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Research Article

Multigroup Synchronization in 1D-Bernoulli Chaotic Collaborative CDMA

Sumith Babu Suresh Babu and R. Kumar

Department of Electronics and Communication Engineering, SRM University, Chennai, India

Correspondence should be addressed to Sumith Babu Suresh Babu; sumithbabusb@yahoo.co.in

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Code-division multiple access (CDMA) has played a remarkable role in the field of wireless communication systems, and its capacity and security requirements are still being addressed. Collaborative multiuser transmission and detection are a contemporary technique used in CDMA systems. The performance of these systems is governed by the proper accommodation of the users and by proper synchronization schemes. The major research concerns in the existing multiuser overloaded CDMA schemes are (i) statistically uncorrelated PN sequences that cause multiple-access interference (MAI) and (ii) the security of the user's data. In this paper, a novel grouped CDMA scheme, the 1D-Bernoulli chaotic collaborative CDMA (BCC-CDMA), is introduced, in which mutually orthogonal chaotic sequences spread the users' data within a group. The synchronization of multiple groups in this scheme has been analyzed under MAI limited environments and the results are presented. This increases the user capacity and also provides sufficient security as a result of the correlation properties possessed by the chaotic codes. Multigroup synchronization is achieved using a 1D chaotic pilot sequence generated by the Bernoulli Map. The mathematical model of the proposed system is described and compared with the theoretical model of the synchronization in CDMA, the simulation results of which are presented.

1. Introduction

The demand for high capacity wireless systems is increasing day by day. Wireless communication system generations including the 3rd generation (3G), the 4th generation (4G), and the upcoming 5th generation (5G) strive to achieve the ever increasing needs for faster data transfer and higher security. Code-division multiple access (CDMA) has always been fulfilling these requirements and is expected to be an effective solution for future systems too. An important aspect of CDMA is to increase the capacity or the number of users, with acceptable error performance. Several grouped CDMA schemes are being studied intensively and are widely used to meet the capacity needs of several modern communication systems. The collaborative CDMA scheme increases the capacity by grouping a small number of users that share the same pseudorandom (PN) spreading sequence and enables group spreading and despreading operations [1]. It also outperforms the CDMA multiuser detection (MUD) schemes using group pseudo decorrelating detector (GPD) and layered space time (LAST) MUD [2]. Advanced MUD techniques incorporate more users than the number of the spreading sequences but at the expense of considerable performance degradation [3, 4]. Also, orthogonal spreading sequences are shared by more than one user in a group-based collaborative spreading process [5]. Various schemes with reusability of the spreading sequences have been tested under different channel scenarios [3, 6]. Hence, such schemes provide a brief research outlook, to multiuser scenarios, in order to accommodate the ever increasing number of users.

The proposed system inherits capabilities like interference rejection, antijamming, fading reduction, and low probability of interception from the conventional direct sequence spread spectrum (DSSS) systems [7]. In conventional DSSS systems, the users transmit their information using Walsh functions or wavelets [8]. Chaotic sequences can also be used as spreading codes instead of PN sequences. They can be generated by simple or complex differential equations and are dependent on the initial conditions. A very small change in the differential equation's initial conditions can cause a large deviation in the system states over time, which makes these systems difficult to intercept. Sequences, with good cross-correlation properties, generated using chaotic maps can be used in CDMA systems [9]. Systems using chaotic sequences both as carrier of users' data and as pilot are analyzed [10]. Various methods have been proposed to obtain binary sequences from chaotic trajectories generated by nonlinear ergodic maps [11]. Synchronization within such chaos based DS-CDMA systems is an active area of research due to the lack of robust synchronization techniques [12, 13]. A theoretical analysis of synchronization in DSSS using chaotic sequences has also been analyzed [14]. Nonlinear dynamic chaotic sequences provide message concealment using chaotic phase shift keying techniques [6, 15].

