance gain, as compared with the conventional DCSK-WC, while retaining its hardware complexity unchanged. Moreover, the proposed system can greatly enhance the robustness against intersymbol interference in a wireless multipath fading channel. Therefore, the new system is deemed to provide a good alternative transmission scheme for wireless communication based on chaotic modulation, in such as indoor applications of the transmitted-reference ultrawideband. The theoretical analysis and simulated noise performances of the proposed system demonstrate their high consistence.

**Index Terms**—Bit error rate (BER) performance, differentially differential chaos-shift keying (DDCSK), multi-access, Walsh code (WC).

## I. INTRODUCTION

THE DIFFERENTIAL CHAOS-shift keying (DCSK) technique offers excellent performance for multipath fading or time-varying channels [1]. Its hardware complexity advantage has motivated considerable interest to design better wireless personal area networks (WPANs) [2]–[6]. Some variants of the DCSK are presented in [7] and [8].

A possible and desirable application of DCSK in WPAN is its combination with a multi-access system. Initially in [9], a Walsh function was introduced to ensure the orthogonality of DCSK channels. The resultant system is called DCSK–Walsh code (DCSK-WC) system, which can avoid the interference among different users. Later, a DCSK-WC single-input multiple-output system was presented in [10] with some significant advantages over the Direct Spread-Vertical Bell Lab Space-Time scheme, whereas a more recent study [11] suggests

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that multi-access DCSK cooperation based on WCs can avoid the near–far effect, as compared with the conventional code division multiple access communication systems.

In general, a noncoherent receiver based on generalized maximum likelihood (GML) [12] detection and an autocorrelation is employed for the DCSK demodulation [11]. Nevertheless, the BER performance of DCSK has a lag of about 3 dB, as compared with the coherent modulation schemes because of the unmodulated references [13]. Thus, as basic research on DCSK, some improved versions have been proposed in [14]–[16]. However, all the previous works were based on a one-user system without further discussions about enhancements of the multiuser system and the capacity of anti-inter-symbol-interference (ISI). This brief presents a differentially DCSK-WC (DDCSK-WC) transmitting system. Compared with the conventional DCSK-WC, without increasing hardware complexity, the DDCSK-WC can achieve a performance gain of about 2 dB over a low-delay-spread channel or even more over a high-delay-spread channel. Moreover, it is a general technique that can be easily combined with other wireless communication systems, e.g., with the cooperation technique.

## II. SYSTEM MODEL

To introduce the DDCSK-WC system, the basic DDCSK modulation and the conventional DCSK-WC are first reviewed.

### A. DDCSK Modulation

The basic idea of DCSK is that, through a chaotic mapping method [17], e.g., the simple logistic chaotic map, each bit sequence to be sent consists of two chaotic sample functions: The first sample function serves as a reference, followed by its same or inverted copy, depending on the bit information (1 or 0) [1]. Then, a value is obtained for each bit by correlating the two sample functions at the receiver: The positive value indicates bit 1, and the negative indicates bit 0. Unlike DCSK, in DDCSK, one chaotic sequence represents the current bit information as well as the reference of the next bit in a data frame, which leads to no energy wasted for unmodulated references. Let  $c$  denote a chaotic function of length  $\xi$ . Then, the DDCSK modulation for one data frame is

$$\begin{aligned} s_0 &= c_{1,\dots,\xi} \\ s_l &= (2b_l - 1)s_{l-1} \end{aligned} \quad (1)$$

where  $s_0$  denotes a chaotic reference for the first transmitted bit and  $b_l$  is the  $l$ th bit to be sent. Because one bit is indicated

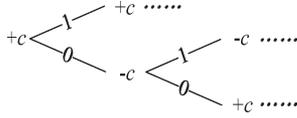


Fig. 1. One data-frame transmission for the DDCSK system.

jointly by the previous and the current chaotic sequences, it follows from (1) that the spread factor of DDCSK is  $2\xi$ . This transmission is further illustrated in Fig. 1.

