www.ietdl.org

Published in IET Communications
Received on 16th June 2012
Revised on 13th March 2013
Accepted on 24th March 2013
doi: 10.1049/iet-com.2012.0763

ISSN 1751-8628

Performance comparison of chaotic spreading sequences generated by two different classes of chaotic systems in a chaos-based direct sequence-code division multiple access system

Nazila Rahnama, Siamak Talebi

Department of Electrical Engineering, Shahid Bahonar University of Kerman, Kerman, Iran
E-mail: nzl_1986@yahoo.com

Abstract: In the world of wireless communications, achieving a highly secure transmission at the lowest possible performance degradation has presented a major challenge and a number of conventional direct-sequence-code division multiple access (DS-CDMA)-based solutions have been put forward that deals with the issue. This study aims to overcome the challenge by introducing a new approach that employs a chaotic sequence in DS-CDMA system over fading channels. The proposed algorithm, which assumes a perfect sync between the transmitter and the receiver, generates a binary code by using a three-dimensional (3D) chaotic system. Simulations based on a flat-fading channel with additive white Gaussian noise and inter-user interference reveal that the new approach outperforms codes generated by other classes of chaotic systems, that is, the 1D chaotic system. The results also proved the proposition's performance is comparable to conventional pseudo-noise spreading codes, the Gold code, in several key aspects including security of transmission, bit-error rate, code generation speed and the number of possible code sequences.

1 Introduction

In recent years, using chaotic signals to address the challenges posed by secure communication has received a lot of attention. Chaotic systems are totally dependent on the initial conditions and parameters of the system. A very small change in these two factors can lead to vastly different system states, which makes these systems difficult to intercept and signal predictions becomes very hard, that is, the very issues of interest in cryptography. Chaotic signals are also aperiodic, therefore chaotic output streams are completely uncorrelated. These systems are specified by a set of differential equations [1–3]. Since their noise-like and broadband power spectra they are a good candidate to fight narrow-band effects such as frequency-selective fading or narrow-band disturbances in communication systems. Thus a chaotic system exhibits many properties of a stochastic process that could meet the basic requirements of the spread spectrum communications.

In conventional spread-spectrum communications, pseudo-random codes such as the Gold code are generated by using linear shift-register generators [4]. The pseudo-random sequences combined with the information signal then generate a spread signal which is then sent to the receiver through the unsecure communication channel. At the side receiver, the original information is recovered by correlating the received spread signal with a synchronised replica of the code signal in the dispreading process. Spreading the bandwidth by the pseudo-randomness code has two benefits: it results in a secure transmission, and also makes the signal resistant to noise. The transmitted signal usually has a bandwidth that is much greater than the minimum bandwidth necessary to send the information [5, 6].

However, in spread spectrum communications, because of some desirable properties of the chaotic codes etc., a chaotic system deserves a lot more attention. Thus in this paper, we propose a scheme based on a certain class of chaotic dynamical system, that is, a three-dimensional (3D) chaotic system to generate pseudo-random codes for encryption of information in direct sequence-code division multiple access (DS-CDMA) systems. In this model, a perfect synchronisation between the receiver and the transmitter is assumed (synchronisation could be obtained by schemes in [7–9]). Among the advantages of employing a 3D chaotic system rather than a 1D chaotic system is their higher consternation and highly dimensional behaviour. Thus, in this case security is better which makes prediction of the code very hard. As will be seen later, the analysis and numerical evaluations confirm that the proposed chaotic code is superior to typical 1D-chaotic-based codes or is (in some cases) even comparable with conventional pseudo-random codes in several key aspects such as security, bit-error rate (BER), code generation speed and the number of possible code sequences.

The rest of the paper is organised as follows: a summary of some related approaches is explained in the next section and then in Section 3 chaos-based DS-CDMA system is covered followed by an overview of the design and analysis of the transmitter, a communication channel and the receiver. In Section 4, probability of error of chaos-based DS-CDMA system is fully explored. The next section presents the simulations results and makes performance comparisons against other coding algorithms. The concluding section, Section 6, ends the paper by summarising the paper's objective and what it contributes towards secure transmission in a wireless communication system.

2 Related work

Section 1 argued thatthe necessary requirement to spreading the spectrum of the signal for a secure transmission is proper pseudo-random codes. These codes are being invariably used in many of today's advanced communication systems such as code division multiple access (CDMA), spread spectrum communication.

After the seminal works of Pecora and Caroll [10], a great number of Secure Communication Systems based on chaos have been proposed [11–15] and at the same time the application of chaotic sequences in spread spectrum communication systems has also seen a growing interest.

A survey of published literature on this subject reveals what advances have been made to date, among them:

In 2005, Wang *et al.* [16] proposed a scheme to generate binary code for baseband spread-spectrum communication by using a chain of coupled chaotic maps. They demonstrated that in a spread-spectrum communication environment their code is superior to the Gold code. In 2001, Chen *et al*. [17] reported a study that focused on the design of chaotic sequences. Rovatti *et al.* [18] presented a chaos-based system by introducing a system performance evaluation methodology. By merging theories of communication and non-linear dynamical systems, they used some analytical tools for the performance investigation. Setti *et al.* [19] considered and analysed an acquisition mechanism to identify analytical expressions of suitable system performance parameters such as outage probability, link startup delay and expected time to service. In 2002, Pursley [20] employed direct-sequence spread spectrum to resolve multipath signals and also described the role of a rake receiver and examined tradeoffs in the selection of the chip rate for the spread-spectrum system.

Jovic and Unsworth [21] in 2007 devoted their investigation to the performance of chaos-based DS-CDMA system over a Rayleigh channel, and computed BER values by performing numerical simulations using A Gaussian approximation.