After analyzing several such techniques, the proposed scheme addresses the synchronization of multiple groups in a highly secure and high capacity chaotic grouped CDMA system using chaotic sequences which are used as the carrier and the pilot. The proposed scheme provides better synchronization and can be integrated into less complex wireless systems.

Section 2 describes the defects in classical multiuser schemes. Section 3 explains the proposed system model and presents its principle and mathematical realization. Section 4 discusses the simulation results. Finally, the conclusion and future work are given in Section 5.

2. The Defects in Classical Multiuser Scheme

Overloading of users is a major problem as far as future communication systems are concerned. Taking into account the CDMA systems, an increase in the number of the users increases the MAI. But the number of PN sequences cannot be increased in accordance with the growing number of simultaneous users. Hence, the number of users per group is restricted in the grouped CDMA case. The collaborative CDMA scheme is an example which achieves a maximum of 90 users only per cell sector, with three users sharing a PN sequence, in an additive white Gaussian noise (AWGN) channel. Also, it is possible for an opponent to imitate the transmission by decoding the PN sequences by their bit timings. Synchronizing the systems under such conditions is impractical. The proposed system addresses this issue by using chaotic sequences, generated by 1D map, both as carrier and as synchronization pilot.

3. The Proposed System Model

3.1. BCC-CDMA Multiuser Transmitter Design. The baseband model for the proposed multigroup synchronization in the BCC-CDMA system is shown in Figure 1.

The transmitter signal $s_t(t)$ is

$$s_t(t) = \sum_{k=1}^{G}\sum_{l=1}^{T} s_{kl}(t) = \sum_{k}\sum_{l} V_{kl}(t) B_{Ck}(t). \quad (1)$$

At the transmitter side, the total number of users (**K**) is divided into **G** groups, each consisting of **T** users. Users, with encoded message V_{1T} within a group, will use the same chaotic-spreading sequence B_{CG}. Users within a group use the same chaotic sequence generated by the 1D map. Sequences of length $1\times N$ are generated (where N is the order of the spread code matrix) using the 1D-Bernoulli transformation given by

$$f(x) = \begin{Bmatrix} 2x; & 0 \le x < 0.5 \\ 2x-1; & 0.5 \le x < 1 \end{Bmatrix}. \quad (2)$$

The piecewise linear function (2) generates the iterated function map. A unique initial condition generates the chaotic sequence and is mapped onto the ijth element of the $N\times N$ matrix. The ith row constitutes the spreading sequences for the ith group in the BCC-CDMA scheme.

The klth user sequence is

$$\begin{aligned} s_{kl}(t) &= V_{kl}(t)\cdot B_{Ck}(t) \\ &= \begin{Bmatrix} -1\cdot B_{Ck}(t), & V_{kl}(t) = -1, & \text{for } t \in [(i-1)T_c, iT_c] \\ +1\cdot B_{Ck}(t), & V_{kl}(t) = +1, & \text{for } t \in [(i-1)T_c, iT_c] \end{Bmatrix}, \end{aligned} \quad (3)$$

where "i" denotes the ith transmitted bit. Now, for the synchronization block, a chaotic pilot sequence modulated by "ones" is considered (generated from the same chaotic map with a special initial condition):

$$S_{00}(t) = V_{00}(t) B_{C0}(t) = +1\cdot B_{C0}(t), \quad \text{for } t \in [(i-1)T_c, iT_c]. \quad (4)$$

The pilot sequence is a periodic sequence with finite duration and determines the starting point of the spreading of the individual user groups. Hence, when the received pilot is synchronized with its stored reference, it can determine the beginning of the individual user groups.

3.2. Multigroup Synchronization in BCC-CDMA. The data is spread and transmitted at the beginning of the pilot sequence. In order to achieve this, the received pilot has to be synchronized with its locally generated replica. The received pilot is a time shifted replica of the transmitted chaotic pilot and is given by $B_{C0}(t-\tau)$. As the pilot is synchronized, the control variable B_{Csync} is generated by the synchronization block. The control variable reduces the time delay using the feedback loop. This control signal will align the Gth user group at the instant of the Gth group of the transmitted sequence.