At the beginning of the transmission,  $+c$  is sent first. Then, if the first bit is 1, sequence  $+c$ , which is the same copy as the previous one, is sent; otherwise, the inverted copy  $-c$  is sent, and the same operation is carried out for the next bit, as shown in Fig. 1. One also observes in Fig. 1 that two forms  $c \times [+1 +1]$  and  $c \times [-1 -1]$  represent bit 1 and two forms  $c \times [+1 -1]$  and  $c \times [-1 +1]$  represent bit 0.

### B. Conventional DCSK-WC System

In the conventional chaotic-based DCSK-WC system [9], the orthogonal WC sequences [18] are adopted to eliminate interference among users. In such multiaccess systems [11], the WCs  $\hat{W}_{2^n}$  ( $n = 0, 1, 2, \dots$ ) of  $2U$ -order is predefined to accommodate  $U$  users, starting from  $\hat{W}_{2^0} = \hat{W}_1 = [+1]$ . The  $2^n$ -order WC sequences are recursively constructed as follows:

$$\hat{W}_{2^n} = \begin{bmatrix} \hat{W}_{2^{n-1}} & \hat{W}_{2^{n-1}} \\ \hat{W}_{2^{n-1}} & -\hat{W}_{2^{n-1}} \end{bmatrix}, \quad n = 1, 2, 3, \dots \quad (2)$$

A chaotic signal is used as the carrier, and one element of the WCs is multiplied with the chaotic carrier segment to indicate one bit of the data frame. However, the conventional WC sequences for the DCSK-WC system are not suitable for the proposed DDCSK-WC. Therefore, a new structure of the WCs needs to be designed.

### C. Proposed DDCSK-WC System

Based on the above discussion, a new DDCSK-WC multi-access system is proposed here. Similar to the construction of the conventional WCs for DCSK-WC, a basic WC to generate the WCs for the DDCSK-WC system is first given by

$$W_2 = \begin{bmatrix} +1 & +1 \\ -1 & -1 \\ +1 & -1 \\ -1 & +1 \end{bmatrix} \begin{cases} b_l = 1 \\ b_l = 0 \end{cases} \quad (3)$$

Recall the DDCSK described in Section II-A. it is observed that  $W_2$  is also the corresponding WC of the DDCSK system, which suggests that the DDCSK system equals to one-user DDCSK-WC system, whose demodulator is depicted in Fig. 2, where the weighted energy received is

$$E_j = \int_{T/2}^T [r(t)w_{k,2} + r(t - T/2)w_{k,1}]^2 dt, \quad j = 0, 1 \quad (4)$$

where  $T$  is the bit duration,  $r(t)$  is the received signal and  $w_{k,i}$  values (i.e.,  $j = 1, k = 1$  or  $2$ ;  $j = 0, k = 3$  or  $4$ ) are the

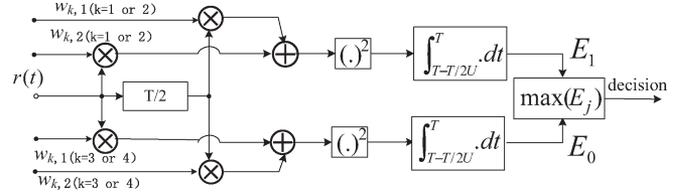


Fig. 2. One-user DDCSK-WC demodulator using GML detection.

corresponding elements in  $W_2$ , to evaluate the energy for bits 1 and 0. The demodulator needs to find index  $j$  that maximizes  $E_j$  and then make a decision on the bit, i.e., either 1 or 0.

Considering a more generalized DDCSK-WC system of  $U$  users ( $U \geq 2$ ), which is derived from the  $W_2$ , the  $2U$ -order WCs are designed as

$$W_{2^n} = \begin{bmatrix} W_{2^{n-1}} & W_{2^{n-1}} \\ W_{2^{n-1}} & -W_{2^{n-1}} \end{bmatrix}, \quad n = 2, 3, \dots \quad (5)$$

Equation (5) means that, for each user, two WC forms, i.e., two row vectors of  $W_{2^n}$ , are used to indicate the transmitted bit with 1 or 0.

