Nonlinear Multiuser Receiver for Optimized Chaos-Based DS-CDMA Systems

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Abstract: Chaos based communications have drawn increasing attention over the past years. Chaotic signals are derived from non-linear dynamic systems. They are aperiodic, broadband and deterministic signals that appear random in the time domain. Because of these properties, chaotic signals have been proposed to generate spreading sequences for wide-band secure communication recently. Like conventional DS-CDMA systems, chaos-based CDMA systems suffer from multi-user interference (MUI) due to other users transmitting in the cell. In this paper, we propose a novel method based on radial basis function (RBF) for both blind and non-blind multiuser detection in chaos-based DS-CDMA systems. We also propose a new method for optimizing generation of binary chaotic sequences using Genetic Algorithm. Simulation results show that our proposed nonlinear receiver with optimized chaotic sequences outperforms in comparison to other conventional detectors such as a single-user detector, decorrelating detector and minimum mean square error detector, particularly for under-loaded CDMA condition, which the number of active users is less than processing gain.

Keywords: Chaos-based Communication, DS-CDMA, Radial Basis Function, Multi-User Detection.

1 Introduction

The major interest into the application of chaos to communications started in 1990 with the discovery by Pecora and Carroll [1] that chaotic systems can be synchronized. Since then, a large number of papers investigating the application of chaos in secure communications have appeared [2–13]. These chaotic communication systems offer increased security of transmission because of the high sensitivity of chaotic signals to parameter and initial condition perturbations, the random-like nature and the broadband spectrum. In many cases, when studying chaotic communication systems, only single-user systems are considered [2–8]. Alternatively, multi-user chaotic communication techniques, based on the direct sequence code division multiple access (DS-CDMA) principle, have been studied in [9–16], demonstrating their robust nature.

Although CDMA has a higher capacity compared to other multiple access schemes, this system suffers from multiple access interference (MAI) due to other users transmitting in the cell and inter symbol interference (ISI) due to multipath nature of channels in the presence of additive white Gaussian noise (AWGN). The MAI can seriously degrade the bit-error-rate (BER) performance of CDMA system.

In 1984 Verd´u addressed the multiuser detection (MUD) [17] in order to cancel the near-far effect. His works ignite lots of research in this area. A variety of multiuser detectors (MUDs) have been proposed to deal with MUI through demodulation of mutually interfering signals. Initial efforts dealt with simple linear detectors: matched filter (MF) [18], decorrelating detector (DD) [19], minimum mean-square-error (MMSE) linear detector [20], and decision feedback detectors [21]. With the advent of neural networks, detectors based on well-known structures like multilayer perceptrons (MLPs) [22], [23] and radial basis function (RBF) [24] were proposed. With increasing attention focused on the application of neural networks to the field of pattern recognition, more neural network–based MUDs were implemented. These covered MUDs based on neural matched filters [25], recurrent neural networks [26], Hopfield networks [27], transiently chaotic neural networks [28], and self-organized maps [29]. In following years, blind MUD has become a worldwide research topic and a number of methods for blind MUD has been proposed, such as least-mean-square(LMS) algorithm [30], the recursive least-square(RLS) algorithm [31], [32] and Kalman's algorithm [33]. In

this paper, we propose both blind and non-blind RBF based multiuser detector for chaos-based DS-CDMA system. We also proposed a novel idea for optimized generation of chaotic sequences, using the genetic algorithm. The paper is organized as follows. In Section two, the DS-CDMA communication system's model with K users and some standard algorithms for multiuser detection is presented. Section three describes the chaotic spreading code generation and new proposed algorithm for optimization. Section four covers the proposed RBF-based multiuser detection techniques in both blind and non-blind condition. Simulation results are provided in Section five. Finally, a conclusion is given in Section six.

2 System Model
2.1 DS-CDMA Communication System

Figure 1 depicts the transmitter and receiver system model of a baseband DS-CDMA communication system with K users. Each user transmits binary symbols $S(n) \in \{-1, +1\}$ using BPSK modulation. The k_{th} user of the source symbol sequence with T_b symbol period, denoted by $S_k(n)$, is spread by a pseudo-noise code of length L with a chip duration of T_c. Thus, the spreading gain of the system can be expressed as $L = T_b/T_c$. The spreading sequence of the k_{th} user can be written in a vector $c_k = [c_k(0), c_k(1), c_k(2), \ldots, c_k(L-1)]^T$, where $c_k(i) = +1$ or -1, $i = 0,1,2,\ldots,L-1$ and $(.)^T$ is a transpose operator. On the receiver part, a bank of correlators (or an adaptive filter) is used, followed by hard decision devices that are applied to produce hard decision output.

Assuming a quasi-static channel, the amplitude and timing delay of each user can be considered as constants during the transmission in a frame of M bits. The continuous form of received signal after down-conversion to baseband, therefore is

$$r(t) = \sum_{n=1}^{M} \sum_{k=1}^{K} a_k b_k^{(n)} S_k(t - nT_s - \tau_k) + n(t) \qquad (1)$$

where

$$S_k(t - nT_s) = \sum_{j=0}^{L-1} c_k(j + nL) p(t - jT_c - nT_s), \quad S_k(t) \in [0, T_s) \qquad (2)$$

$S_k(t)$ is the deterministic signature waveform for user k, normalized to have unit energy. $p(t)$ is a rectangular pulse of duration T_c. T_s is the symbol interval, a_k is the received amplitude of the k_{th} user's signal, $b_k^{(n)} \in \{-1,1\}$ is the BPSK modulated n_{th} raw data bit transmitted by the k_{th} user, τ_k is the time delay of user k and $n(t)$ is the white Gaussian channel noise with zero mean and variance δ^2.