The received signal is

$$\begin{aligned} r(t) &= \left(\sum_{k=0}^{G}\sum_{l=0}^{T} h_{kl}V_{kl}\cdot B_{Ck}\right)\sqrt{2}A\cos(\omega_c t+\phi) + \xi_t(t) \\ &= \left(\sum_{k=0}^{G}\sum_{l=0}^{T} V_{kl}\cdot B_{Ck}\right) \\ &\quad\cdot \sqrt{2}A\left[\cos\omega_c t\cos\phi + \sin\omega_c t\sin\phi\right] + \sqrt{2}\xi_t^I(t) \\ &\quad\cdot \cos\omega_c t - \sqrt{2}\xi_t^Q(t)\sin\omega_c t, \end{aligned} \quad (5)$$

where ϕ is a phase difference assumed between the carriers at transmitter and receiver, $I = \sqrt{2}\cos\omega_c t$, $Q = \sqrt{2}\sin\omega_c t$,

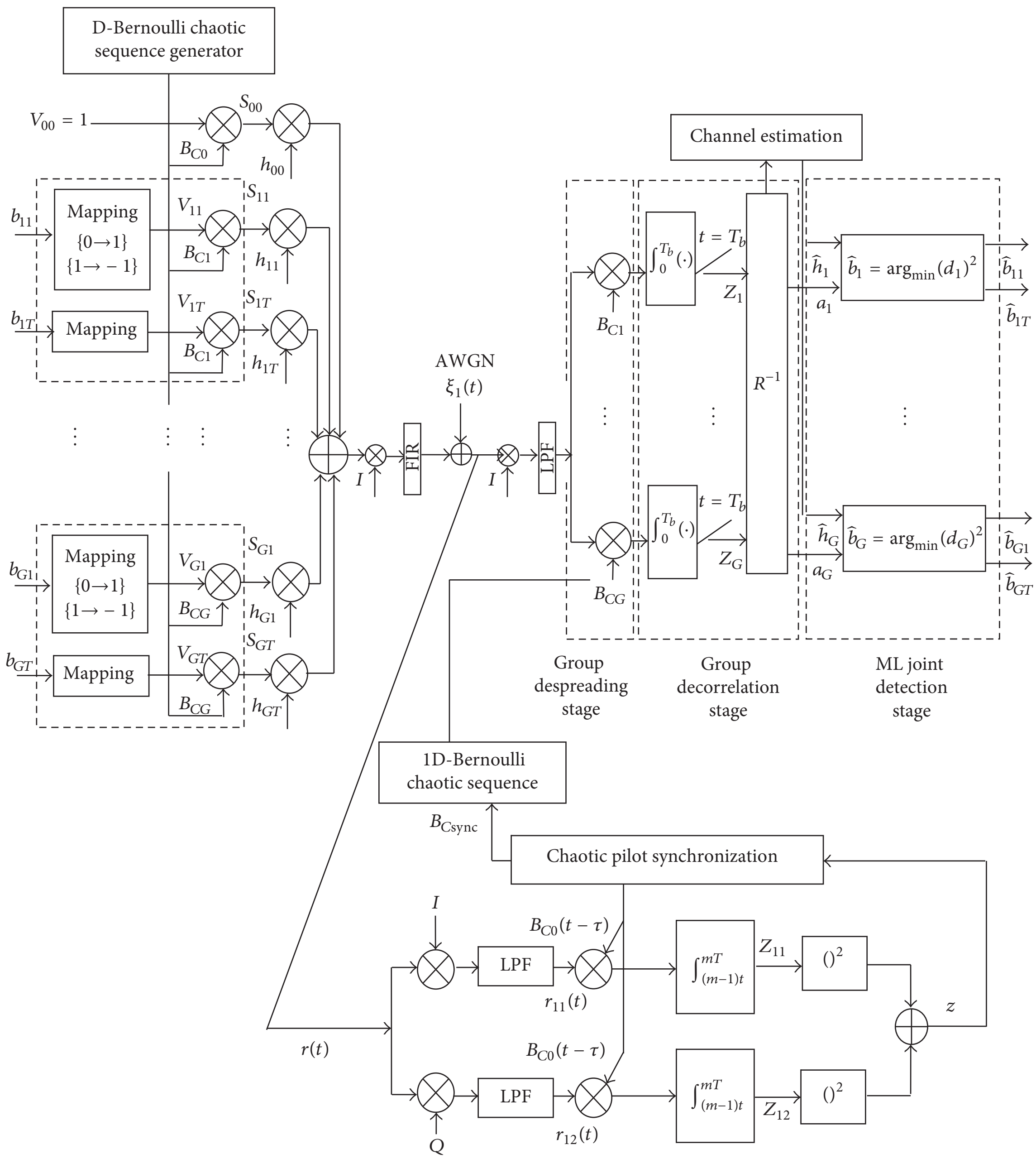

Figure 1: Baseband model for the proposed multigroup synchronization in BCC-CDMA.

the amplitude of the pilot is $A = \sqrt{2E_c/T_c}$, and $h_{kl} = 1$ is the channel gain coefficient of the klth user.

Now, the received signal is multiplied by the in-phase component to get

$$\begin{aligned} r_{11}(t) &= r(t)\sqrt{2}A\cos(\omega_c t) = \left\{\left(\sum_{k=0}^{G}\sum_{l=0}^{T} V_{kl}\cdot B_{Ck}\right)\right. \\ &\cdot \sqrt{2}A\left[\cos\omega_c t\cos\phi + \sin\omega_c t\sin\phi\right] + \sqrt{2}\xi_t^I(t) \\ &\left.\cdot \cos\omega_c t - \sqrt{2}\xi_t^Q(t)\sin\omega_c t\right\}\sqrt{2}A\cos(\omega_c t) \\ &= \left(\sum_{k=0}^{G}\sum_{l=0}^{T} V_{kl}\cdot B_{Ck}\right)A\left[1+\cos 2\omega_c t\right]\cos\phi \\ &+ \left(\sum_{k=0}^{G}\sum_{l=0}^{T} V_{kl}\cdot B_{Ck}\right)A\sin 2\omega_c t\sin\phi + \xi_t^I(t)\left[1\right. \\ &\left.+\cos 2\omega_c t\right] - \xi_t^Q(t)\sin 2\omega_c t. \end{aligned} \tag{6}$$