By observing (2) and (5), we can see that the main difference between the conventional and the proposed WC structures is that there are two forms to indicate  $b_l^u$  in the latter, where either form of  $b_l^u$  can be chosen to calculate its weighted energy in the receiver because the two forms only differ in their signs, which does not have an impact on the GML decision.

In this proposed system, let  $b_l^u$  ( $u = 1, 2, \dots, U$ ) denote the  $l$ th bit that the  $u$ th user sends in a data frame. Analogous to (1), the  $b_l^u$  can be expressed as follows:

$$\begin{aligned} \left( s_0^{(u)} \right) &= [w_{2u-1,1} \ w_{2u-1,2} \ \dots \ w_{2u-1,U}] \cdot c \\ s_l^{(u)} &= (2b_l^u - 1)s_{l-1}^{(u)} \end{aligned} \quad (6)$$

where  $c$  denotes a chaotic carrier of length  $\xi$  and transmission duration  $T/(2U)$ ;  $w_{2u-1,i}$ ,  $i = 1, 2, \dots, U$  is an element of  $W_{2^{n-1}}$ ,  $s_0^{(u)}$  formed by  $w_{2u-1,i}$  and  $c$  is the reference for the first transmitted bit of the  $u$ th user, and hence, the WC  $W_{2^n}$  for  $U$  users is derived naturally from  $W_{2^{n-1}}$  in the data frame transmission, which will be further examined in Section II-D. The demodulation of this  $U$ -user DDCSK-WC system can be readily extended from DDCSK with GML detection. The weighted energy of the  $u$ th user bit is expressed as

$$E_{u,j} = \int_{T-T/2U}^T \left[ \sum_{i=0}^{2U-1} r\left(t - i \frac{T}{2U}\right) w_{2u-m+(1-j)2U, 2U-i} \right]^2 dt$$

$$j = 0, 1, \quad u = 1, 2, \dots, U, \quad m = 0 \text{ or } 1 \quad (7)$$

where  $j = 0, 1$  denotes the decision of the  $u$ th user and  $w_{2u-m+(1-j)2U, 2U-i}$  is an element of the generated  $W_{2^n}$ . Because either WC form of a bit can be used to demodulate,  $m$  can be chosen to be either 0 or 1. The maximum  $E_{u,j}$  of the index  $j$  for the  $u$ th user can be found to make the bit decision.

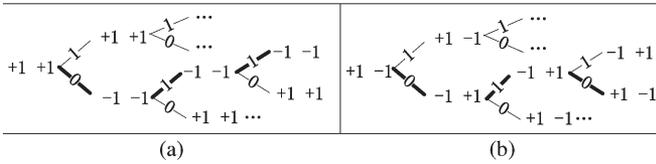


Fig. 3. Transmission of one data frame of the two-user DDCCSK-WC system. (a) First user. (b) Second user.

#### D. DDCCSK-WC Two-User System Model

To explicitly describe and explain the DDCCSK-WC multiuser system, the two-user ( $U = 2$ ) system is used as an example. Let  $b_{u,j}$  ( $u = 1, 2, j = 0, 1$ ) denotes one bit of value  $j$  that user  $u$  sends in a data frame. According to (6), given the WC  $W_2$ , at the start of transmission, for the first user, its transmitter generates a chaotic function  $c^a$  of length  $\xi$  and then sends a chaotic sequence of length  $2\xi$  formed by  $c^a$  multiplied by the first row of  $W_2$ :  $[+1 +1]$ , followed by a copy of the previous chaotic sequence for  $b_{1,1}$  or the inverted copy of the previous sequence for  $b_{1,0}$ . As for the second user, it also generates a chaotic function  $c^b$  of length  $\xi$  and then sends a sequence formed by  $c^b$  multiplied by the third row of  $W_2$ :  $[+1 -1]$ , and some operations similar to that for the first user are carried out for  $b_{2,1}$  and  $b_{2,0}$ . Obviously, the chaotic sequence decided by the current bit and the previous sequence also serves as a reference for the next bit in the frame.