From (1), the received signal $\mathbf{r}$, which has been time-discretized by anti-alias filtering and sampling at the rate $1/T_s$, has the following discrete form over a data block of M symbols.
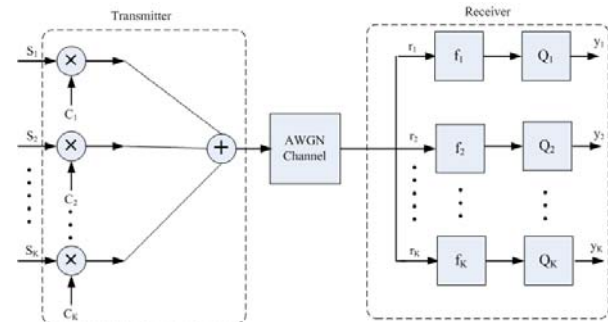

Fig. 1 DS-CDMA communication system model with K users.

$$\mathbf{r} = \mathbf{S}\mathbf{A}\mathbf{b} + \mathbf{n} \in \mathbf{C}^{(SLM) \times 1} \qquad (3)$$

where $\mathbf{S}$ is the number of samples per chip. In this equation, signature matrix of all users is a SLM×KM matrix denoted by $\mathbf{S}$ and $\mathbf{A}$ is KM×KM diagonal matrix of total received amplitudes; $\mathbf{b}$ is the KM×1 data vector with BPSK symbol alphabet and $\mathbf{n}$ is the channel noise vector with zero mean and covariance of $\delta^2\mathbf{I}$. The matched filter output vector $\mathbf{y}$ has the following expression.

$$\mathbf{y} = \mathbf{S}^T\mathbf{r} = \mathbf{R}\mathbf{A}\mathbf{b} + \mathbf{w} \in \mathbf{C}^{(KM) \times 1} \qquad (4)$$

where the correlation matrix R in (4) has the expression

$$\mathbf{R} = \mathbf{S}^T\mathbf{S} \in \mathbf{C}^{(KM) \times (KM)} \qquad (5)$$

and $\mathbf{w}$ is the noise vector with zero mean and covariance of $\delta^2\mathbf{R}$.

2.2 Multiuser Detection Techniques for DS-CDMA Systems

Multiuser Detection (MUD) is the intelligent estimation/demodulation of transmitted bits in the presence of Multiple Access Interference (MAI). MAI occurs in multi-access communication systems (CDMA/TDMA/FDMA) where simultaneously occurring digital streams of information interfere with each other. Conventional detectors based on the matched filter just treat the MAI as additive white Gaussian noise (AWGN). However, unlike AWGN, MAI has a correlative structure that is quantified by the correlation matrix of the signature sequences($\mathbf{R}$). Hence, detectors that take into account this correlation would perform better than the conventional matched filter-bank.

2.2.1 MLSE Optimal Detector

The optimal synchronous multiuser detector (OMD) designed by Verdu, is widely accepted as the optimal multiuser detector. It is optimal in the sense that the detector yields the minimum achievable probability of bit error rate. Unfortunately, this performance comes at the cost of high computational complexity, which makes the receiver unrealizable for partial applications. The OMD performs the joint demodulation by solving a quadratic optimization problem. When this optimization

is performed, the bit vector (**b**) that minimizes the error probability is found to be:

$$\mathbf{b}_{opt} = \arg\max\{2\mathbf{b}^T\mathbf{A}\mathbf{y} - \mathbf{b}^T\mathbf{A}\mathbf{R}\mathbf{A}\mathbf{b}\} \in \mathbf{C}^{(KM)\times 1} \qquad (6)$$

The optimization in (6) is performed by an exhaustive search of all possible bit sequences.

2.2.2 The Decorrelating Detector

In considering the MF it was seen that if the interfering user's power is sufficiently strong, it will cause the receiver to make erroneous decisions. The Decorrelating Detector (DD) uses the natural strategy of completely removing the effect of the interfering terms. Decorrelating strategy is accomplished by multiplying the received signal by the inverse of the correlation matrix.

$$\hat{\mathbf{b}} = \text{sign}\{\mathbf{R}^{-1}\mathbf{y}\} \in \mathbf{C}^{(KM)\times 1} \qquad (7)$$

The decorrelator thus has the distinct advantage over the MF in that it can demodulate error free in the absence of noise. It also does not need to have accurate estimates of users 'amplitudes, and is the optimum linear detector if the amplitudes are not known.

2.2.3 The Minimum Mean Square Error Detector

The linear minimum mean square error detector (MMSE) represents the maximum level of improvement for linear detectors. This additional improvement comes by assuming one has knowledge of each user's received power levels. The MMSE works by applying a linear transformation that minimizes the mean square error between the outputs and the data. The estimation equation using MMSE is given by (Verdu, 1998),

$$\hat{\mathbf{b}} = \text{sign}\{(\mathbf{R} + \delta^2\mathbf{A}^{-2})^{-1}\mathbf{y}\} \in \mathbf{C}^{(KM)\times 1} \qquad (8)$$

This relation shows that the MMSE is basically a compromise between the conventional detector and the decorrelator. In particular, the MMSE also achieves optimum near far resistance; however, accurate estimates of the user's power levels must be known.

3 Optimized Chaotic Codes for Multiuser Communication System Model

In this section, some of the standard chaotic sequences and their characteristic are implied and then the novel optimization algorithm will be discussed.

3.1 Chaotic Sequences Properties

Recently, chaotic signals, having a wideband nature, have been proposed as carriers for spread-spectrum communications. This is because chaos-based spread spectrum systems can offer several advantages over conventional spread-spectrum systems. For example, wideband chaotic signals can be generated using very simple circuitry. Thus, the cost of hardware can be much cheaper. Furthermore, due to the non periodic nature of the chaotic signal, the message cannot be easily intercepted, and hence the security is enhanced. In addition, chaotic signals have very good auto- and cross-correlation properties. These are important features in a multiple access environment because they can produce low co-channel interference and finally better system performance. Last but not least, a large number of chaotic signals can be easily generated by using different initial conditions and these signals can be very useful in differentiating users under a multi-user environment. The chaotic dynamical systems can be broadly classified into continuous-time and discrete-time types. In a continuous-time system, the chaotic signal is derived from a set of differential equations and In a discrete time chaotic system, the chaotic sample is generated from a set of difference equations, i.e.,

$$x_k = g(x_{k-1}) = g^{(k)}(x_0) \qquad (9)$$

where **x** is the state vector and g(.) denotes the iterative function, which is usually called a chaotic map. Figure 2 plots a chaotic signal, generated by a one dimensional chaotic map, against normalized time.

It can be observed that the signal never repeats itself, looks at random-like and is bounded. In addition, chaotic signals are characterized by their impulse-like autocorrelation and very low cross-correlation properties. Figure 3 shows the auto-correlation function of two chaotic sequences generated by one famous chaotic map with two initial values $x_{(0)} = 0.07$ and $x_{(0)} = 0.07001$. Although their initial values are just slightly different, the generation of binary chaotic spreading code sequences is very sensitive to the initial condition. A slight difference in the initial condition will generate a totally different chaotic sequence; which is the basis for higher security. Due to noise like nature of the autocorrelation function in chaotic sequences; their spectrum has a wideband property, which is important in spread spectrum communication.