Coulon and Roviras [22] in 2009 addressed the challenge posed by multi-user detection for a multiple-access system based on chaotic communications. Two kinds of transmissions were considered: synchronous transmissions, and asynchronous transmissions. Different detectors were studied for both kinds of transmissions, including an optimal receiver, an adaptive least-mean-square (LMS) detector and detectors that were based on the estimation of the chaotic sequences. The reported simulation results on all these detectors confirmed that the chaotic-sequence estimation-based detectors were only suitable for synchronous transmissions, but not for asynchronous transmissions because of poor performance. In contrast, LMS-based receivers were found to achieve superior practical performance. In particular, the performances obtained for asynchronous transmissions approach those of synchronous transmissions.

In 2010, Kaddoum *et al*. [23] presented a study of the BER performance of a chaos-based DS-CDMA system over an *m*-distributed fading channel. Here, the transmitted bit energy after spreading the chaotic signal was not considered to be constant so as to make a precise evaluation of the BER for such system. By deploying the Gold sequence, the DS-CDMA's performance was compared against that of the chaos-based DS-CDMA. Their work showed a perfect match between simulations and analytical results on BER behaviour and hence proved the exactitude of the approach.

3 Chaos-based DS-CDMA modelling

In this investigation, a chaos-based DS-CDMA system involving U number of synchronous users is considered (a similar arrangement can also be made to study asynchronous users). The discrete-time baseband equivalent

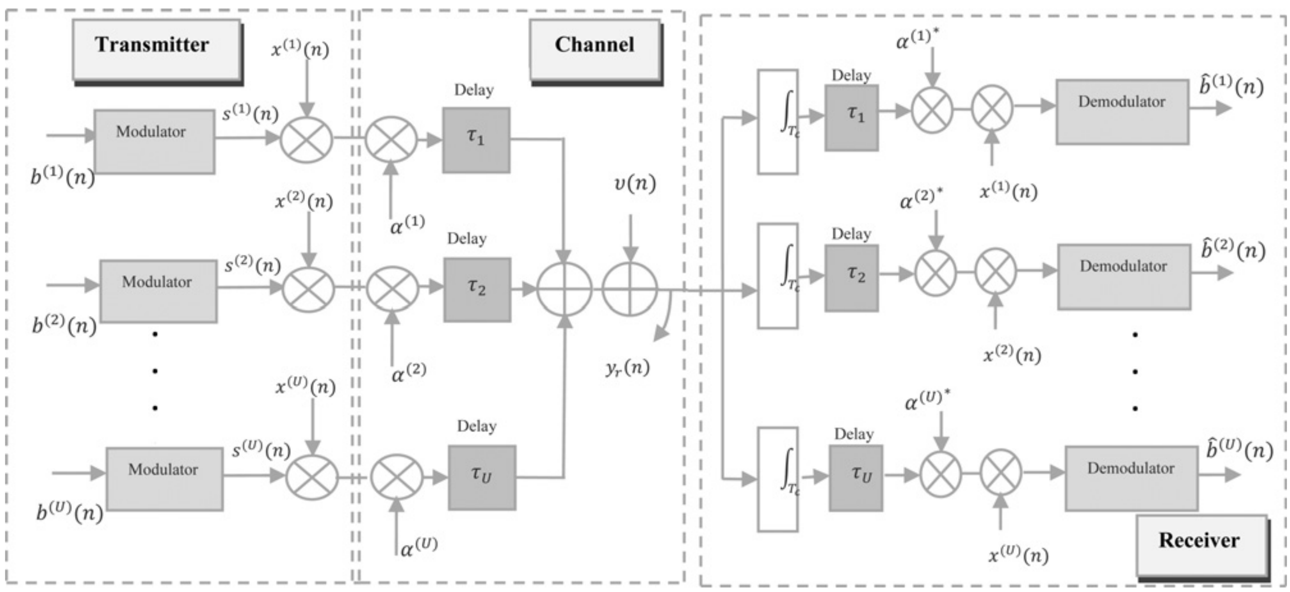

Fig. 1 *Chaos-based DS-CDMA transmission system over a fading channel*

block diagram of the system is shown in Fig. 1. The system consists of a transmitter module, a communication channel and a receiver module as described below.

3.1 Transmitter

The transmitter module consists of a chaotic system, a modulator and a multiplier. In this scheme (see Fig. 1), the data information bits $b^{(u)}(n)$ generated by independent sources are passed through the modulator and at the output of the modulators (one for each user) symbols $s^{(u)}(n)$ are obtained. Having generated the symbols sequence which is of period N_s it is then fed to the multiplier where it is spread by a chaotic sequence $x^{(u)}(n)$. For all users the same chaotic generator with different initial conditions and parameters of the system is used to generate chaotic sequences. The chaotic samples can be expressed by the differential equation as follows

$$x^{(u)}(n) = f\left(x^{(u)}(n-1)\right) \quad (1)$$

where $f(.)$ is called a smooth function.

Hence, the signal transmitted by user u can be defined as

$$y_t^{(u)}(n) = \sum_n \sum_{i=0}^{\beta-1} s^{(u)}(n)\; x^{(u)}(n\beta + i) g\big(n - (n\beta + i)N_c\big) \quad (2)$$

where $g(n)$ is the rectangular pulse of $1/N_c$amplitude on [0, N_c], that is

$$g(n) = \begin{cases} 1/N_c & 0 \le n < N_c \\ 0 & \text{elsewhere} \end{cases}$$

The ratio of the transmitted signal bandwidth w_{yt} to the original signal bandwidth w_s is called the spreading factor β. It should be noted that integer β can also be defined by $\beta = N_s/N_c$where N_c denotes the chip duration of $x^{(u)}(n)$.