As illustrated in Fig. 3, assuming that the three bits to be sent for the first user are  $\{0 \ 1 \ 1\}$  and for the second user are  $\{0 \ 1 \ 0\}$ , and following the paths marked in bold in the figure, the chaotic signals  $c^a \times \{+1 +1 -1 -1 -1 -1 -1 -1\}$  and  $c^b \times \{+1 -1 -1 +1 -1 +1 +1 -1\}$  are sent for each user, respectively. As shown in Fig. 3, there are two WC forms for  $b_{u,j}$  in the transmission: For  $b_{1,1}$ , there are  $[+1 +1 +1 +1][-1 -1 -1 -1]$ ; for  $b_{1,0}$ , there are  $[+1 +1 -1 -1][-1 -1 +1 +1]$ ; for  $b_{2,1}$ , there are  $[+1 -1 +1 -1][-1 +1 -1 +1]$ ; and for  $b_{2,0}$ , there are  $[+1 -1 -1 +1][-1 +1 +1 -1]$ . These forms are just the row vectors of the  $W_4$ , written as

$$W_4 = \begin{bmatrix} W_2 & W_2 \\ W_2 & -W_2 \end{bmatrix} = \begin{bmatrix} +1 & +1 & +1 & +1 \\ -1 & -1 & -1 & -1 \\ +1 & -1 & +1 & -1 \\ -1 & +1 & -1 & +1 \\ +1 & +1 & -1 & -1 \\ -1 & -1 & +1 & +1 \\ +1 & -1 & -1 & +1 \\ -1 & +1 & +1 & -1 \end{bmatrix} \begin{matrix} \left. \vphantom{\begin{matrix} +1 \\ -1 \\ +1 \\ -1 \end{matrix}} \right\} b_{1,1} \\ \left. \vphantom{\begin{matrix} +1 \\ -1 \\ +1 \\ -1 \end{matrix}} \right\} b_{2,1} \\ \left. \vphantom{\begin{matrix} +1 \\ -1 \\ +1 \\ -1 \end{matrix}} \right\} b_{1,0} \\ \left. \vphantom{\begin{matrix} +1 \\ -1 \\ +1 \\ -1 \end{matrix}} \right\} b_{2,0} \end{matrix} \quad (8)$$

Thus, the WC  $W_4$  for this two-user system is naturally generated from the  $W_2$  in the transmission. Note that either form of  $b_{u,j}$  is orthogonal to other forms of  $b_{u,k}$  ( $k = 0, 1$ ). Thus, the interference between two users is theoretically zero.

In this system model, all channels are independent and subjected to static block frequency-selective fading. Signals at the receiver can be expressed as

$$r(t) = H_1 \otimes X_1(t) + H_2 \otimes X_2(t) + Z(t) \quad (9)$$

where  $\otimes$  is the convolution operator,  $X_u(t)$  is the signal transmitted by the  $u$ th user ( $u = 1, 2$ ), and  $Z(t)$  is a white

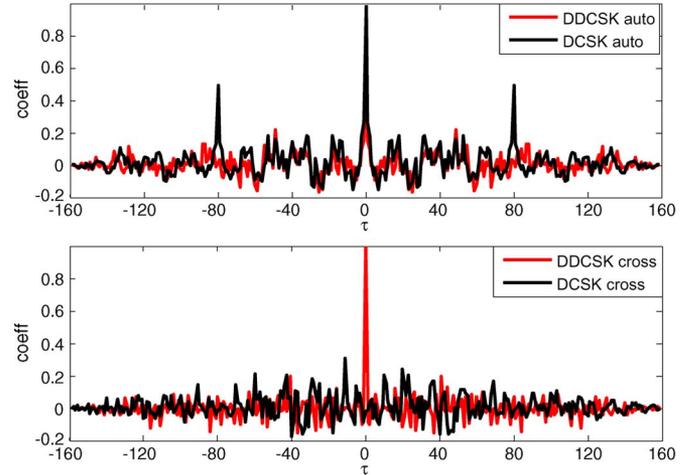


Fig. 4. Auto/cross-correlation comparisons between DDCCSK (red) and DCSK (black) signals.