3.2 Standard Algorithms for Generation of Chaotic Sequences

With respect to the intrinsic characteristics of all chaotic sequences such as non- periodicity and pseudo-noise behavior, it is possible to use most of them in broadband communication systems. However, some items like the synchronization possibility, implementation complexity and desired security condition may practically restrict the wide area of these sequences.

Because of the implementation simplicity and the explicit mathematical formula of discrete chaotic generators modeled as a difference equation, these generators are widely used in chaotic communication designs. Among these equations, some of them like Logistic and Bernoulli maps are extensively used [34].

Clearly the chaotic sequence produced by difference equations with real values must be converted to binary sequences, which was done by passing the sequence through linear quantizer (fixed threshold level).
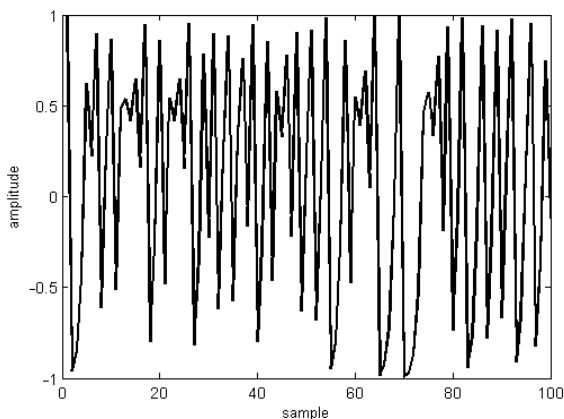
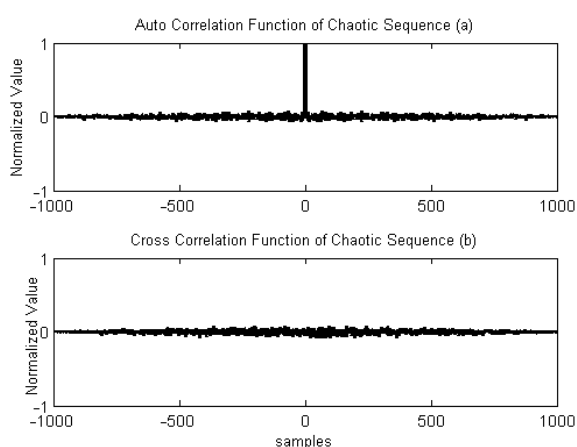**Fig. 2** Time series of the logistic map with initial value 0.07.

Fig. 3 (a) Auto-correlation function of logistic map chaotic sequence with initial value $x_{(0)} = 0.07$ (b) Cross correlation function of two chaotic sequences generated by logistic map with two initial values $x_{(0)} = 0.07$ and $x_{(0)} = 0.07001$.

In multi-user environments, several binary sequences should be produced according to the number of active users, which is usually accomplished based on the high sensitivity of chaotic generators to the small differences in the initial value of sequences. Although using different generators for each active user, has been offered in some texts [34] but in the usual methods, all the users have equal generator equation, and one has only a slight difference in initial point toward another, which leads users' codes to be considered as pseudo-orthogonal even despite very little differences in the start point.

3.3 Proposed Algorithm for Performance Optimization of Chaotic Sequences

Spread spectrum applications with short codes, require K binary sequences with SG samples for each user, where K denotes the total number of active users, G is the number of chips in each data symbol, i.e. processing gain, and S are the number of samples per chip. As mentioned before, to produce these sequences,

K different start points are selected for unique discrete generator for each start point (each user). And then SG sample of chaotic sequence is calculated and converted into G bit binary sequence by passing through linear quantizer. However, there is no plain way for selecting the K different initial values of all users in this algorithm until now. Too closed values for these initial points may lead to high correlation between signature sequences, and far values may lead to the sequence divergence and consequently, performance reduction. In addition to this problem, there is no answer to this question that "why the first SG samples of all chaotic time-series should be selected as a signature code of each user?" while generally such values can be selected among the Nth to N+SG-1th samples of each user chaotic sequence and not necessarily the first SG samples of it (N=1).

Thus, one could say that in the most general mode, three main parameters are important in the performance of chaotic binary sequences; the type of the chaotic generator among different discrete mathematical equations, K initial values for allocation to various users and eventually the method of selecting the SG required samples for each user. To consider the above parameters which are important in chaotic generator design, we have used the genetic algorithm as a heuristic optimization algorithm. At the beginning of this algorithm, one quality measure for assigned signature codes should be defined, which should be directly related to the improvement of system performance and decreasing multiuser interference effect. In addition its calculation should be simple. For this reason, by looking at the quality functions introduced in some papers [34, 35, 36], and with respect to the simulations, the following criterion for the quality evaluation of a K number family of chaotic sequences was offered. According to mentioned notes, in the first step, correlation value, $R(S_i, S_j)$, should be calculated for different values of i and j.

$$R(\mathbf{S}_i, \mathbf{S}_j) = E(\mathbf{S}_i \times \mathbf{S}_j^H) = \sum_{k=0}^{SG-1} S_i(k) S_j^*(k) \quad (10)$$

where, $\mathbf{S}_i$ and $\mathbf{S}_j$ are ith and jth user signature codes. The normalized correlation value can be defined as follows:

$$\rho(i, j) = \frac{R(\mathbf{S}_i, \mathbf{S}_j)}{\sqrt{R(\mathbf{S}_i, \mathbf{S}_i) \times R(\mathbf{S}_j, \mathbf{S}_j)}} \quad (11)$$

At the end, with respect to (10) and (11), the final criterion for the quality measurement of family of binary codes can be calculated from the sum of the non-diagonal elements of the correlation matrix:

$$CC = \sum_{i>j} |\rho(i, j)| \quad (12)$$

By adapting this target function for the genetic algorithm, three mentioned structural parameters (the chaotic generator type, K initial value and start point for selecting the SG value of chaotic series for each user)

are coded into a single binary code sequence (one chromosome in genetic algorithm) and by applying Mutation and Crossover operators, the new generations of selected chromosomes are produced. This process will be repeated until the maximum number of the generations achieved. Finally, the optimum value for three parameters will be obtained by using the genetic algorithm and furthermore by substituting these values, the optimized chaotic sequences will be achieved.