3.1.1 Chaotic generator:

Here, authors opted for the 3D chaotic systems to generate the spreading code rather than the more typically utilised 1D chaos-based DS-CDMA system. Owing to commonly binary codes are require in spread spectrum communication, we obtains binary chaotic sequence as follows

$$m_k = \text{round}\left(x_k^{(u)}(n) \times 10^{\gamma}\right) \mod 2 \quad (3)$$

where γ is an integer selected such that 10^{γ} is of the order of the inverse of the computer precision and $x_k^{(u)}(n)$ is the kth state of $f(.)$, [in Fig. 1, $x^{(u)}(n) \equiv x_k^{(u)}(n)$]. In general, each of the three states of 3D chaotic systems can be used to generate the spreading code and in this paper, we have considered only the third state of 3D chaotic systems to obtain spreading code in our simulations.

Binary sequence m_k is generated as a sequence of 0 and 1 s then converted according to $0 \to -1$ and $1 \to 1$ through (4)

$$m'_k = 2m_k - 1 \quad (4)$$

and the upshot of each element of the sequence m'_k is either 1 or -1.

In the proposed scheme, chaotic signal spreading is a periodic sequence of period β which can be obtained from $B_k = A_{k \bmod \beta}$ where A is a chaotic sequence.

Let us now consider the differential equations (maps) of the two different chaotic classes which are widely utilised in the design of chaos-based communication systems, see [3, 11, 12, 21, 24, 25]:

First class: 3D chaotic systems

1. *Rössler map:*

$$\begin{aligned} x_1(n+1) &= -x_2(n) - x_3(n) \\ x_2(n+1) &= x_1(n) + 0.2\, x_2(n) \\ x_3(n+1) &= 0.2 + x_3(n)\big(x_1(n) - 5.7\big) \end{aligned}$$

2. *Chua map:*

$$f(x) = \frac{2}{7}\, x_1(n) - \frac{3}{14}\big(\left| x_1(n) + 1 \right| - \left| x_1(n) - 1 \right|$$

$$\begin{aligned} x_1(n+1) &= 9x_2(n) - f(x) \\ x_2(n+1) &= x_1(n) - x_2(n) + x_3(n) \\ x_3(n+1) &= -14.286\, x_2(n) \end{aligned}$$

3. *Lorenz map:*

$$\begin{aligned} x_1(n+1) &= 10\;\big(x_2(n) - x_1(n)\big) \\ x_2(n+1) &= 28\, x_1(n) - x_2(n) - x_1(n)\, x_3(n) \\ x_3(n+1) &= x_1(n)x_2(n) - \frac{8}{3}\, x_3(n) \end{aligned}$$

4. *Genesio-Tesi map:*

$$\begin{aligned} x_1(n+1) &= x_2(n) \\ x_2(n+1) &= x_3(n) \\ x_3(n) &= -6\, x_1(n) - 2.92\, x_2(n) - 1.2\, x_3(n) + x_1(n)^2 \end{aligned}$$

Second Class: 1D chaotic systems

1. *Chebyshev polynomial function (CPF) map:*

$$x(n+1) = 1 - 2x^2(n)$$

2. *Cubic map:*

$$x(n+1) = 4x^3(n) - 3x(n)$$

3.2 Channel model

The discrete-time channel of the uth user is represented by discrete impulse response (see Fig. 1).

Base-band impulse response can be expressed as

$$C^{(u)}(n) = \alpha^{(u)}\delta\big(n - \tau_u\big) \quad (5)$$

here τ_u is the time delay of user u and since these delays are the same for all users, this means they are in synchronous and δ is Dirac delta function. (Note that this paper can easily be generalised to include an asynchronous transmission).

IET Commun., 2013, Vol. 7, Iss. 10, pp. 1024–1031
doi: 10.1049/iet-com.2012.0763

Moreover, the propagation channel is assumed frequency-flat and the gains $\alpha^{(1)}$, $\alpha^{(2)}$, …, $\alpha^{(u)}$ are independent random variables of the form

$$\alpha^{(u)} = \sqrt{2\,K^{(u)}} + a^{(u)} + jb^{(u)} \tag{6}$$

where $K^{(u)}$ is the channel gain of user u and $a^{(u)}$, $b^{(u)}$ are the two independent Gaussian random variables with zero mean and variances equal to 1. The channel distribution depends on the value of $K^{(u)}$. For $K^{(u)} = 0$, the channel can be seen as a Rayleigh channel, but when $K^{(u)} \gg 1$, it is a Gaussian channel. For intermediate values of $K^{(u)}$, the channel follows the Rice distribution. The channels of all users are independent.

At this stage, an additive complex white Gaussian noise $\upsilon(n)$ is added to the output of the channels, with a two-side power spectral density equal to $2N_0$. The multi-user received signal at the side receiver is finally given by

$$\begin{aligned} y_r(n) = \sum_{u=1}^{U} \sum_{n} \sum_{i=0}^{\beta-1} \alpha^{(u)}\, s^{(u)}(n)\ x^{(u)}(n\beta + i) \\ \times g\big(n - (n\beta + i)N_c - \tau_u\big) + \upsilon(n) \end{aligned} \tag{7}$$

so that $x^{(u)}(n + \beta) = x^{(u)}(n)$ since $x^{(u)}(n)$ is a periodic sequence of period β.

3.3 Receiver

As shown in Fig. 1, in order to detect the bit n of user v, the received signal $y_r(n)$ is passed through the $g(n)$ matched filter in the interval $[(n\beta + i)N_c + \tau_u;\ (n\beta + i + 1)N_c + \tau_u]$, $\forall i$ where $0 < i < \beta - 1$.