The signal in (6) is now low pass filtered to get

$$r_{11}(t) = \left(\sum_{k=0}^{G}\sum_{l=0}^{T} V_{kl}\cdot B_{Ck}\right)A\cos\phi + \xi_t^I(t)$$

$$= V_{00} \cdot B_{C0} A \cos\phi + \left(\sum_{k=1}^{G} \sum_{l=1}^{T} V_{kl} \cdot B_{Ck} \right) A \cos\phi + \xi_t^I(t) = B_{C0} A \cos\phi + \xi_a(t) \quad (\text{Since, pilot } V_{00} = +1), \tag{7}$$

where $\xi_a(t)$ contains the interuser interference and AWGN.

Analogously, we get

$$r_{12}(t) = B_{C0} A \sin\phi + \xi_b(t). \tag{8}$$

Now, r_{11} and r_{12} are multiplied by a reference sequence (m-bit time shifted version of the received pilot) with M chips ($M = T/T_c$) and then integrated to get z_{11} and z_{12} as follows:

$$\begin{aligned} z_{11} &= \int_{t=(m-1)T_c}^{t=mT} r_{11}(t) B_{C0}(t-\tau)\, dt \\ &= \int_{t=(m-1)T_c}^{t=mT} \left[B_{C0} A \cos\phi + \xi_a(t) \right] B_{C0}(t-\tau)\, dt \\ &= A\cos\phi \int_{t=(m-1)T_c}^{t=mT} B_{C0} B_{C0}(t-\tau)\, dt + \int_{t=(m-1)T_c}^{t=mT} \xi_a(t) B_{C0}(t-\tau)\, dt \\ &= A\cos\phi TR(\tau) + N_1 = \sqrt{\frac{2E_c}{T_c}} \cos\phi TR(\tau) + N_1. \end{aligned} \tag{9}$$

The first correlation value is obtained by aligning the M chips of the pilot and multiplying and summing them with the reference sequence. If the correlation value is greater than the threshold value, the process is stopped; else, the step is repeated for next chip intervals until synchronization is achieved.