4 RBF-Based Nonlinear Receiver with Chaotic Sequences

Recently, many new types of nonlinear receivers have been created using artificial neural networks (ANN) .The application of neural networks to the de-modulation of spread spectrum signals has shown great promise due to their adaptability. The learning stage makes NN very robust and highly adaptive. Neither the optimal receiver nor any of the linear receivers previously discussed are adaptive in nature. Thus performance degrades, if user/channel parameters change. Additionally, neural networks, like the optimal detector, are nonlinear in nature and hence should be able to provide better results than their linear receiver counterparts.

4.1 Pattern Recognition Representation of DS-CDMA Receivers

In conventional communication systems, the receiver returns n-bit vectors with even or odd parity. If one considers each element of this vector as a dimension, then this vector can be represented by a point in an n-dimensional hyper-space. Code division multiple access signals can be readily transformed, with a geometrical interpretation given to them. Each possible combination of the received signal forms a corner on a hypercube in the input space of the signal. The dimensionality of the input space is dependent upon the number of users given by K where K is the number of users. The received signal for the n_{th} user, in a CDMA system was defined as,

$$\hat{b} = < \sum_{k=1}^{K} A_k b_k^{(n)} S_k(t) + \boldsymbol{\delta} n(t), \ s_n > \qquad (13)$$

where $S_k(t)$ is the transmitted symbol of k_{th} user, A_k and b_k are the amplitude and bit vector of each user and n(t) is a white Gaussian noise with variance δ^2 .If we are interested in user 1, then for a two user system, the equation can be simplified to,

$$\hat{b}_1 = A_1 b_1 + A_2 b_2 \rho + n'(t) \qquad (14)$$

and similarly for user 2,

$$\hat{b}_2 = A_2 b_2 + A_1 b_1 \rho + n'(t) \qquad (15)$$

where ρ is a correlation value between two users of system. By setting the amplitude to unity in (14) and (15), Figure 4 shows the received regions for two and three users respectively. Bits of positive parity are white, while bits of negative parity are shaded. If the spreading codes are orthogonal then the correlation matrix would be the identity matrix, and the received signals form a square in 2 dimensions, a cube in 3dimensions, and a hyper cube in higher dimensions. Once the hypercube has been constructed, pattern classification techniques can be applied to determine signals of even or odd parity. Neural networks have been shown to encode large amounts of data for quick retrieval, as well as being nonlinear and adaptive in nature. Using these networks can lead to a series of classifiers, which should be able to obtain the near optimal performance of the Verdu receiver at much lower computational cost.

4.2 RBF Receiver for Chaotic DS-CDMA System

Since the decision boundary of the optimal detector is known, any suboptimal receiver will try to emulate this decision region as best as possible. RBF networks are often referred to as universal approximator, and are well suited to curve fitting approximation problems. The key to the approximation problem is the transformation of the received input vector to a high dimensional space, in a nonlinear manner. The complex pattern transformed nonlinearly can be linearly separable in this high dimensional space. In first section, we explain RBF structure briefly and in second proposed single-RBF receiver will be introduced.

4.2.1 RBF Structure

The RBF network structure is defined as:

$$y(\mathbf{r}) = \sum_{m=1}^{M} w_m \ \phi\left(\frac{\|\mathbf{r} - \mathbf{c}_m\|^2}{\delta_m}\right), \qquad (16)$$

where $\phi (.)$ is a continuous, nonlinear kernel function, $\mathbf{r}$ the input data vector, $\mathbf{c}_m$ is called a center of the RBF neuron, and δ_m is the spread of the neuron and w_m are the linear weights. Each center $\mathbf{c}_m$ corresponds to a row of a generating matrix. The adjustable parameters include mean square error (MSE), spread factor, and number of neurons, which can be added to hidden layer for satisfying of the error condition in every step. At the
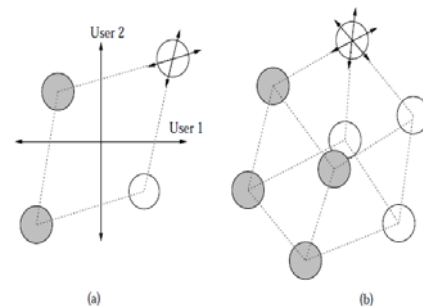

Fig. 4 CDMA received signal constellation for (a) 2 user and (b) 3 users respectively.

input of each neuron, the distance between the neuron center and the input vector is calculated. The output of the neuron is then formed by applying the basis function to this distance.

4.2.2 Single-RBF Receiver for Chaotic DS-CDMA

The job of the receiver is to estimate the transmitted signal $x_i(k)$ of the desired user using the information content in the input data vector. In this receiver structure, the input signal doesn't pass from the matched filter and directly is processed at chip level in RBF structure. The structure of this chip-level RBF receiver is shown in Figure 5. The input to the RBF network is given by input vector **r** from (3) and the output of the RBF network is given from calculating distanced from (16). The goal of the RBF is to learn the association between the input vector and the desired response. This is done by learning the decision boundary which separates the classes of signals in the feature space. In terms of CDMA applications, the network learns the association between the input vector and the desired response in training stage. The main advantage of this receiver is that it doesn't have any knowledge about main parameters of DS-CDMA system such as the code sequence matrix (**S**) and user amplitude matrix (A).

4.3 Proposed MF-RBF Receiver for Chaotic DS-CDMA System

Consider the construction of RBF-Based nonlinear receiver in previous section for optimized chaos-based DS-CDMA system. In a general idea, Preprocessing can be done with different pre-filter structures for enhancing the performance of proposed RBF receiver. The preprocessing approach taken in this section rests upon the matched filtering idea, before nonlinear multiuser detector. In addition to SNR improvement of receiver due to matched filtering stage of it, dimension of signal is considerably reduced.