Note that the synchronous transmission is a special case of (5) where all delays are identical. Without loss of generality, this common value τ_u can be set to zero. Hence, for all $i =$ 0, …, $\beta - 1$, we can define the following expression:

$$\varphi_{n,\,i}^{(v)} \triangleq \sum_{n=(n\beta+i)N_c}^{(n\beta+i+1)N_c} y_r(n)\, g\big(n - (n\beta + i)N_c\big) \tag{8}$$

This expression is illustrated by the integral boxes in Fig. 1.

After channel compensation (which assumes that the channel gain for user v is known), the input of demodulator is

$$r(n)^{(v)} = \big(\alpha^{(v)}\big)^{*} \sum_{i=0}^{\beta-1} \varphi_{n,\,i}^{(v)}\, x^{(v)}(n\beta + i) \tag{9}$$

Next, by simplifying $r(n)^{(v)}$ we obtain

$$r(n)^{(v)} = \big|\alpha^{(v)}\big|^2 s^{(v)}(n) \sum_{i=0}^{\beta-1} \big(x^{(v)}(n\beta + i)\big)^2 + \sum_{u\neq v} \psi^{uv} + \upsilon^{(v)}(n) \tag{10}$$

Thus, $(x^{(v)}(n\beta + i))^2 = 1$, where ψ^{uv} denotes the interference from user u on user v and $\upsilon^{(v)}(n)$ is a zero-mean Gaussian variable representing the noise term.

The bit estimation $\hat{b}^{(v)}(n)$ value is calculated from the output of the demodulator.

4 Probability of error expression of chaos-based DS-CDMA system

The interference term on the vth user can be regarded as a sum of zero mean, independent random variables [19].

Hence

$$\big(\sigma^v\big)^2 = E\left[\left(\sum_{u\neq v,\, u=1}^{U} \psi^{uv}\right)^2\right] \tag{11}$$

where $E[.]$ is the mean value of all symbols transmitted. Equation (11) states that the variance of multi-user interference rises as the number of users is increased.

Note that in the mono-user case ($U = 1$) and noiseless case we have

$$r(n) = |\alpha|^2 s(n) \sum_{i=0}^{\beta-1} \big(x^{(v)}(n\beta + i)\big)^2 \tag{12}$$

If $E_s \triangleq \sum_{i=0}^{\beta-1} \big(x^{(v)}(n\beta + i)\big)^2$ and the symbols are equally distributed on the set $\{-1,\ 1\}$, we can, in the presence of other users and interference term, define the BER as

$$P_{\text{err}} = Q\left(\sqrt{|\alpha|^2 E_s/\sigma^v}\right) \tag{13}$$

where $Q(x) = 1/\sqrt{2\pi}\int_x^{\infty} \mathrm{e}^{-(y^2/2)}\,\mathrm{d}y$ represents the error function. In the presence of noise, the BER becomes

$$P_{\text{err}} = Q\left(\sqrt{|\alpha|^2 E_s/(\sigma^v + \sigma)}\right) \tag{14}$$

where σ is the variance of the additive Gaussian white noise. The mean BER of the system is obtained by integrating (14) over the channel gain value.

The proposed chaotic code sequences can perform almost as well as the Gold sequence in terms of the BER in a DS-CDMA system. As described in the following section, this conclusion is further validated through simulations and comparison of the BER against the signal-to-noise ratio.

5 Simulation results and discussions

In this section, the BER performance of the proposed scheme is evaluated against other techniques by running different simulations and comparing the results. In particular, the different chaotic maps presented in Section 3.1.1 are investigated.

Figs. 2*a* and *b* displays the BER results for a chaos-based CDMA system involving three users, that is ($U = 3$), in which a binary phase shift keying (BPSK) modulator is employed for generating symbols. Moreover, this figure displays the simulated BER curve which was obtained from a conventional DS-CDMA system using the Gold codes. In this case, both systems have identical spreading factors (in Fig. 2*a*, $\beta = 15$, and in Fig. 2*b*, $\beta = 127$), which allows one to compare performances. Since, the multi-user interference is dependent on variation of the spreading factor, the proposed system is simulated for a fixed channel gain, $K = 2$, and different values of the spreading factors. It is quite easy to see that our solution offers improved performance when the spreading factor is low. This is due to the fact that in this case the cross-correlations of the Gold codes are