Gaussian noise random process with zero mean and the two-sided power spectral density  $N_0/2$ . The channel multipath impulse responses  $H_u$  are modeled as the linear time-invariant process  $H_u = \sum_{l=1}^L \alpha_l \delta(t - \tau_l)$ , where  $\alpha_l$  and  $\tau_l$  denote the attenuation and delay spread of the  $l$ th path, and  $L$  is the number of the multipath of the channels. Applying (7) with  $m$  equal to one, the demodulation for two users can be written as

$$E_{u,j} = \int_{T-T/4}^T \left[ \sum_{i=0}^3 r \left( t - i \frac{T}{4} \right) w_{2u-4j+3,4-i} \right]^2 dt \quad j = 0, 1, \quad u = 1, 2 \quad (10)$$

where  $w_{2u-4j+3,4-i}$  is an element of  $W_4$  and  $m$  of value one means that the first form of bit is chosen in the demodulation.

### III. PERFORMANCE ANALYSIS

#### A. Comparison of Auto-/Cross-Correlation Between DCSK and DDCCSK

In this section, auto-/cross-correlation of DCSK (one-user DCSK-WC) and DDCCSK (one-user DDCCSK-WC) are compared. Assuming two chaotic sequences with a length of 160 to indicate two successive bits, the sequences denoted by  $g_1$  and  $g_2$  are generated via DCSK, i.e., both  $g_1$  and  $g_2$  contain two same or inverted chaotic segments with a length of 80, and two sequences  $g_3$  and  $g_4$  are generated via DDCCSK. According to (1),  $g_4$  is either the same or the inverted copy of  $g_3$ . The autocorrelation of  $g_1$  and  $g_3$  are plotted in the upper part of Fig. 4, where the sequence  $g_3$  has lower autocorrelation side lobe than the  $g_1$ , which particularly shows a high histogram when delay spread is 80. It indicates that DCSK scheme performs worse than DDCCSK one over a multipath delay spread channel because high sidelobes may pick up more interfering signals.

The cross-correlation between  $g_1$  and  $g_2$ , and between  $g_3$  and  $g_4$  are given in the lower part of Fig. 4, respectively. It can be seen that the cross-correlation of  $g_3$  and  $g_4$  is as prominent as that of  $g_1$  and  $g_2$ . As reported in [9], the finite lengths of the

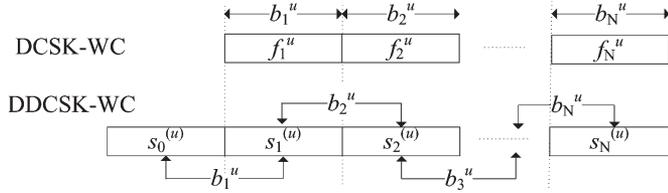


Fig. 5. Frame formats of the  $u$ th user in DCSK-WC and DDCSK-WC.

chaotic signals lead to low-level noise in the correlation, which can be expressed approximately as

$$E \left[ \int_0^T g_3(t)g_4(t+\tau)dt \right] \approx \begin{cases} 1, & \text{if } \tau = 0 \\ 0, & \text{otherwise} \end{cases} \quad (11)$$

where  $E[\cdot]$  denotes the expectation operator. Finally, one can conclude that the ISI caused by the delay spread  $\tau$  can be mitigated more effectively by DDCSK than by DCSK, which holds true for comparison between multiuser DCSK-WC and DDCSK-WC cases.

### B. Data Rate and Energy-Consumption Analysis

In a  $U$ -user WC-based system, the averaged energy and time required to transmit a chaotic sample is 1. Each bit is represented by  $2U$  carrier segments, and one data frame to be sent consists of  $N$  bits. The data frame formats of the  $u$ th user in multiuser DCSK-WC and DDCSK-WC systems are shown in Fig. 5.

