Research Article

Novel Chaos Secure Communication System Based on Walsh Code

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A multiuser communication scheme which is a hybrid of Walsh code with DCSK and CDSK is proposed to improve low data transmission rate of Differential Chaos Shift Keying (DCSK), poor bit error ratio (BER) performance of Correlation Delay Shift Keying (CDSK), and disadvantage of orthogonality in traditional multiuser DCSK. It not only overcomes the disadvantages of DCSK and CDSK, but also has better performance than CDSK and higher transmission data rate than DCSK. It has been proved that the novel multiuser CDSK-DCSK has better properties than traditional Multiple Input Multiple Output-Differential Chaos Shift Keying (MIMO-DCSK) and Modified-Differential Chaos Shift Keying (M-DCSK). Also the multiuser interference is greatly suppressed due to the orthogonality of Walsh code.

1. Introduction

Spread spectrum technology is used in communication system to bear low data rate information by using spread spectrum sequence due to its broad bandwidth characteristics. The technology has advantages such as high security, anti-interference, and antimultipath fading and being easy to be realized in code division multiple access (CDMA) [1]. In recent years, chaotic spread spectrum communication system has been deeply researched in spread spectrum technology [2]. It is different from the traditional spread spectrum technology since the carriers are high speed chaotic signals which are generated by different chaotic maps. Chaotic signal has the advantages of high bandwidth, being nonperiodic, being difficult to predict, and good autocorrelation and cross correlation features [3].

According to the way of demodulation, chaotic communication system is divided into two types: the coherent and the noncoherent demodulation [4]. Coherent demodulation needs the receiver to reconstruct chaotic signal, which means that the security and noise immunity are better than noncoherent demodulation. But it is difficult to realize chaotic synchronization. The security in noncoherent demodulation is worse than in coherent demodulation, but it is easy to

implement and the cost of hardware is much lower. In the existing noncoherent systems, reference signal is used for despreading in most of the receivers [5–10]. Differential Chaos Shift Keying (DCSK) has disadvantages of low data rate [11]. In Correlation Delay Shift Keying (CDSK), the data rate is 2 times that of DCSK [12], but the BER performance is worse than DCSK [13]. Much attention has been attracted since the concept of multiple access DCSK has been proposed [14]. In [15], different interval between transmit signal and carrier is used to distinguish different users. But the orthogonality is poor when using the smaller spread factor.

A combination of multiuser CDSK-DCSK with Walsh coded scheme is proposed in this paper. It can not only overcome the disadvantages of DCSK and CDSK, which means that the BER is better than CDSK and the data rate is higher than DCSK, but also suppress multiuser interference well, due to the orthogonality of Walsh code.

2. Novel Multiuser CDSK-DCSK System

The novel multiuser CDSK-DCSK scheme is shown in Figure 1, where the system has U users totally, and the u th user is discussed for special purpose.

FIGURE 1: U users through Additive White Gaussian Noise (AWGN) channel.

FIGURE 2: Transmitting end of user u .

Chaotic signal is generated by the logistic map firstly. Then, chaotic sequence x_k is generated after the symbolic function mapping as follows:

$$\begin{aligned} y_{k+1} &= 1 - 2y_k^2, \quad y_k \in (-1, 1), \\ x_k^u &= \text{sgn}(y_k), \end{aligned} \quad (1)$$

$$k = 0, 1, 2, \dots,$$

where y_k is chaotic signal, $\text{sgn}()$ is symbolic function, and x_k^u is chaotic sequence of the u th user.

The transmitter is illustrated in Figure 2. A pair of bit (b_l^u, b_{l+1}^u) is modulated and transmitted in a frame, where $b_l^u, b_{l+1}^u \in \{+1, -1\}$. In the l th frame, x_k^u and x_{k-N}^u are transmitted in the first slot, where N is the time delay of x_k^u and $N > M$. In the second and third slots, b_l^u and b_{l+1}^u are multiplied with chaotic sequence and the assigned Walsh code, respectively. Transmitting signal of u th user is shown in

$$s_k^u = \begin{cases} x_k^u + x_{k-N}^u, & 3lM + 1 < k < (3l+1)M, \\ b_l^u x_{k-M}^u w_{1,k}^u, & (3l+1)M + 1 < k < (3l+2)M, \\ b_{l+1}^u x_{k-N-2M}^u w_{2,k}^u, & (3l+2)M + 1 < k < (3l+3)M, \end{cases} \quad (2)$$

where M is the spread factor. $w_{1,k}^u$ and $w_{2,k}^u$ are Walsh code of u th user.

FIGURE 3: Receiving end of user u .

