Paper

Channel Identification Using Chaos for an Uplink/Downlink Multicarrier Code Division Multiple Access System

Miloud Frikel, Said Safi, Boubekeur Targui, and Mohammed M'Saad

Abstract—A scheme of chaotic spreading sequence for multicarrier code division multiple access system (MC-CDMA) is proposed to estimate the transmission channel. This system spreads spectrum and identifies the channel, simultaneously. The proposed scheme uses a chaotic sequence generated by a logistic map as a training signal and estimate channel parameters according to dynamics of the chaotic sequence. Encoding data by chaotic sequences is first built and then the orthogonal codes are used to spread the encrypted data for multiusers scheme. At the reception, first the channel parameters are identified using a training chaotic sequence in order to equalize the received data, and then the encrypted information is decoded for the desired user. The studies reveal that the proposed system (chaos plus orthogonal codes) significantly outperforms the Walsh-Hadamard code spreading in MC-CDMA system. The performance of the system is considered in the multiuser case by means of simulation. The simulation result shows that the proposed chaotic code spreading approach for channel identification achieves significant improvement in the channel identification, comparing to using others training sequence or the least square method.

Keywords—channel identification, chaos code, equalization, MC-CDMA system.

1. Introduction

The chaotic signals have some properties such as broadband, orthogonality and complexity aspects, which motivate researches in the area of communication and signal processing to investigate if chaos based communication offers advantages over classical communication systems in the last years.

Potential applications of chaos resulting directly from those aspects are spread-spectrum, multiuser communication, and cryptography [1]–[4]. In chaotic communications, a chaotic sequence is transmitted through the transmission channel [5]. If the channel is not ideal, which is often the case in practice, the transmitted signal is corrupted before it reaches the receiver. Hence, channel equalization is required to reduce the bit error rate of the receiver as small as possible.

In many practical cases, channel parameters are unknown. Hence, channel equalization must be performed from the corrupted signal alone, and this is called the blind channel equalization [6], [7]. In classical communication systems, most of the channel equalization algorithms are based on the statistical properties of the transmitted signal [8]. However, since a chaotic sequence is a deterministic signal, the statistics-based equalization techniques will not achieve optimum estimation accuracy for chaotic communication systems because they do not take into account the inherent properties specific to a chaotic signal. Various chaotic blind identification and equalization techniques based on different properties of the transmitted chaotic signal have been developed recently [9].

The multicarrier code division multiple access (MC-CDMA) system is based on the combination of code division multiple access (CDMA) and orthogonal frequency division multiplexing (OFDM) [10]–[13] which is potentially robust to channel frequency selectivity. Furthermore, it has good spectral efficiency, multiple access capability and it's easy to be implemented with fast Fourier transform (FFT). For the scheme based on a combination of CDMA and multicarrier technique spreads the original data stream over different subcarriers using a spreading code in the frequency domain [14]. Indeed, in the past decade, there is growing need for technological innovations to satisfy the increase demand for personal wireless radio communications. This technology must be able to allow users to efficiency share common resources, whether it involves the frequency spectrum and computational load. That is why the MC-CDMA [14], the one of representative of the multicarrier techniques, has been considered as a promising system for the next generation of wireless communication. One large advantage of this technology is its robustness in case of multi-path propagation, and it's capable to combat frequency selective fading, flexible to generate different data rates and provides bandwidth efficiency [12].

Multicarrier systems are very sensitive to synchronization errors such as carrier frequency offset and phase noise. Synchronization errors cause loss of orthogonality among subcarriers and considerably degrade the performance especially when large number of subcarriers presents. There have been many approaches on synchronization algorithms in literature [15]–[17]. MC-CDMA designed for multiusers using the same channel, so the problem of channel identification appears, in this paper we propose to encode chaotically data before its spreading in order to use this sequence for system identification.

2. Time and Frequency Domain MC-CDMA System Description

In order to transmit data of a large number of users, the frequency band should be, optimally, used. The objective is to transmit, in simultaneous over the same channel the maximum of information, so the use of multiplexing. Indeed, in CDMA [15], the users have access, in the same time, to the totality of the frequency band, in the receiver, to distinguish between them, we use a different codes affected for each user. That was possible thanks to the technique of spectral spreading, in condition that the emitted signals by different users have some proprieties allowing them to separate.