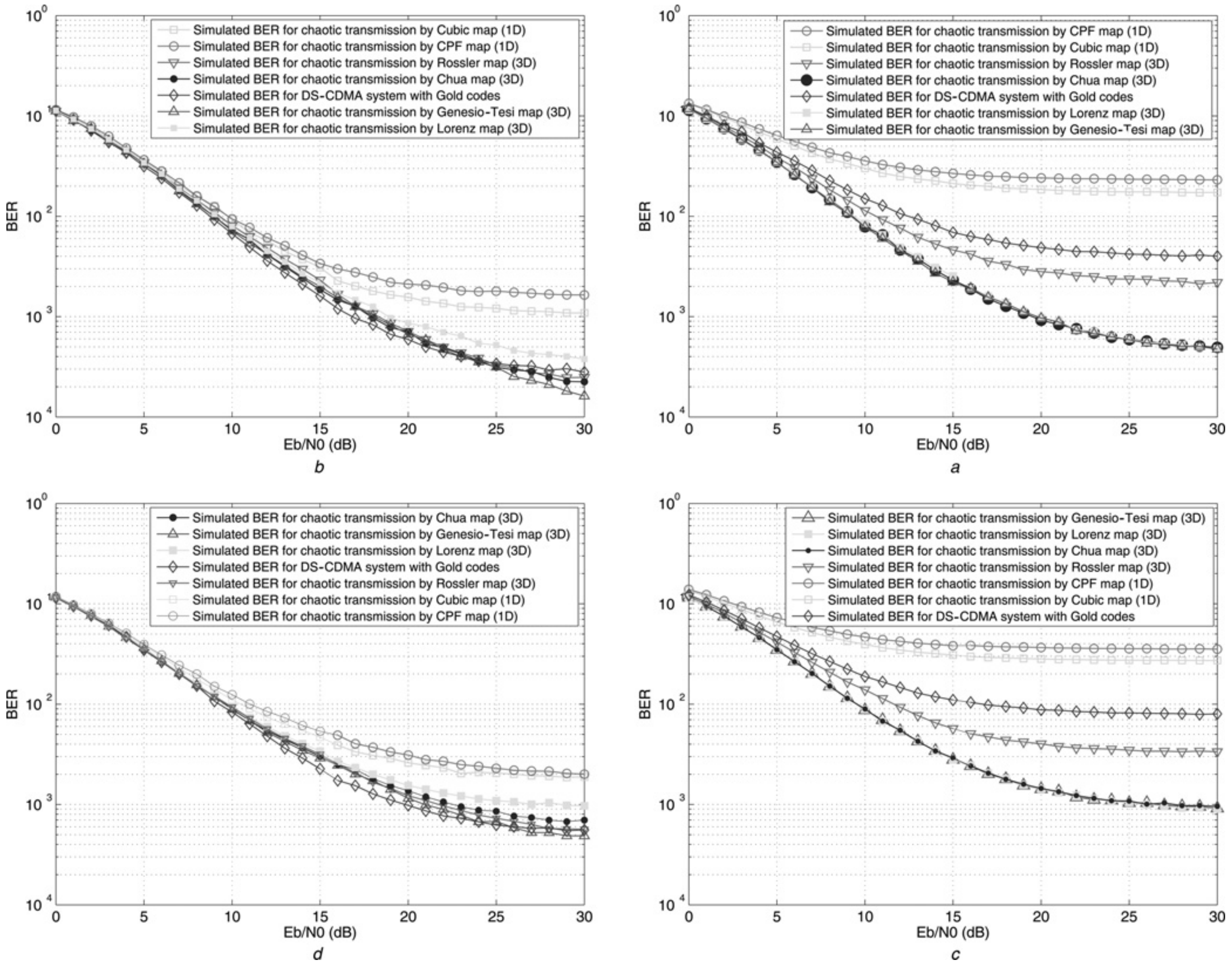

Fig. 2 *BERs in DS-CDMA applications: for 1D and 3D chaotic systems and the Gold codes*

a,b $U = 3$, $K = 2$ dB, BPSK constellation
c,d 4-QAM constellation
$\beta = 15$ (in *a*, *c*) and $\beta = 127$ (in *b*, *d*)

higher than the chaotic sequences [26]. When the spreading factor is high, $\beta = 127$, the correlations are similar, consequently, the performances of both systems become very close. Hence, to obtain low BERs, higher spreading factors must be considered for any system (chaotic or non-chaotic). Meanwhile, 3D chaotic systems outperform 1D chaotic systems for both of the above spreading factors. Figs. 2*c* and 2*d* also show the simulation results under the same condition over a flat-fading channel but for 4-quadrature amplitude modulation (QAM) constellation. We can see that the results are similar to the previous case (i.e. Figs. 2*a* and *b*).

The use of 3D chaotic systems for generating spreading code instead of the Gold codes relies on an improved security of the transmission at the cost of a very small degradation (in performance), especially when the spreading factor is high.

The BER response of the system in Fig. 1 that employs a BPSK modulator, over a flat-fading channel, ($K = 0$ dB) with additive white Gaussian noise, are shown in Figs. 3*a*–*c* for 5, 10 and 15 users, respectively. Spreading factor of 127 chips is generated using the Rössler, Chua, Lorenz and Genesio-Tesi systems of first class, and the chaotic Cubic map of the second class. Moreover, Fig. 3 sketches the BER performance curves for the specified range of the bit energy to noise power spectral density ratio in a DS-CDMA system using the Gold codes. As can be seen from Fig. 3, with respect to the BER values, our solution, that is, the utilisation of 3D chaotic systems for generating spreading code, in all cases ($U = 5$, 10 and 15) outperforms both the cubic code and the Gold code.

Fig. 4 shows the theoretical and simulated BER against E_b/N_0 using the same parameters including chaotic maps, spreading factors, channel gain and number of users in conjunction with BPSK constellation in all cases. One can see that by employing any one of the 3D chaotic systems such as the Rössler, Chua, Lorenz and Genesio-Tesi, and also by changing parameters β and K, arbitrary and/or desirable performances can be attained. Moreover, it can be observed from Fig. 4 that simulation results of the chaos-based DS-CDMA system completely coincide with the analytical ones.