From Figure 1 and (2), the total transmitting signal s_k is easy to be obtained. The received signal after transmission is shown as follows:

$$\begin{aligned} r_k &= s_k + \xi_k = \sum_{u=1}^U s_k^u + \xi_k \\ &= \begin{cases} \sum_{u=1}^U (x_k^u + x_{k-N}^u) + \xi_k, & 3lM + 1 < k < (3l+1)M, \\ \sum_{u=1}^U (b_l^u x_{k-M}^u w_{1,k}^u) + \xi_k, & (3l+1)M + 1 < k < (3l+2)M, \\ \sum_{u=1}^U (b_{l+1}^u x_{k-N-2M}^u w_{2,k}^u) + \xi_k, & (3l+2)M + 1 < k < (3l+3)M, \end{cases} \end{aligned} \quad (3)$$

where ξ_k is assumed as Additive White Gaussian Noise (AWGN) and U is the total number of users.

Figure 3 shows the receiver's structure. Walsh code is multiplied with r_k and r_{k-M} or r_{k-2M} . The Walsh code in the u th receiver must agree with the one of the u th transmitter. After correlation demodulation the original signal is obtained and is shown in

$$\begin{aligned} c_l^u &= \sum_{k=1}^M r_k r_{k-M} w_{1,k}^u \\ &= \sum_{k=1}^M ((s_k + \xi_k)(s_{k-M} + \xi_{k-M}) w_{1,k}^u) \\ &= \sum_{i=1}^U \sum_{j=1}^U \sum_{k=1}^M b_l^j x_{k-M}^j x_{k-M}^i w_{1,k}^j w_{1,k}^i + \sum_{i=1}^U \sum_{k=1}^M x_{k-M}^i \xi_k w_{1,k}^u \\ &\quad + \sum_{i=1}^U \sum_{k=1}^M x_{k-N-2M}^i \xi_k w_{1,k}^u \\ &\quad + \sum_{j=1}^U \sum_{k=1}^M b_l^j x_{k-M}^j w_{1,k}^j w_{1,k}^u \xi_{k-M} \\ &\quad + \sum_{i=1}^U \sum_{j=1}^U \sum_{k=1}^M b_l^j x_{k-M}^j x_{k-N-2M}^i w_{1,k}^j w_{1,k}^u \\ &\quad + \sum_{k=1}^M \xi_k \xi_{k-M} w_{1,k}^u. \end{aligned} \quad (4)$$

In order to simplify the output, c_l^u can be divided into three parts A , B , and C as follows:

$$A = \sum_{i=1}^U \sum_{j=1}^U \sum_{k=1}^M b_l^j x_{k-M}^i x_{k-M}^j w_{1,k}^j w_{1,k}^u$$

$$= \sum_{i=1; i \neq j}^U \sum_{j=1}^U \left(\sum_{k=1}^M b_l^j x_{k-M}^i x_{k-M}^j w_{1,k}^j w_{1,k}^u \right) \quad (5)$$

$$+ \sum_{j=1; j \neq u}^U \left(\sum_{k=1}^M b_l^j x_{k-M}^j x_{k-M}^j w_{1,k}^j w_{1,k}^u \right) + b_l^u M,$$

$$B = \sum_{i=1}^U \sum_{k=1}^M x_{k-M}^i \xi_k w_{1,k}^u + \sum_{i=1}^U \sum_{k=1}^M x_{k-N-M}^i \xi_k w_{1,k}^u$$

$$+ \sum_{j=1}^U \sum_{k=1}^M b_l^j x_{k-M}^j w_{1,k}^j \xi_{k-M} w_{1,k}^u \quad (6)$$

$$+ \sum_{i=1}^U \sum_{j=1}^U \sum_{k=1}^M b_l^j x_{k-M}^j w_{1,k}^j x_{k-N-M}^i w_{1,k}^u,$$

$$C = \sum_{k=1}^M \xi_k \xi_{k-M} w_{1,k}^u. \quad (7)$$

The chaotic sequence has the following properties [16]:

- (1) Chaotic sequence generated by the same map but with different initial value is noncorrelated.
- (2) The chaotic sequence is the same as impulse function after normalized autocorrelation.