In opposition of the other techniques of multi-access such frequency division multiple access (FDMA) and time division multiple access (TDMA), where the capacity of the number of users is limited by the frequency and time resources, respectively, the number of users in CDMA is fixed by the proprieties of used spreading codes [18]. That is why the CDMA is an alternative to the others multiplexing techniques to increase the re-use frequency factor and eventually the spectral efficiency of communication systems. A different approach to further increase the system capacity without allocating additional frequency spectrum is the use of code multiplexing.

The MC-CDMA modulator spreads the data of each user in frequency domain (we consider a binary phase shift keying (BPSK) data), the complex symbol g_j of each user j is, firstly, multiplied by each chips $c_{j,k}$ of spreading code SC_j, and then applied to the modulator of multicarriers. Each subcarrier transmits an element of information multiplied by a code chip of that subcarrier.

We consider, for example, the case where the length L_c of spreading code is equal to the number N of subcarriers. The optimum space between two adjacent subcarriers is equal to inverse of duration T_c of chip of spreading code in order to guarantee the orthogonality between subcarriers. The MC-CDMA signal is given by

$$s(t) = \sum_{k=0}^{N-1} a_k c_{m,k} e^{2i\pi f_k t}\,, \qquad (1)$$

where m is the user number.

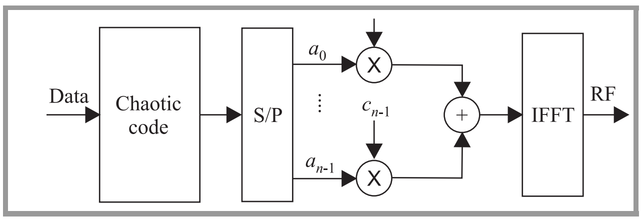

Fig. 1. Chaotic MC-CDMA transmitter. Explanation: S/P – serial/parallel.

We consider the channel invariant in time and characterized by P paths of magnitudes β_p and phase θ_p. The impulse response is given by

$$h(\tau) = \sum_{p=0}^{P-1} \beta_p e^{i\theta_p} \delta(\tau - \tau_p)\,.$$

The relationship between the emitted signal $s(t)$ and the received signal $r(t)$ is given by

$$r(t) = h(t) * s(t) + n(t)\,,$$

where $*$ is the convolution product and $n(t)$ is the additive white Gaussian noise (AWGN):

$$\begin{aligned} r(t) &= \int_{-\infty}^{+\infty} \sum_{p=0}^{P-1} a_k \beta_p e^{i\theta_p} \delta(\tau - \tau_p) s(t-\tau) d\tau + n(t) \\ &= \sum_{p=0}^{P-1} a_k \beta_p e^{i\theta_p} s(t-\tau) + n(t)\,, \qquad (2) \end{aligned}$$

where P is the number of paths.

The transmitter of the MC-CDMA scheme using both time domain and frequency domain is shown in Fig. 1.

The discrete chaotic sequence is: $\chi = [a_0,\ a_1,\ \ldots,\ a_{N-1}]$, where N is the chaotic sequence duration.

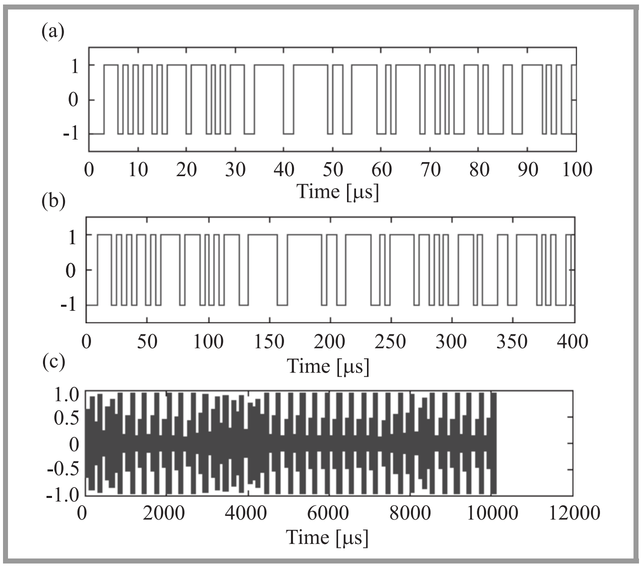

Fig. 2. Binary phase shift keying data (a), spreaded by the Walsh-Hadamard code (b), and by the chaotic code (c).