In Fig. 5,  $b_l^u$  is the  $l$ th bit sent by the  $u$ th user, i.e.,  $l = 1, 2, \dots, N$ .  $f_l^u$  indicating  $b_l^u$  is the result of the chaotic carrier  $c$  multiplied by its assigned WCs in DCSK-WC [9].  $s_{l-1}^{(u)}$  and  $s_l^{(u)}$  are two successive sequences jointly determining  $b_l^u$ , as defined in (6) for DDCSK-WC. Let  $\beta$  and  $\xi$  denote the lengths of each carrier segment for the conventional and the proposed systems. Assume that the transmit energy per bit for DCSK-WC is

$$E_{b1} = 2U \cdot \beta \cdot E \{ (c)^2 \}. \quad (12)$$

Because one bit determined by DDCSK-WC takes advantage of the previous sequence, the energy and the number of chaotic samples indicating one bit in the DDCSK-WC both double those in the DCSK-WC, i.e., written as

$$E_{b2} = 2U \cdot \xi \cdot E \{ (c)^2 \}, \quad \xi = 2\beta. \quad (13)$$

One can see in Fig. 5 that the conventional and the proposed systems require time of  $2UN$  and  $2U(N+1)$  to transmit one data frame with energy values of  $2UN$  and  $2U(N+1)$ , respectively. Although the DDCSK-WC shows a slight energy consumption and time loss, as compared with the DCSK-WC, the loss is almost negligible for sufficiently large  $N$ .

### C. Performance Evaluation

It is assumed that multipath time delay is much shorter than the bit duration that the ISI could be negligible. Multi-access interference is ignored due to the orthogonality of different WCs assigned to different users. The performance formula for

DCSK-WC and DDCSK-WC multiuser systems is given. For a  $U$ -user ( $U \geq 2$ ) system, the respective signals sent by  $U$  users suffer from the same  $L$ -ray fading channel. The SNR  $\gamma_b$  per bit at the receiver can be written as

$$\gamma_b = \sum_{l=1}^L \gamma_l = \frac{E_b}{N_0} \sum_{l=1}^L \alpha_l^2, \quad \gamma_l = \alpha_l^2 \frac{E_b}{N_0} \quad (14)$$

where  $E_b$  denotes the transmit energy per bit,  $\gamma_l$  is the instantaneous SNR of  $l$ th path. Assuming that  $\alpha_l$  are independent and identically distributed Rayleigh random variables, the power of each path is allocated evenly, denoted by  $E[\alpha_l^2] = 1/L$ . The probability density function of the received SNR  $\gamma_b$  is expressed as

$$f(\gamma_b) = \frac{1}{\bar{\gamma}^L (L-1)!} \gamma_b^{L-1} e^{-\frac{\gamma_b}{\bar{\gamma}}} \quad (15)$$

where  $\bar{\gamma}$  is the average received SNR per path  $\bar{\gamma} = E_b / (N_0 \cdot L \cdot U)$ . With the constant transmit energy assigned to one data frame, as shown by (12) and (13),  $E_b$  of the DDCSK-WC is twice as that of the DCSK-WC, i.e., the values of  $E_b$  are 1 and 2 in  $\bar{\gamma}$  for DCSK-WC and DDCSK-WC, respectively. In addition, the conditional BER as a function of  $\gamma_b$  is given by [19]

$$\text{BER}(\gamma_b) = \frac{1}{2} \text{erfc} \left( \left[ \frac{4}{\gamma_b} + \frac{2M}{\gamma_b^2} \right]^{-\frac{1}{2}} \right) \quad (16)$$

where  $M$  denotes the length of each carrier segment in the multiuser systems. Let  $M$  be  $\beta$  for DCSK-WC and  $\xi$  for DDCSK-WC, and as described in Section III-B, the  $\xi$  is twice the value of  $\beta$ :  $\xi = 2\beta$ . Finally, the averaged unconditional BER of the multiuser systems is

$$\text{BER} = \int_0^\infty \text{BER}(\gamma_b) f(\gamma_b) d\gamma_b. \quad (17)$$