Similarly, we get

$$\begin{aligned} z_{12} &= A\sin\phi \int_{t=(m-1)T_c}^{t=mT} B_{C0} B_{C0}(t-\tau)\, dt + \int_{t=(m-1)T_c}^{t=mT} \xi_b(t) B_{C0}(t-\tau)\, dt \\ &= A\sin\phi TR(\tau) + N_2 = \sqrt{\frac{2E_c}{T_c}} \sin\phi TR(\tau) + N_2, \end{aligned} \tag{10}$$

where N_1 and N_2 are Gaussian random variables with zero mean and variance $N_0T/2$ and can be expressed as $N_1, N_2 \Rightarrow G(0, N_0T/2)$. Therefore, z_{11} and z_{12} are also Gaussian and can be expressed as

$$\begin{aligned} z_{11} &\Longrightarrow G\left(\sqrt{\frac{2E_c}{T_c}} \cos\phi TR(\tau), \frac{N_0T}{2} \right), \\ z_{12} &\Longrightarrow G\left(\sqrt{\frac{2E_c}{T_c}} \cos\phi TR(\tau), \frac{N_0T}{2} \right). \end{aligned} \tag{11}$$

The correlation and synchronization are controlled by the decision variable "z" and are given by (substituting the values of "A" and "M")

$$\begin{aligned} z &= z_{11}^2 + z_{12}^2 = \frac{N_0T}{2} \left[\left(2\sqrt{\frac{ME_c}{N_0}} \cos\phi R(\tau) \right)^2 + \left(2\sqrt{\frac{ME_c}{N_0}} \sin\phi R(\tau) \right)^2 \right] \\ &= \frac{N_0T}{2} \left[4\frac{ME_c}{N_0} \cos^2\phi R^2(\tau) + 4\frac{ME_c}{N_0} \sin^2\phi R^2(\tau) \right] \\ &= \frac{N_0T}{2} \cdot 4\frac{ME_c}{N_0} R^2(\tau) \left[\cos^2\phi + \sin^2\phi \right] = \frac{N_0T}{2} \cdot \lambda, \end{aligned} \tag{12}$$

where $\lambda = 4(ME_c/N_0)R^2(\tau)$ is a noncentral chi-squared random variable with two degrees of freedom.

Thus, the probability density function (PDF) of the control variable "z" is

$$P_z(\psi) = \left\{ \begin{array}{ll} \dfrac{1}{2\sigma^2} e^{-(1/2)(\lambda+\psi/\sigma^2)} I_0\left(\sqrt{\dfrac{\lambda\psi}{\sigma^2}} \right), & \psi > 0 \\ 0, & \text{otherwise} \end{array} \right\}. \tag{13}$$

Now, the decision is made with respect to the following hypotheses.

Null Hypothesis

H_0: locally generated sequence is not aligned with the received sequence:

$$\begin{aligned} H_0&: |\tau| > T_c \Longrightarrow \\ R(\tau) &\cong 0. \end{aligned} \tag{14}$$

Actual Hypothesis

H_1: locally generated sequence is aligned with the received sequence within one chip duration:

$$\begin{aligned} H_1&: |\tau| \le T_c \Longrightarrow \\ R(\tau) &> 0. \end{aligned} \tag{15}$$