The receiver isn't blind, because all main parameters of DS-CDMA system are assumed known. Figure 6 shows the structure of this MF-RBF receiver.
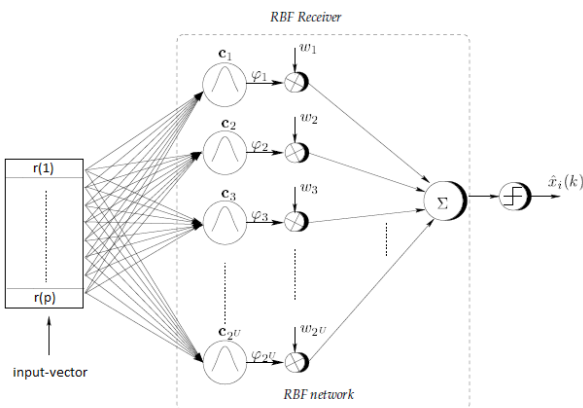

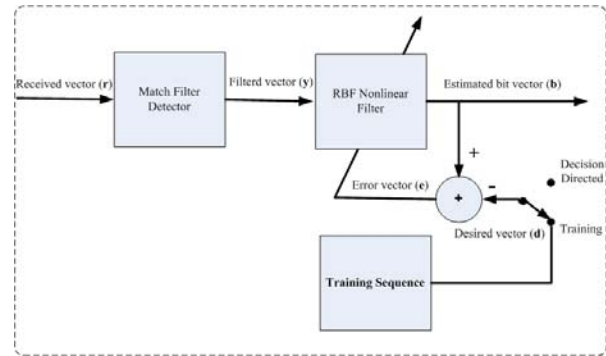**Fig. 5** The structure of the single-RBF receiver for chaos-based DS-CDMA system.

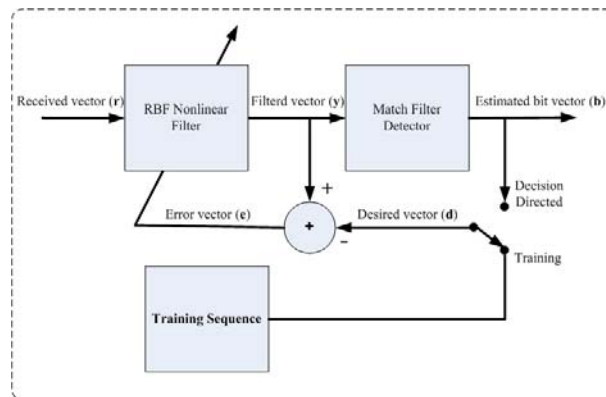**Fig. 6** The structure of MF-RBF receiver for chaos-based DS-CDMA system.

Fig. 7 The structure of RBF-MF receiver for chaos-based DS-CDMA system.

4.4 Proposed RBF-MF Receiver for Chaotic DS-CDMA System

In this section, other proposed receiver will be described. The general approach in this receiver is to assume MAI reduced signal at the matched filter input. This is achieved by embedding a RBF multi-user detector filter between the input and the matched filter detector. Although similar to previous section, this receiver needs to all of main parameters of DS-CDMA system and cannot assume blind receiver, but RBF multiuser detector, reduces MAI in preprocessing stage can lead to better performance than the previous receiver. Figure 7 shows the structure of this RBF-MF receiver.

5 Simulation Results

This section first reviews the numerical results of the code optimization algorithm, and then we evaluate the performance of various RBF-based proposed receivers. The BER performance of the proposed detectors will be compared to other conventional detectors with and without using optimized chaotic codes.

Unless otherwise stated, in our simulation, all chaotic sequence powers are normalized, and all users use the same channel to transmit their signals. The standard "maximal length" Pseudo- noise sequences are used for simulation of standard DS-CDMA systems [37,

38]. Here we used Logistic map as a discrete equation for initial (non-optimized) chaotic sequence generation.

$$x[n] = A - B(x[n-1])^2 \qquad (17)$$

where A and B are positive parameters and when the parameters A=1, B=2 this system behaves chaotically. In order to produce required binary sequences of the users, a positive real constant is defined, which is called "user step". By adding this constant to initial value of previous user, current user's initial value will be calculated, and this process will continue until all needed initial numbers are available. For example, if the number of active users fixed to K=4 and initial value of first user fixed to s0= - 0.2, by setting "user step" constant to step = 0.06, one could create three other initial values by above-mentioned procedure as -0.14, -0.08 and -0.02. It is evident that the value of user step constant should be chosen in such a way that all users' sequences remain chaotic. The great values of this parameter lead to the creation of non-chaotic sequences -particularly in great numbers of users- and its very low value will create high correlation among signature codes. Figure 8 illustrates real and binary values of generated signature codes for K=4 active user. Based on predefined quality function in equation 12 and optimization algorithm presented in section 3, the following assumptions were made.

5.1 Optimized Chaotic Generation Results

Three well-known discrete-time chaotic generators-Bernoulli, Logistic and Tent map-were selected. The initial value of the first user in all maps was assumed as a variable number between -0.2 to 0.2 and User step constant was assumed between 0.001to 0.35. Finally, the start point for selection of SG sample in each sequence (N) was assumed as a natural number between 1 to 100. Clearly, the GA-optimized structure is optimal only within the limits of the above- mentioned
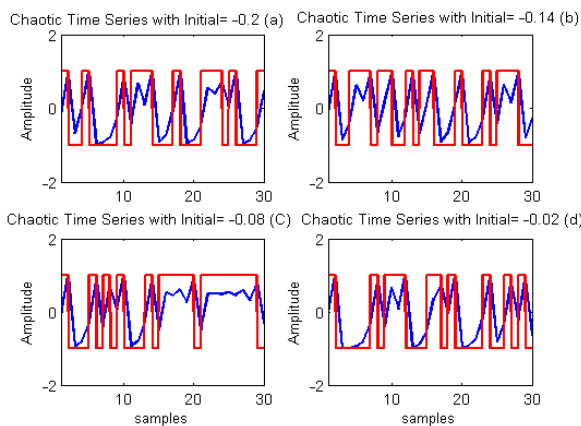
assumptions not the best solution which could be imagined.

After binary coding of the mentioned parameters, the genetic algorithm was simulated using MATLAB software. The number of generations was limited to 100 and Roulette Wheel Method was used for selection strategy. Crossover and Mutation probability values were assumed to 0.8 and 0.05 through trial and error. Table 1 shows simulated map equations, and Figure 9 indicates the plot of the predefined quality function in (12) for Logistic chaotic map versus user step and start point parameters. Table 2 refers to the correlation matrix for initial chaotic sequences, while the number of users = 4, processing gain is 7, starting index is 1, initial point for chaos generator = -0.2 and user step parameter is fixed at 0.06.

The optimization results which obtained for a chaos-based communication system, indicates that the value of correlation function in (12) was reduced from 1.79 in the non-optimized chaotic generator (Table 2) to 0.41 for the GA-optimized generator (Table 3). Optimized structure proposed by GA, use logistic map equation while GA-proposed initial point, user step and starting index parameters are 0.05, 0.07 and 63 separately. The correlation matrix of optimized chaotic sequences is shown in Table 3.