## IV. SIMULATION RESULTS

Using the above-described system model and assuming that each data frame to be sent consists of 1000 bits, both the DCSK-WC and the DDCSK-WC systems have been simulated over two-ray Rayleigh fading channels, which have the same multipath impulse responses. The length  $\beta$  of the carrier of the conventional system is 40; thus, the  $\xi$  of the proposed model is equivalent to 80. For two-user and four-user systems, corresponding fourth-order and eighth-order WCs are chosen. Fig. 6 shows the simulated BER performances of both systems over channels with a low delay spread  $\tau(0, 1T_s/f)$ , where  $T_s$  is the sampling period of the chaotic signals and  $f$  denotes the global spread factor. The theoretical BER estimated by (14)–(17) agree well with the simulated results. As expected, it is clear that both two-user and four-user DDCSK-WC systems show performance gains about 2 dB over its DCSK-WC counterparts. Moreover, as Fig. 7 shows, the gains become more remarkable when the channels are subjected to higher delay spread  $\tau(0, 5T_s/f)$ ; in particular, the gain is much larger when

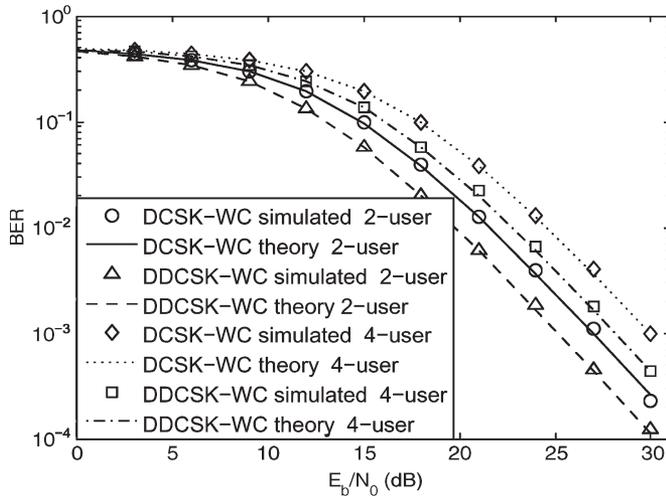


Fig. 6. Performance comparison between DCSK-WC and DDCSK-WC, including two-user and four-user systems, over two-Ray channel with delay spread  $(0, 1T_s/f)$ .

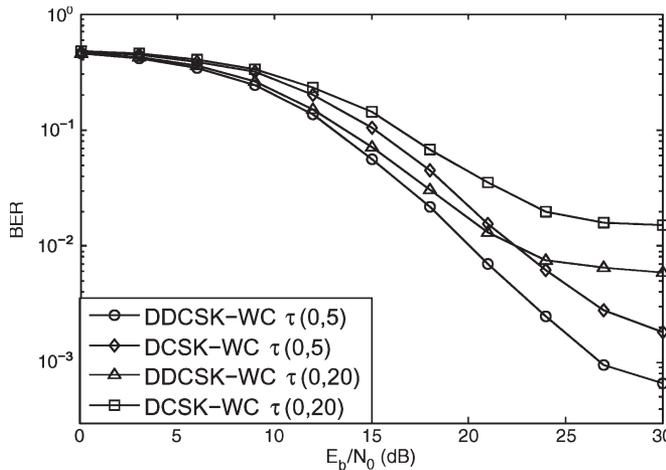


Fig. 7. Performance comparison between DCSK-WC and DDCSK-WC, with two-user systems over two-Ray channel with high delay spread  $(0, 5T_s/f)$ ,  $(0, 20T_s/f)$ .

delay spread is  $\tau(0, 20T_s/f)$ . Thus, as supported by the additional analysis given in Section III-A, it is doubly confirmed that the proposed system outperforms the conventional one even more as  $\tau$  gets higher, which leads to the conclusion that the ability of the proposed system against ISI is also improved.

## V. CONCLUSION

In this brief, a novel DDCSK-WC transmitting system has been proposed. Both theoretical and simulated results are consistent, suggesting that, in comparison with the conventional DCSK-WC system and at the minor cost of a negligible data rate and energy loss, the proposed system not only improves

the noise performance but also has lower sensitivity to ISI. It has been demonstrated that its performance gain over the conventional system is even more remarkable at the presence of larger delay spread. Therefore, the proposed system is fairly suitable for wireless communications based on chaotic modulation, particularly indoor applications based on the transmitted-reference ultrawideband technique and over channels of high delay spread, i.e., in office, residential, and commercial areas.

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