Based on the above hypotheses, the conditioned probability density functions are

$$\begin{aligned} P_z(\psi \mid H_0) &= \frac{1}{2\sigma^2} e^{-(1/2)(\psi/\sigma^2)} \\ P_z(\psi \mid H_1) &= \frac{1}{2\sigma^2} e^{-(1/2)(\lambda+\psi/\sigma^2)} I_0\left(\sqrt{\frac{\lambda\psi}{\sigma^2}} \right). \end{aligned} \tag{16}$$

Therefore, the probability of false alarm for the first case (i.e., $m = 1$) is

$$\begin{aligned} P_F(m=1) &= P_z(\psi > T_H \mid H_0) \\ &= \int_{T_H}^{\infty} \frac{1}{2\sigma^2} e^{-(1/2)(\psi/\sigma^2)} d\psi = e^{-(1/2)(\psi/\sigma^2)}, \end{aligned} \tag{17}$$

where the threshold is set at

$$T_H = -N_0 T \ln p_F (m = 1). \quad (18)$$

Similarly, the detection probability is

$$\begin{aligned} P_D (m = 1) &= P_z (\psi > T_H \mid H_1) \\ &= \int_{T_H}^{\infty} \frac{1}{2\sigma^2} e^{-(1/2)(\lambda + \psi/\sigma^2)} I_0 \left(\sqrt{\frac{\lambda\psi}{\sigma^2}} \right) d\psi \\ &= e^{-(1/2)(\psi/\sigma^2)}. \end{aligned} \quad (19)$$

Now, considering the transformation $\psi = (x\sigma)^2$, (19) can be expressed as

$$P_D (m = 1) = \int_{\sqrt{T_H/\sigma^2}}^{\infty} x e^{-(1/2)(\lambda + x)} I_0 \left(\sqrt{\lambda x} \right) dx. \quad (20)$$

Equation (20) resembles Marcum's Q-Function and therefore P_D can be expressed as

$$P_D (m = 1) = Q_M \left(\sqrt{\lambda}, \sqrt{\frac{T_H}{\sigma^2}} \right). \quad (21)$$

When the condition $R(\tau) \cong R(0) = 1$ is fulfilled, the system achieves synchronization and the upper bound is obtained as (substituting values of λ and T_H)

$$P_D (m = 1) \le Q_M \left(2\sqrt{M \frac{E_c}{N_0}}, \sqrt{-2 \ln p_F (m = 1)} \right). \quad (22)$$

Thus, for a particular value of E_c/N_0, Q_M varies with respect to the value of M enabling it to synchronize the receiver.

4. Performance Analysis and Numerical Results

The BER performance is investigated and compared with that of conventional collaborative CDMA scheme. In Figure 2, the performance of BCC-CDMA system, with synchronization, is analyzed with a spreading length of 31 choosing $\mathbf{G} = 30$ and $\mathbf{T} = [2, 4]$ such that it accommodates groups of 30×2 and 30×4 users, giving a total number of $\mathbf{K} = 60$ and 120 users, respectively. The performance is compared with that of conventional CDMA, with 30×1 users, and collaborative CDMA with 60 and 90 users ($\mathbf{G} = 30$ and $\mathbf{T} = [2, 3]$).

The BCC-CDMA and collaborative CDMA give a BER of 1.44×10^{-3} and 2.16×10^{-2}, respectively, accommodating 60 users, at SNR 15 dB. It is clearly shown that the BCC-CDMA scheme achieves a BER improvement of 2.01×10^{-2} at 15 dB with equal number of users. As $\mathbf{K}$ is increased, BCC-CDMA achieves a BER improvement of 38% accommodating 120 users (additional number of 30 users).

The synchronization of the system is better understood by considering the detection and false alarm probabilities.