In Fig. 2, we represent an example of BPSK data spread by the Walsh-Hadamard code and by the chaotic code. In the following equation we represent an example of the Walsh-Hadamard code C (e.g., for four users):

$$C = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}.$$

In a system of M users the emitted signal through a channel is given by

$$s(t) = \sum_{m=0}^{M-1}\sum_{k=0}^{N-1} a_m[k] c_{m,k} e^{2i\pi f_k t} . \tag{3}$$

The received signal after passing through the channel is:

$$r(t) = \sum_{m=0}^{M-1}\sum_{p=0}^{P-1}\sum_{k=0}^{N-1} a_m[k]\beta_p e^{i\theta} g_{m,k} c_{m,k} e^{2i\pi(f_0+k/T_s)} \times \delta(t-\tau_p) + n(t) . \tag{4}$$

At the reception, we demodulate the signal according to N subcarriers, and then we multiply the received sequence by the code of the desired user (Fig. 3). Equalization is, then, applied to estimate the frame $g_{m,k}$.

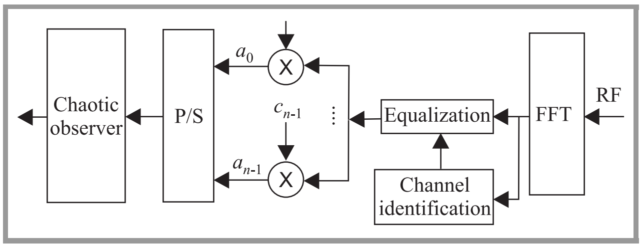

Fig. 3. Chaotic MC-CDMA receiver.

When there are M active users, the received signal is:

$$r(t) = \sum_{m=0}^{M-1}\sum_{k=0}^{N-1} h_{m,k} c_m[k] a_m[k] \cos(2\pi f_c t + 2\pi k \frac{F}{T_b} t + \theta_{m,k}) + n(t) , \tag{5}$$

where the effects of the channel have been included in $h_{m,k}$ and $\theta_{m,k}$, $n(t)$ is AWGN with a one-sided power spectral density of N_0.

We assume that $m = 0$ corresponds to the desired signal. With this model, there are N matched filters with one matched filter for each subcarrier. The output of each filter contributes one component to the decision variable, ϑ_0. Each matched filter consists of an oscillator with a frequency corresponding to the frequency of the particular BPSK modulated subcarrier that is of interest and an integrator. In addition, a phase offset equal to the phase distortion introduced by the channel, $\theta_{m,k}$, is included in the oscillator to synchronize the receiver to the desired signal in time.

To extract the desired signal's component, the orthogonality of the codes is used. For the kth subcarrier of the desired signal, the corresponding chip, $c_0[k]$, from the desired user's code is multiplied with it to undo the code. If the signal is undistorted by the channel, the interference terms will cancel out in the decision variable due to the orthogonality of the codes. As the channel will distort the subcarrier components, equalization gain, $g_{0,k}$, may be included for each matched filter branch of the receiver.

Applying the receiver model to the received signal given in Eq. (4) yields the following decision variable for the kth data symbol assuming the users are synchronized in time:

$$\vartheta_0 = \sum_{m=0}^{M-1}\sum_{k=0}^{N-1} h_{m,k} c_m[k] a_m[k] \frac{2}{T_b} \int_{kT_b}^{(k+1)T_b} \cos\left(2\pi f_c t + 2\pi k \frac{F}{T_b} t + \theta_{m,k}\right) \cos\left(2\pi f_c t + 2\pi k \frac{F}{T_b} t + \widehat{\theta}_{0,k}\right) dt + \eta , \tag{6}$$

where $\widehat{\theta}_{0,k}$ denotes the receiver's estimation of the phase at the kth subcarrier of the desired signal and the corresponding AWGN term, η is given as

$$\eta = \sum_{k=0}^{N-1} \int_{kT_b}^{(k+1)T_b} n(t) \frac{2}{T_b} \cos(2\pi f_c t + 2\pi k \frac{F}{T_b} t + \widehat{\theta}_{0,k}) dt . \tag{7}$$