Similar to the previous tables, the optimization results for different number of users evaluated where the number of users is fixed to 12, processing gain to 7 and user step, starting index and initial point to 0.03, 1 and 0.05 separately. The optimization results indicate that the value of correlation function was reduced from 21.01 in non-optimized chaotic generator to 15.427 for optimized scheme while the optimized structure use logistic equation and initial point, user step and starting index parameters are 0.05, 0.021 and 4 separately.

Fig. 8 Real and continuous values of the logistic chaotic map for a) initial value = -0.2, b) initial value = -0.14, c) initial value = -0.08, d) initial value = -0.02. Number of samples per chip (S) fixed to 10.

Table 1 Different Equations for Optimized Selection of Chaos Generators.

Name	Equation and Parameters
Logistic Map	$x[n] = A - B(x[n-1])^2$ A=1,B=2
Tent Map	$x[n] = A - B(\lvert x[n-1] \rvert)$ A=0.5 ,B=2
Bernouli Map	$x[n] = Bx[n-1] - A\,\mathrm{sign}(x[n-1])$ A=0.5 , B=1.75

Table 2 Correlation matrix for initial logistic chaotic sequences for k=4 user, Processing gain=7, user step=0.06, starting index=1 and initial point=-0.2.

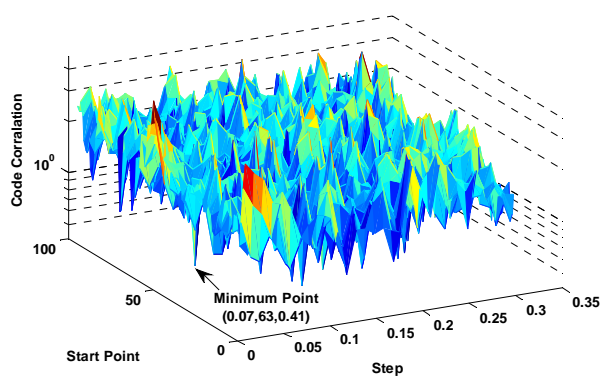| Cor. Value	User 1	User 2	User 3	User 4
User 1	1	0.369	0.060	0.201
User 2	0.369	1	0.351	0.154
User 3	0.060	0.351	1	0.660
User 4	0.201	0.154	0.660	1

Fig. 9 Code correlation diagram of generated chaotic codes versus user step and start points parameters for logistic map when k=4, Processing gain=7 and initial point=0.05.

Table 3 Correlation matrix for ga-optimized chaotic sequences for k=4 user and Processing gain=7.

Cor.Value	User 1	User 2	User 3	User 4
User 1	1	-0.035	0.052	-0.118
User 2	-0.035	1	-0.037	0.054
User 3	0.052	-0.037	1	-0.113
User 4	-0.118	0.054	-0.113	1

5.2 BER Performance of Proposed RBF-Based Receivers with Optimized Chaotic Codes

Unless otherwise stated, in the simulation of DS-CDMA system, without loss of generality, we assume that the user of interest is the first user and All other interferers have power uniformly distributed but with fixed mean value normalized to unity. Data bits are BPSK modulated and rectangular chip pulses are used for spreading. The number of bits required to evaluate the BER value for each point is 10^5 bit. The BER is then calculated by averaging over the number of long sub streams.

In Figure 10, we examine the performances of conventional matched filter receiver for the optimized chaos-based DS-CDMA system indicated by ChO, non-optimized chaos-based DS-CDMA system indicated by ChI and an standard PN-based maximal length DS-CDMA system indicated by M symbol with K = 2 and 4 users when processing gain is fixed to 7. In a non-optimized chaotic system, matched filter receiver has a bad performance, especially in 4 user environment which the receiver is rendered useless as its BER is about 10^{-1} but with optimization algorithm, significant improvement in BER performance occurs. In addition to remarkable performance comparing with non-optimized system, due to using optimized chaotic codes this system performs slightly better than conventional maximal length DS-CDMA systems too. Figure 11 shows the performance improvement of the optimized chaotic system with K=8 and 12 users over non optimized system, comparing with conventional maximal length receiver as a reference.

To verify our simulation results, BER performances for different system parameters are shown in Figures 12 to 13. Figures 12 and 13 show the BER performance of matched filter receiver when processing gain is fixed to 15. Two diagrams was plotted, first for K=2 and 4 user and second for K=8 and 12 users. Simulation results show the same remarkable performance improvement due to optimization process, except the overloaded system condition where the number of users is high and performance of optimized system has no prominence over conventional maximal length DS-CDMA system. Figure 14 shows this performance for different number of active users when Eb/N0 fixed to 15dB. Useful comparisons was done with Rovatti et al. approach in [14] for generation of optimized chaotic sequences using (n,t) tailed shift chaotic sequences. Rovatti et al. [14] proposed two optimized receiver denoted by optimized chaotic without rake (OCNR) receiver and optimized chaotic with classical rake (OCCR) scheme.

Simulation results confirm above mentioned improvement caused by optimized generation of chaotic spreading codes and show that the performance of the best Rovatti receiver outperforms of our ChO based detector only in overloaded condition when the number of users is larger than processing gain.

We next examine the impact of receiver structure on the performance of the proposed chaotic DS-CDMA system. Figure 15 compares the performances of MMSE detector, Decorrelating detector, and optimal detector when each receiver uses the non optimized chaotic codes, optimized codes or conventional maximal codes for spreading. We observe that the optimized chaotic receivers outperform the all other receivers except optimal detector that serves as a lower bound of BER in all multiuser receiver structures. In Figure 16 the performance of proposed single RBF receiver with chaotic and conventional m-sequences are shown for K=4 users and spreading gain equal to 7.
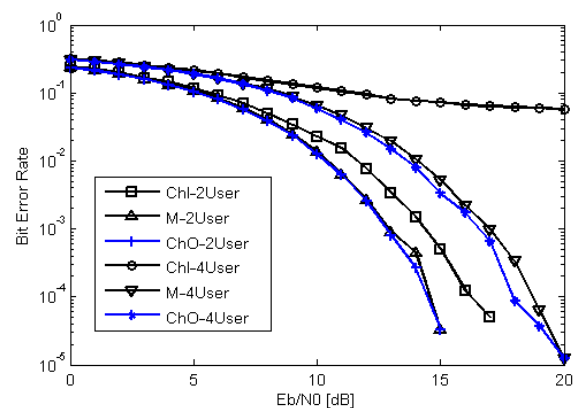