Finally, in order to demonstrate the advantage of our scheme compared with other proposed models we investigated the DS-CDMA system described in Fig. 1, over a frequency selective channel and assumed there were three independent delay paths. Actually, a channel model with delay profile {0, 5 and 10} µs and power profile {5, 1

IET Commun., 2013, Vol. 7, Iss. 10, pp. 1024–1031
doi: 10.1049/iet-com.2012.0763

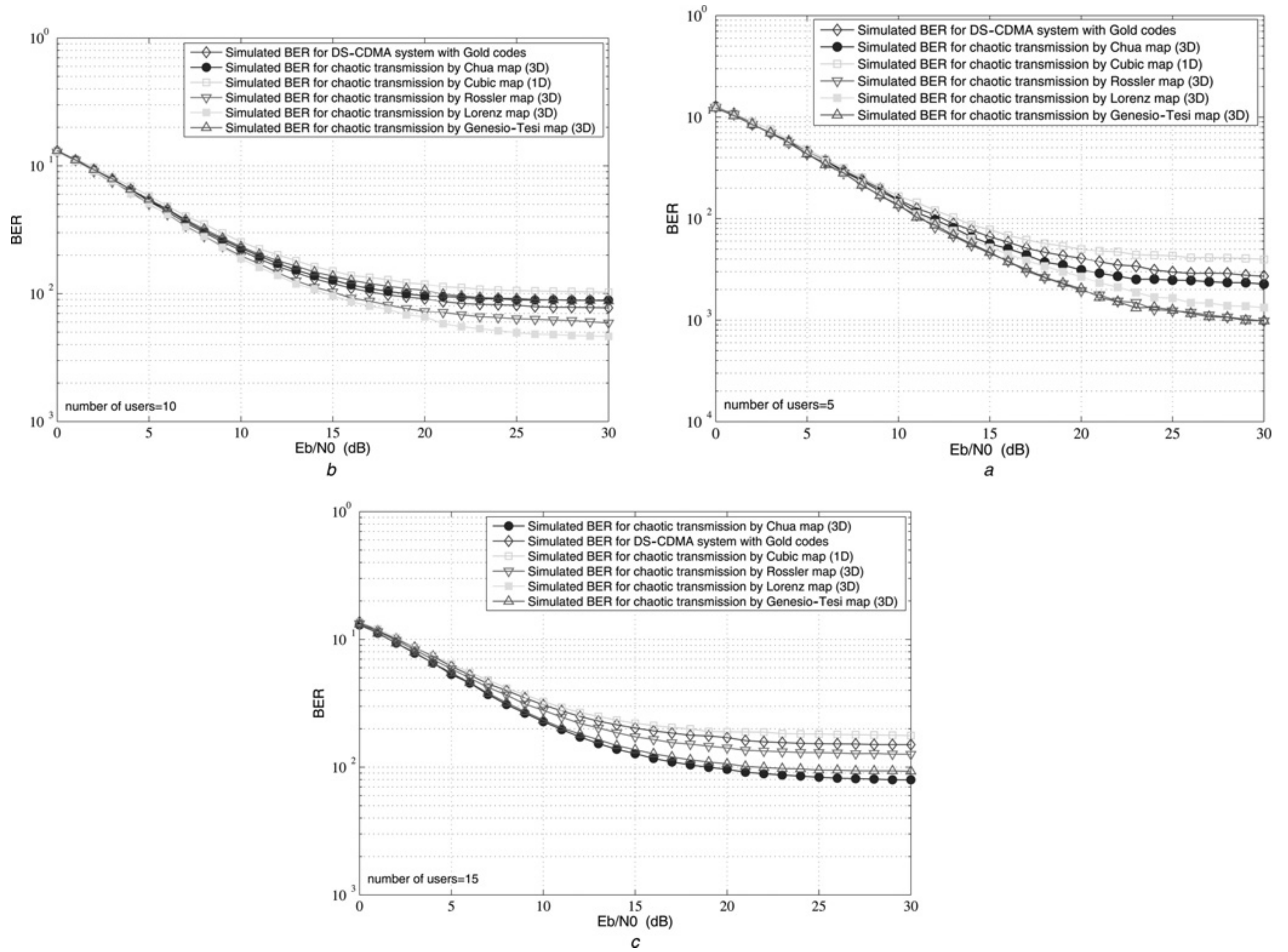

Fig. 3 *BER curves of system in Fig. 1, against different no. of users β = 15, K = 0 dB, BPSK constellation*

a $U = 5$
b $U = 10$
c $U = 15$

and 1} dB was considered, whereas multiplying received signal and conjugate of the complex path amplitude with maximum power. In this case, data symbols were selected from a 4-QAM constellation. The BER simulation results are presented in Figs. 5*a* and *b*. Similar to Fig. 2, the results are obtained for two spreading factors, $\beta = 15$ and 127 using three users. It is obvious from this figure that our solution offers superior performance in both cases.

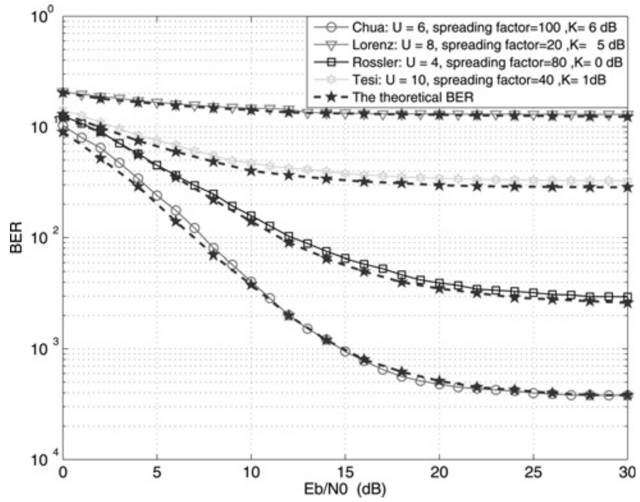

Fig. 4 *Simulated and theoretical BERs of the chaos-based DS-CDMA system for different parameters*

Furthermore, all chaotic systems in this paper (1D and 3D) are examined in terms of computational complexity, and results are presented in Table 1. Although the computational order of sequence generation using the 3D chaotic systems is greater than that of the 1D systems (see Table 1), this complexity can be ignored because calculations are needed be done only once. Also, memories of size N Kb and 3 N Kb are necessary to generate a sequence with length N when 1D and 3D chaotic systems are used, respectively.