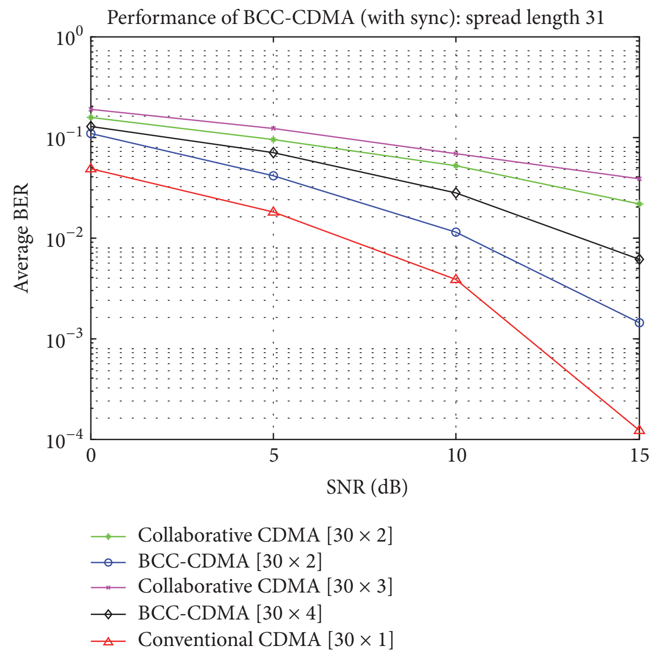

Figure 2: BER performance of the proposed BCC-CDMA (with sync): spread length 31.

The performance criteria are (i) probability of detection P_D and (ii) probability of false alarm P_F. The expressions for P_D and P_F are obtained by taking into account the output of the acquisition part. The synchronization is achieved when the decision variable "z" exceeds the threshold "T_H." Though "z" exceeds "T_H" several times, it is only once that the received signal $r(t)$ is in synchronism with $B_{C0}(t - \tau)$.

To understand this better, the probability of false alarm is expressed by comparing it with Baye's rule as follows:

$$\begin{aligned} P_F (m = 1) &= P_r (\psi_m > T_H \cap H_0) \\ &= \frac{P_r (\psi_m > T_H \cap H_0)}{P_r (H_0)}. \end{aligned} \quad (23)$$

The numerator and denominator terms of (23) can be expressed as

$$\begin{aligned} P_r (\psi_m > T_H \cap H_0) &= \lim_{D \to \infty} \left(\frac{c}{D} \right) \\ P_r (H_0) &= \lim_{D \to \infty} \left(\frac{D - 1}{D} \right), \end{aligned} \quad (24)$$

where "c" is the number of times the decision variable ψ_m overcomes the threshold T_H and "D" is the total number of discrete values of ψ_m.

Substituting (22) and (23) into (21),

$$\begin{aligned} P_F (m = 1) &= \frac{\lim_{D \to \infty} (c/D)}{\lim_{D \to \infty} ((D - 1)/D)} \\ &= \lim_{D \to \infty} \left(\frac{c}{D - 1} \right). \end{aligned} \quad (25)$$

To obtain an accurate result, the experiment has to be run a large number (j) of times, keeping S limited. Thus, the probability of false alarm is

$$P_F(m=1) = \lim_{j\to\infty} \sum_{n=1}^{j} \left(\frac{c_n}{j(D_n - 1)} \right). \quad (26)$$

Now, the probability of detection is

$$P_D(m=1) = \frac{P_r(\psi_m > T_H \cap H_1)}{P_r(H_1)}. \quad (27)$$

There are only two possible outcomes, that is, whether the decision variable ψ_m has exceeded the threshold T_H or not. Therefore, the numerator in (27) can be expressed as

$$P_r(\psi_m > T_H \cap H_1) = \left\{ \begin{matrix} \lim_{D\to\infty} \left(\frac{1}{D}\right) = \frac{1}{D}, & \psi_m > T_H \\ \lim_{D\to\infty} \left(\frac{0}{D}\right) = 0, & \text{Otherwise} \end{matrix} \right\}. \quad (28)$$

The denominator term in (27) can be expressed as

$$P_r(H_1) = \lim_{D\to\infty} \left(\frac{1}{D}\right). \quad (29)$$

Substituting (26) and (27) into (25),

$$P_D(m=1) = \frac{P_r(\psi_m > T_H \cap H_1)}{P_r(H_1)} = \left\{ \begin{matrix} 1, & \psi_m > T_H \\ 0, & \text{otherwise} \end{matrix} \right\}. \quad (30)$$