Fig. 10 BER performance of matched filter receiver for the optimized chaos-based DS-CDMA (ChO), non-optimized chaos-based DS-CDMA system (ChI) and an standard PN-based maximal length DS-CDMA system (M) for K=2 and 4 user when processing gain is fixed to 7.
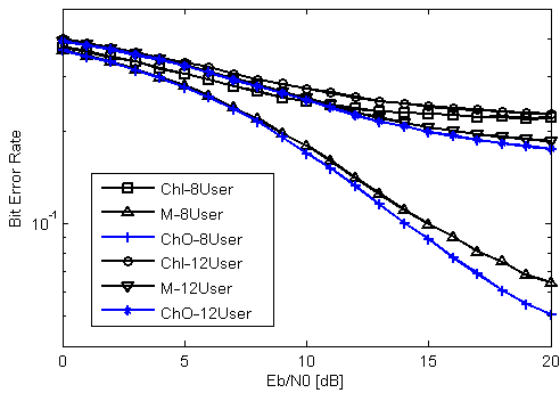
Fig. 11 BER performance of matched filter receiver for the optimized chaos-based DS-CDMA, non-optimized chaos-based DS-CDMA system and an standard PN-based maximal length DS-CDMA system for K=8 and 12 user when processing gain is fixed to 7.
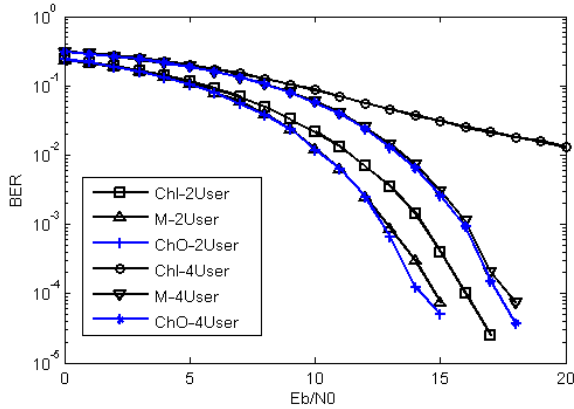

Fig. 12 BER performance of matched filter receiver for the ChO, ChI and the standard M Detector for K=2 and 4 user when processing gain is fixed to 15.
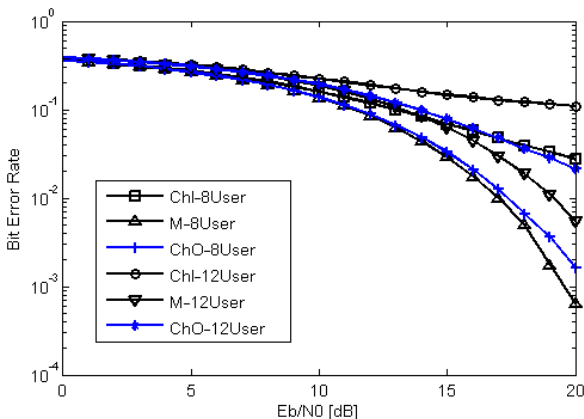

Fig. 13 BER performance of matched filter receiver for the optimized chaos-based DS-CDMA, non-optimized chaos-based DS-CDMA system and an standard PN-based maximal length DS-CDMA system for K=8 and 12 user when processing gain is fixed to 15.
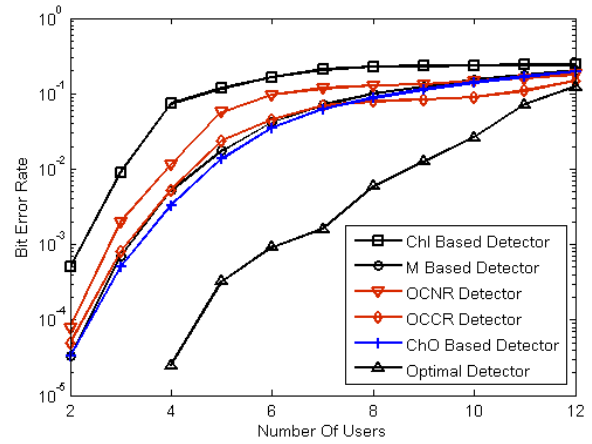

Fig. 14 BER performance of matched filter, ChI, ChO, M, proposed Rovatti et al. (2001) OCNR and OCCR Receiver and optimal detector versus number of active users when processing gain is fixed to 7 and Eb/N0=15 dB.
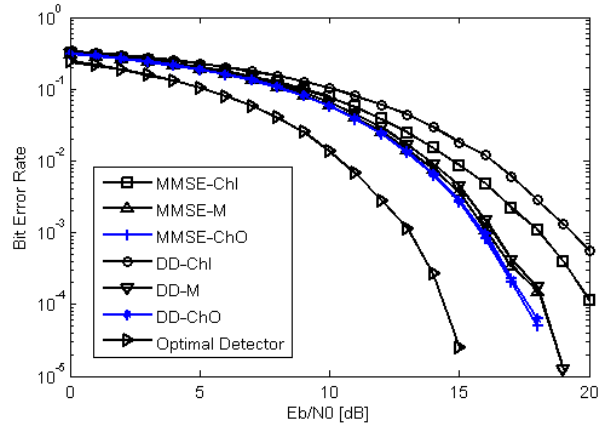

Fig. 15 BER performance of Minimum mean square error detector, decorelating detector and optimal detector for the ChI, ChO and an M Detector for K=4 user when processing gain is fixed to 7.
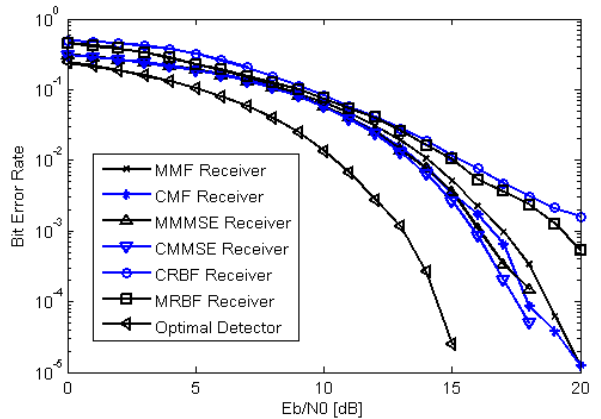

Fig. 16 BER performance of Matched filter detector, Minimum mean square error detector, Single RBF detector and Optimal detector for the ChI, ChO and an M Detector for K=4 user when processing gain is fixed to 7.