5.1 Remarks

This paper has shown that the proposed model offers flexibility which is a significant advantage in comparison with other spreading code schemes, such as the gold codes etc. Moreover, by changing the initial conditions and system parameters, our method makes it possible to select each of the states of chaotic systems and set the variable γ to any desirable value and therefore generate an infinite number of proper spreading codes. This important feature means that our algorithm can support many number of users.

The proposed model also exhibits the following characteristics:

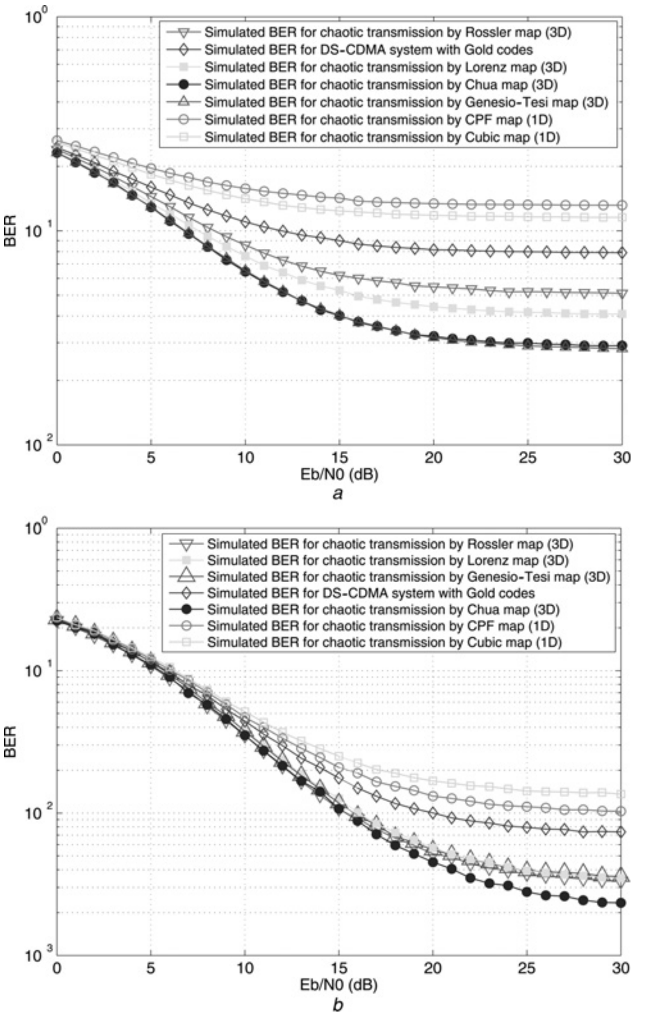

Fig. 5 *BERs in DS-CDMA applications: for 1D and 3D chaotic systems and the Gold codes*

$U = 3$, 4-QAM constellation
a $\beta = 15$
b $\beta = 127$

Table 1 Computational complexity of sequence generation using chaotic systems

Chaotic system	Order of computation
Rössler (3D)	O(6)
Chua (3D)	O(11)
Lorenz (3D)	O(9)
Genesio-Tesi (3D)	O(7)
CPF (1D)	O(3)
Cubic (1D)	O(5)

1. Chaotic spreading code is periodic and pseudorandom.
2. Security of transmission is guaranteed because of the existence of huge disarray in 3D chaotic systems. The scheme also allows for the exploitation of each of the three states of chaotic systems.
3. Greater flexibility is achievable because of the presence of the variable γ in the binary code generation method.

6 Conclusions

In this paper, we unveiled an innovative chaos-based code generation scheme by using a 3D chaotic system and demonstrated its potential for DS-CDMA system applications. We also performed simulations that confirmed the proposed solution's ability to satisfy the basic requirements for secure transmission over a CDMA-based communication environment. To evaluate the proposed algorithm's strength, BER performance comparisons were made against other popular methods and the results were plotted. A study of the results confirmed that the proposed chaotic binary sequences was comparable to the chaotic codes generated by 1D chaotic systems and the Gold code, which are considered optimal codes and are commonly deployed in many modern digital communication systems.

In comparison with classical codes, our approach not only outperforms those coding methods in dealing with noise disturbances and multi-user interferences but it also offers superior properties.

We have seen that: firstly, classical codes generated by linear shift register generators are easily decipherable and secondly, the number of generated sequences is limited. In contrast, because of the sensitivity to the initial conditions as well as to the parameters of the system, and given the high consternation of 3D chaotic systems, the new coding algorithm offers both the advantage of a highly secured transmission and the benefit of generating an infinite number of sequences.

It should also be mentioned that one shortcoming of the scheme in this paper is the requirement that the transmitter and the receiver must be highly synchronised.

These results suggest that a chaotic code generated by high-dimensional chaotic systems is well suited to digital spread-spectrum communication such as DS-CDMA.

As an ongoing research work, authors are aiming to fully investigate the proposed code's performance under an asynchronous transmission set up and also examine the behaviour of a suitable observer in a spread spectrum communication environment.

7 Acknowledgment

This research was partially supported by the Iran Telecommunication Research Center (ITRC), Tehran, Iran.