Besides, due to the orthogonal property of Walsh code such as $\sum_{k=1}^M w_k^j w_k^u = 0$, $w_k^u w_k^u = 1$, and $x_k^u x_k^u = 1$, $b_l^u M$ in (5) is the only useful signal and the rest of (5), (6), and (7) are interference. The first item is the cross correlation of chaotic sequence and the second item equals 0. b_l^u can be demodulated according to the following rules:

$$b_l^u = f(c_l^u) = \begin{cases} -1, & c_l^u < 0, \\ +1, & c_l^u \geq 0. \end{cases} \quad (8)$$

Similarly, the decision rules for b_{l+1}^u are

$$b_{l+1}^u = f(c_{l+1}^u) = \begin{cases} -1, & c_{l+1}^u < 0, \\ +1, & c_{l+1}^u \geq 0. \end{cases} \quad (9)$$

3. Performance Analysis

By central limit theorem, the correlation output approximately obeys the normal distribution. The mean and variance of c_l^u are required to get the system's BER. Features of chaotic sequence and Walsh code are presented in [17].

- (1) For different chaotic sequences x_i ($i = 0, 1, 2, \dots$) and x_j ($j = 0, 1, 2, \dots$) generated by the same map, $E[x_i x_j] = E[x_i] E[x_j] = 0$ and $\text{var}[x_i x_j] = \text{var}[x_i] \text{var}[x_j] = 1$, when $i \neq j$.

- (2) For different Walsh codes w_k^p and w_k^q , where $p, q \in [1, U]$ and $k = (1, 2, \dots, M)$, when $p \neq q$, $\text{var}[w_k^p w_k^q] = \text{var}[w_k^p] = \text{var}[w_k^q] = 1$.

- (3) Correlation among chaotic sequences, AWGN and Walsh codes, is 0.

- (4) For (4), $\text{cov}[A, B] = \text{cov}[A, C] = \text{cov}[B, C] = 0$.

Suppose the u th user's first bit in l th frame is "+1":

$$E\{c_l^u \mid b_l^u = +1\} = EA + EB + EC = M, \quad (10)$$

where E represents the mean of c_l^u . Consider

$$\text{var}(A) = \text{var}\left(\sum_{i=1; i \neq j}^U \sum_{j=1}^U \sum_{k=1}^M x_{k-M}^i x_{k-M}^j w_{1,k}^j w_{1,k}^u + M\right)$$

$$= \sum_{i=1; i \neq j}^U \sum_{j=1}^U \sum_{k=1}^M \text{var}(x_{k-M}^i x_{k-M}^j) \text{var}(w_{1,k}^j w_{1,k}^u)$$

$$= M(U-1)^2$$

$$\text{var}(B)$$

$$= \sum_{i=1}^U \sum_{k=1}^M \text{var}(x_{k-M}^i \xi_k w_{1,k}^u)$$

$$+ \sum_{i=1}^U \sum_{k=1}^M \text{var}(x_{k-N-M}^i \xi_k w_{1,k}^u)$$

$$+ \sum_{j=1}^U \sum_{k=1}^M \text{var}(x_{k-M}^j w_{1,k}^j \xi_{k-M} w_{1,k}^u)$$

$$+ \sum_{i=1}^U \sum_{j=1}^U \sum_{k=1}^M \text{var}(x_{k-M}^j w_{1,k}^j x_{k-N-M}^i w_{1,k}^u) \quad (11)$$

$$= \sum_{i=1}^U \sum_{k=1}^M \text{var}(x_{k-M}^i) \text{var}(\xi_k) \text{var}(w_{1,k}^u)$$

$$+ \sum_{i=1}^U \sum_{k=1}^M \text{var}(x_{k-N-M}^i) \text{var}(\xi_k) \text{var}(w_{1,k}^u)$$

$$+ \sum_{j=1}^U \sum_{k=1}^M \text{var}(x_{k-M}^j) \text{var}(\xi_{k-M}) \text{var}(w_{1,k}^u)$$

$$+ \sum_{i=1}^U \sum_{j=1}^U \sum_{k=1}^M \text{var}(x_{k-M}^j) \text{var}(x_{k-N-M}^i) \text{var}(w_{1,k}^u)$$

$$= 2MUN_0,$$

$$DC = \sum_{k=1}^M D(\xi_k) D(\xi_{k-M}) D(w_{1,k}^u) = \frac{1}{4} M N_0^2,$$

where D represents variance and $N_0/2$ is noise power density.

So the variance of c_l^u is

$$\begin{aligned} D\{c_l^u | b_l^u = +1\} &= D[A] + D[B] + D[C] \\ &\quad + 2\{\text{cov}[A, B] + \text{cov}[A, C] + \text{cov}[B, C]\} \\ &= M(U^2 - U) + 2MUN_0 + \frac{1}{4}MN_0^2, \end{aligned} \quad (12)$$

where cov represents covariance.