Although the performance of the RBF receiver is slightly weaker comparing to matched filter structure and MMSE detector, but this fact that the RBF receiver doesn't need any knowledge about spreading codes and transmitted power matrixes is a main advantage of its structure. In Figure 17 we show the BER performance of proposed MF-RBF Receiver for K=4 user when processing gain is fixed to 7. The performance of receiver is slightly better than MMSE multiuser receiver, without any knowledge about noise level which is necessary for MMSE multiuser detection. In Fig. 18 third proposed receiver performance is shown comparing with MMSE and optimal detector. The performance of this chaotic RBF-MF receiver shows Considerable improvement in BER performance of DS-CDMA systems. To verify the simulation results in the
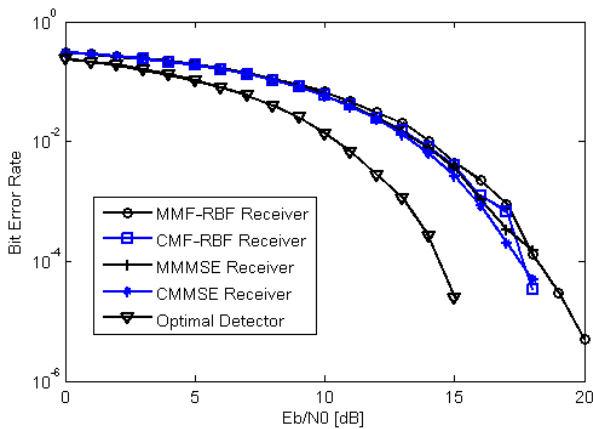

Fig. 17 BER performance of proposed MF-RBF Receiver, Minimum mean square error receiver and Optimal detector for the optimized chaos-based and an standard PN-based DS-CDMA system. Processing gain is fixed to 7 and number of users assumed to be K=4.
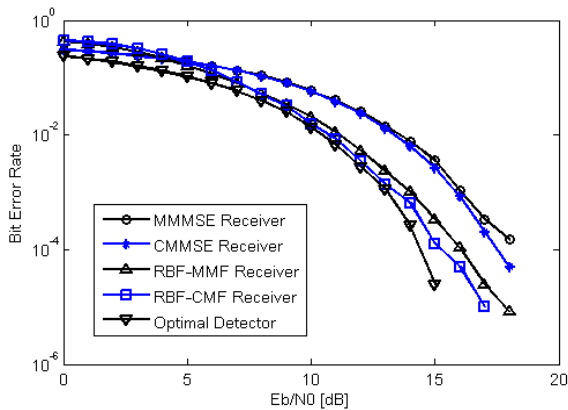

Fig. 18 BER performance of proposed RBF-MF Receiver, Minimum mean square error receiver and Optimal detector for the optimized chaos-based DS-CDMA and an standard PN-based maximal length DS-CDMA system for K=4 user when processing gain is fixed to 7.
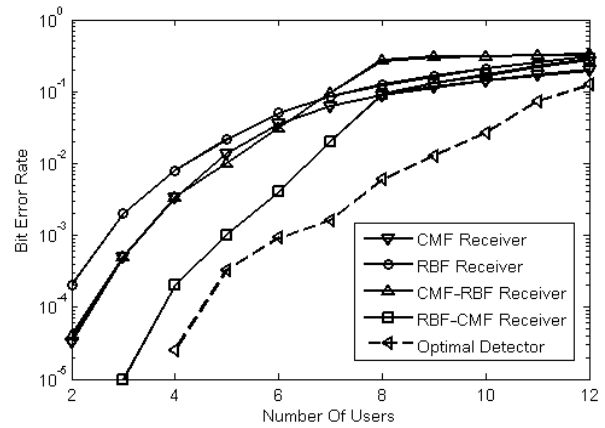

Fig. 19 BER performance of matched filter receiver, single RBF receiver, MF-RBF Receiver, RBF-MF Receiver and Optimal detector for the optimized chaos-based DS-CDMA system for different number of users when processing gain is fixed to 7 and Eb/N0=15 dB.
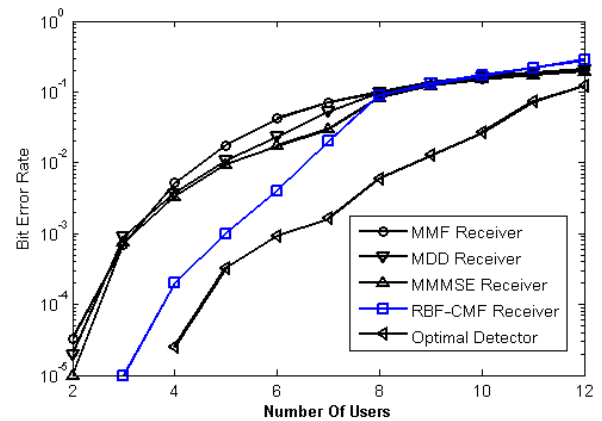

Fig. 20 BER performance of PN-based matched filter receiver, decorrelating detector, minimum mean square error Receiver, Optimal detector and the chaos-based RBF-MF proposed detector versus different number of users when processing gain is fixed to 7 and Eb/N0=15 dB.

other system condition, BER performance of proposed receivers versus different number of users was shown in Figures 19 and 20. Figure 19 shows the BER performance of matched filter receiver, single RBF receiver, MF-RBF Receiver, RBF-MF Receiver and Optimal detector for the optimized chaos-based DS-CDMA system for different number of users when processing gain is fixed to 7 and Eb/N0=15 dB and Figure 20 shows the performance of the best chaotic receiver comparing with conventional maximal length based MMSE and DD detectors. Simulation results show the effect of joint optimization algorithm and hybrid MF-RBF multiuser detection in good performance of this receive especially in the under loaded condition where the number of users is less than spreading code length.

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6 Conclusion

In this paper, a robust techniques for optimized generation of chaotic codes for spreading in DS-CDMA systems is proposed and novel method based on radial basis function (RBF) for both blind and non-blind multiuser detection in chaos-based DS-CDMA systems is derived and three RBF-based receivers were designed. Simulation results show that our proposed nonlinear receiver with optimized chaotic sequences outperforms in comparison to other conventional detectors such as single-user detector, decorrelating detector and minimum mean square error detector, particularly for under-loaded CDMA condition, which the number of active users are less than processing gain.

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