Running the experiment "j" number of times,

$$P_D(m=1) = \lim_{j\to\infty} \sum_{n=1}^{j} \left(\frac{\left\{ \begin{matrix} 1, & \psi_m > T_H \\ 0, & \text{otherwise} \end{matrix} \right\}_n}{j} \right). \quad (31)$$

The results of simulation (theoretical and empirical operating curves) for the proposed system have been plotted (in Figure 3) at $E_c/N_0 = -15$ dB.

The red dashed line is the theoretical simulation obtained by evaluating (22). The detection and false alarm probabilities (P_D and P_F) are not independent; that is, a lower threshold increases P_D but also increases P_F. The value of −15 dB is chosen to represent worse E_c/N_0 due to high traffic. The synchronization of the proposed scheme is analyzed with four different groups of users. The operating curves for $T = [2, 3, 4]$ cases are obtained taking into account the terms $(\sum_{k=1}^{G} \sum_{l=1}^{T} V_{kl} \cdot B_{Ck}) A \cos\phi$ and $(\sum_{k=1}^{G} \sum_{l=1}^{T} V_{kl} \cdot B_{Ck}) A \sin\phi$ in r_{11} and r_{12}, respectively.

The simulation parameters are shown in Table 1.

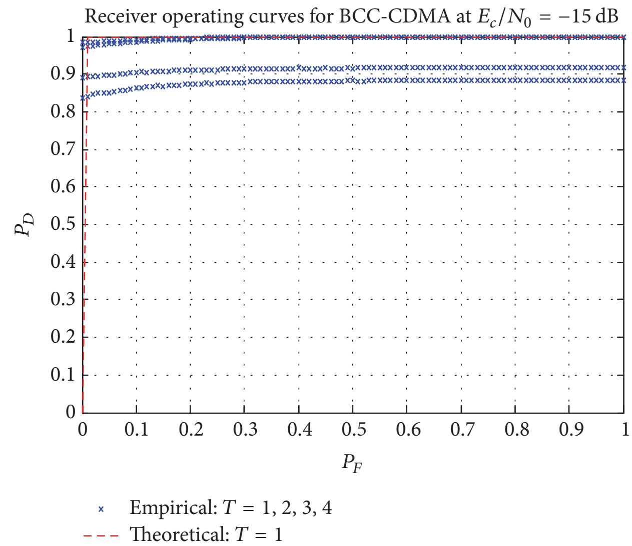

Figure 3: Receiver operating curves for multigroup synchronization in BCC-CDMA.

Table 1: Simulation parameters for the proposed multigroup synchronization scheme.

System parameters	Values
Message length	10000 bits
Spreading length	31 bits
Groups, **G**	30
E_c/N_0	−15 dB
Collaborating users, **T**	[1, 2, 3, 4]
Total number of users, **K**	[30, 60, 90, 120]

5. Conclusions and Future Scope

A highly secure and high capacity grouped scheme is proposed for the CDMA system that accommodates a higher number of full-rate users than the conventional multiuser CDMA schemes. In the proposed scheme, a certain number of users are grouped together that collaborate by sharing orthogonal chaotic-spreading sequences generated by 1D chaotic map. For example, using chaotic sequences of length 31, the proposed scheme supports 120 full-rate users compared to 90 and 30 users supported by collaborative CDMA and the conventional CDMA, respectively. Multigroup synchronization is then achieved using a chaotic pilot sequence, which is modulated by all ones, generated from the same chaotic map. The simulations show that the multiple groups can be synchronized with a probability of detection of more than 85%. Investigations on channel estimation in the proposed scheme are of practical importance. Also, the attractive properties of chaotic sequences may lead to the implementation of three-dimensional (3D) chaotic maps and can be considered for future research.

Competing Interests

The authors declare that they have no competing interests.

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