Similarly, when $b_l^u = -1$, the mean and variance of c_l^u are

$$\begin{aligned} E\{c_l^u | b_l^u = -1\} &= -M, \\ D\{c_l^u | b_l^u = -1\} &= M(U^2 - U) + 2MUN_0 + \frac{1}{4}MN_0^2. \end{aligned} \quad (13)$$

The system's bit error ratio (BER) is

$$\begin{aligned} \text{BER} &= \frac{1}{2}P(c_l^u > 0 | b_l^u = -1) + \frac{1}{2}P(c_l^u < 0 | b_l^u = +1) \\ &= \frac{1}{2} \text{erfc}\left(\frac{E(c_l^u | b_l^u = +1)}{\sqrt{2D(c_l^u | b_l^u = +1)}}\right) = \frac{1}{2} \\ &\quad \cdot \text{erfc}\frac{M}{\sqrt{2M(U-1)^2 + 4MUN_0 + (1/2)MN_0^2}} = \frac{1}{2} \quad (14) \\ &\quad \cdot \text{erfc}\left(\frac{2(U-1)^2}{M} + 12U\left(\frac{E_b}{N_0}\right)^{-1}\right. \\ &\quad \left. + \frac{9M}{2}\left(\frac{E_b}{N_0}\right)^{-2}\right)^{-1/2}, \end{aligned}$$

where erfc is the error function, $\text{erfc}(\varphi) = (2/\sqrt{\pi}) \int_{\varphi}^{\infty} \exp(-x^2)dx$, and E_b is bit energy, $E_b = 3M \text{var}[x_i]$.

From (14), with a certain value of U and E_b/N_0 , there exists M_{opt} to realize the best system performance. Suppose $y = 2(U-1)^2/M + 12U(E_b/N_0)^{-1} + (9M/2)(E_b/N_0)^{-2}$. It is easy to obtain M_{opt} after differentiating y :

$$y' = -\frac{2(U-1)^2}{M^2} + \frac{9}{2}\left(\frac{E_b}{N_0}\right)^{-2}. \quad (15)$$

Suppose that $y' = 0$; the equation of M_{opt} is as follows:

$$M_{\text{opt}} = \frac{2(U-1)}{3} \frac{E_b}{N_0}. \quad (16)$$

By (16), for certain E_b/N_0 , under different U , M_{opt} is different. For example, suppose $E_b/N_0 = 10$ dB; when $U = 3$ and $U = 5$, M_{opt} is 13.33 and 26.66, respectively.

FIGURE 4: BER performance versus E_b/N_0 for different spreading factor M .

FIGURE 5: BER performance versus spreading factor M under $E_b/N_0 = 10$ dB.

4. Simulation Comparisons

Figure 4 shows that the smaller the value of M , the stronger the influence on BER by E_b/N_0 . It is obvious that the intervals between different curves under the same E_b/N_0 in $M = 64$ are significantly larger than that of $M = 256$. With M increasing, BER gets smaller and the system's performance gets better.

Figure 5 shows that selecting an appropriate M has great impact on the system's performance. On one hand, there exists an optimum M to achieve the best BER. If M is increased continuously, the system's performance gets worse. On the other hand, the transmission efficiency is too low if M is too large.

FIGURE 6: BER performance versus different total number of users.

FIGURE 7: Simulated BERs versus E_b/N_0 for multiuser CDSK-DCSK, MIMO-DCSK, and M-DCSK with $M = 5$ and $U = 2$.

Figure 6 displays that multiuser interference increases with the users' total number increasing, so the system's performance gets worse. Under different E_b/N_0 , the BER gradually tends to be constant and unrelated with M .

It can be seen from Figure 7 that the performance of multiuser CDSK-DCSK is slightly inferior to MIMO-DCSK [11] when E_b/N_0 is low. But the proposed system's data rate is 2 times that of MIMO-DCSK. When $E_b/N_0 > 16$ dB, the proposed system's performance is much better than that of MIMO-DCSK. Compared with M-DCSK proposed in [9], in low E_b/N_0 , there is not much difference between multiuser CDSK-DCSK and M-DCSK. But when $E_b/N_0 > 10$ dB, the proposed system's BER is improved one-order magnitude.

5. Conclusion

The excellent autocorrelation and cross correlation characteristics of chaotic signal are used in traditional multiuser DCSK system [15] to distinguish different users. When the spread factor is small, the orthogonality between different chaotic signals is poor. A hybrid CDSK-DCSK combined with Walsh code system is proposed in this paper to realize the multiuser transmission. The signal is transmitted in pairs, so transmitting rate is 2 times the traditional ones. Interference between different users can be reduced due to the application of Walsh code. Also, the simulation results show that, under the same circumstances, the performance of multiuser CDSK-DCSK system is much better than that of M-DCSK and MIMO-DCSK, especially when E_b/N_0 is larger than 16 dB and 10 dB, respectively.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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