8 References

1 Milanovic, V., Zaghloul, M.E.: 'Improved masking algorithm for chaotic communication systems', *Electron. Lett.*, 1996, **32**, (1), pp. 11–12
2 Lu, J., Xiaoqun, W.U., Jinhu, L.Ü.: 'Synchronization of a unified chaotic system and the application in secure communication', *Phys. Lett. A*, 2002, **305**, (6), pp. 365–370
3 Yang, T.: 'A survey of chaotic secure communication systems', *Int. J. Comput. Cognit.*, 2004, **2**, pp. 81–130
4 Dixon, R.C.: 'Spread spectrum systems' (Wiley, New York, 1984, 2nd edn.)
5 Hofmann-Wellenhof, B., Lichtenegger, H., Collins, J.: 'Global positioning system: theory and practice' (Springer Verlag, Berlin, 2001, 5th edn.)
6 Vladeanu, C., Banica, I., Assad, S.E.: 'Periodic chaotic spreading sequences with better correlation properties than conventional sequences – BER performances analysis'. Int. Symp. on Circuits and Systems, July 2003, vol. 2, pp. 649–652
7 Boutayeb, M., Darouach, M., Rafaralahy, H.: 'Generalized state-space observers for chaotic synchronization and secure communication', *IEEE Trans. Circuits Syst. I, Fundam. Theory Appl.*, 2002, **49**, (3), pp. 345–349
8 Jovic, B., Unsworth, C., Sandhu, G., Berber, S.M.: 'A robust sequence synchronization unit for multi-user DS-CDMA chaos based communication systems', *Signal Process.*, 2007, **87**, (7), pp. 1692–1708

doi: 10.1049/iet-com.2012.0763

9 Kaddoum, G., Roviras, D., Chargé, P., Fournier-Prunaret, D.: 'Robust synchronization for asynchronous multi-user chaos-based DSCDMA', *Signal Process.*, 2009, **89**, (5), pp. 807–818

10 Pecora, L.M., Caroll, T.L.: 'Synchronization in chaotic systems', *Phys. Rev. Lett.*, 1990, **64**, (8), pp. 821–824

11 Bowong, S., Kakmeni, F.M.M., Siewe, M.S.: 'Secure communication via parameter modulation in a class of chaotic systems', *Commun. Nonlinear Sci. Numer. Simul.*, 2007, **12**, (3), pp. 397–410

12 Yeh, J.P., Wu, K.L.: 'A simple method to synchronize chaotic systems and its application to secure communications', *Math. Comput. Model.*, 2008, **47**, (9–10), pp. 894–902

13 Kharel, R., Busawon, K., Ghassemlooy, Z.: 'A chaos-based communication scheme using proportional and proportional-integral observers', *Iran. J. Electr. Electron. Eng.*, 2008, **4**, (4), pp. 127–139

14 Smaoui, N., Karouma, A., Zribi, M.: 'Secure communications based on the synchronization of the hyperchaotic Chen and the unified chaotic systems', *Commun. Nonlinear Sci. Numer. Simul.*, 2010, **16**, (8), pp. 3279–3293

15 Leung, H., Fallahi, K.: 'A chaos secure communication scheme based on multiplication modulation', *Commun. Nonlinear Sci. Numer. Simul.*, 2010, **15**, (2), pp. 368–383

16 Wang, X., Zhan, M., Gong, X., Lai, C.H., Lai, Y.C.: 'Spread-spectrum communication using binary spatiotemporal chaotic codes', *Phys. Lett. A*, 2005, **334**, (1), pp. 30–36

17 Chen, C., Yao, K., Umeno, K., Biglieri, E.: 'Design of spread-spectrum sequences using chaotic dynamical systems and ergodic theory', *IEEE Trans. Circuits Syst.*, 2001, **48**, (9), pp. 1110–1114

18 Rovatti, R., Setti, G., Mazzini, G.: 'Toward sequence optimization for chaos-based asynchronous DS-CDMA systems'. Proc. IEEE GLOBECOM, Sydney, Australia, 1998, no 4, pp. 2174–2179

19 Setti, G., Rovatti, R., Mazzini, G.: 'Synchronization mechanism and optimization of spreading sequences in chaos-based DS-CDMA systems'. Proc. Transactions on Fundamentals of Electronics Communications and Computer Sciences, 1999, E82-A, (9), pp. 1737–1746

20 Pursley, M.B.: 'Direct-sequence spread-spectrum communications for multipath channels', *IEEE Trans. Microw. Theory Tech.*, 2002, **50**, (3), pp. 653–661

21 Jovic, B., Unsworth, C.: 'Performance comparison of multi-user chaosbased DS-CDMA synchronisation unit within AWGN and Rayleigh fading channel', *Electron. Lett.*, 2007, **43**, (18), pp. 988–989

22 Coulon, M., Roviras, D.: 'Multi-user receivers for synchronous and asynchronous transmissions for chaos-based multiple-access systems', *Signal Process.*, 2009, **89**, (4), pp. 583–598

23 Kaddoum, G., Coulon, M., Roviras, D., Charge, P.: 'Theoretical performance for asynchronous multi-user chaos-based communication systems on fading channels', *Signal Process.*, 2010, **90**, (11), pp. 2923–2933

24 Charge, P., Fournier-Prunaret, D., Guglielmi, V.: 'Features analysis of a parametric PWL chaotic map and its utilization for secure transmissions', *Chaos Soliton Fractal*, 2008, **38**, (5), pp. 1411–1422

25 Kaddoum, G., Charge, P., Roviras, D., Fournier-Prunaret, D.: 'Comparison of chaotic sequences in a chaos based DS-CDMA system'. Proc. Int. Symp. on Nonlinear Theory and its Applications, Vancouver, Canada, 2007, pp. 16–19

26 Umeno, K., Kitayama, K.: 'Improvement of SNR with chaotic spreading sequences for CDMA'. Proc. IEEE Information Theory Workshop, 1999, p. 106

doi: 10.1049/iet-com.2012.0763