Assuming perfect phase correction, $\widehat{\theta}_{0,k} = \theta_{0,k}$, the decision variable reduces to

$$\vartheta_0 = a_0[k] \sum_{k=0}^{N-1} h_{0,k} + \sum_{m=0}^{M-1}\sum_{k=0}^{N-1} a_m[k] c_m[k] c_0[k] h_{m,k} \cos(\widehat{\theta}_{m,k}) + \eta , \tag{8}$$

where $\widehat{\theta}_{m,k} = \theta_{0,k} - \theta_{m,k}$. If $\theta_{0,k}$ and $\theta_{m,k}$ are i.i.d. uniform r.v.'s on the interval $[0, 2\pi]$, then $\widehat{\theta}_{m,k}$ is also uniformly distributed on the interval $[0, 2\pi]$. Note that the decision variable consists of three terms.

The first term corresponds to the desired signal's component, the second corresponds to the interference and the last corresponds to a noise term:

$$\vartheta_0 = \xi_{inf} + \beta_{int} + \eta , \tag{9}$$

where ξ_{inf} and β_{int} are the terms of information and interferences, respectively, defined by

$$\xi_{inf} = a_0[k] \sum_{i=0}^{N-1} h_{0,k}, \tag{10}$$

$$\beta_{int} = \sum_{m=0}^{M-1}\sum_{k=0}^{N-1} a_m[k] c_m[k] c_0[k] h_{m,k} \cos(\widehat{\theta}_{m,k}),$$

$$\eta = \sum_{k=0}^{N-1} \int_{kT_b}^{(k+1)T_b} n(t) \frac{2}{T_b} \cos(2\pi f_c t + 2\pi i \frac{F}{T_b} t + \widehat{\theta}_{0,k}) dt .$$

The noise can be approximated by a zero-mean Gaussian random variable with the following variance:

$$\sigma_\eta^2 = N \frac{N_0}{T_b} E[g_{0,k}^2] . \tag{11}$$

3. Chaotic Codes

Chaos based communication systems qualify as broadband systems in which the natural spectrum of the information signal is spread over a very large bandwidth [19]. This class of systems is called spread spectrum communication systems since they make use of a much higher bandwidth than that of the data bandwidth to transmit the information. Nowadays, pseudo-noise sequences such as Gold sequences and Walsh-Hadamard sequences are so far the most popular spreading sequences and have good correlation properties, limited security and can be reconstructed by linear regression attack for their short linear complexity [20]. A chaotic sequence generator can visit an infinite number of states in a deterministic manner and therefore produce a sequence which never repeats itself [4].

There is the flexibility in choosing the spreading gain as the sequences can be truncated to any length. The search for the best set of codes contributing reduced multiple access interference (MAI) is still one of the severe requirements of future MC-CDMA systems.

This chaotic spreading code is used before the use of an orthogonal code for multiuser transmission. These chaotic and Walsh-Hadamard codes have produced good result in utility and reducing MAI [21].

A single system described by its discrete chaotic map can generate a very large number of distinct chaotic sequences, each sequence being uniquely specified by its initial value [22]. This dependency on the initial state and the nonlinear characteristic of the discrete map make the MC-CDMA system highly secure. A chaotic map is a dynamic discrete-time continuous-value equation that describes the relation between the present and next value of chaotic system. Let x_{n+1} and X_n be successive iterations of the output x and M is the forward transformation mapping function. The general form of multidimensional chaotic map is $x_{n+1} = M(x_n, x_{n-1}, ..., xn - m)$. A simple logistic map is given in the following equation:

$$x_{n+1} = \mu(1 - x_n)x_n \tag{12}$$

and $1 \leq \mu \leq 4$, where μ is the bifurcation parameter and the system exhibits a great variety of dynamics depending on the value of μ $(3.6 \leq \mu \leq 6)$.

In Fig. 4 we represent logistic map for different constant number μ.

Using logistic map the chaotic spreading sequences for the BPSK system is generated. After assigning different initial condition to each user, the chaotic map is started with the initial condition of the intended receiver and iterated repeatedly to generate multiple codes.

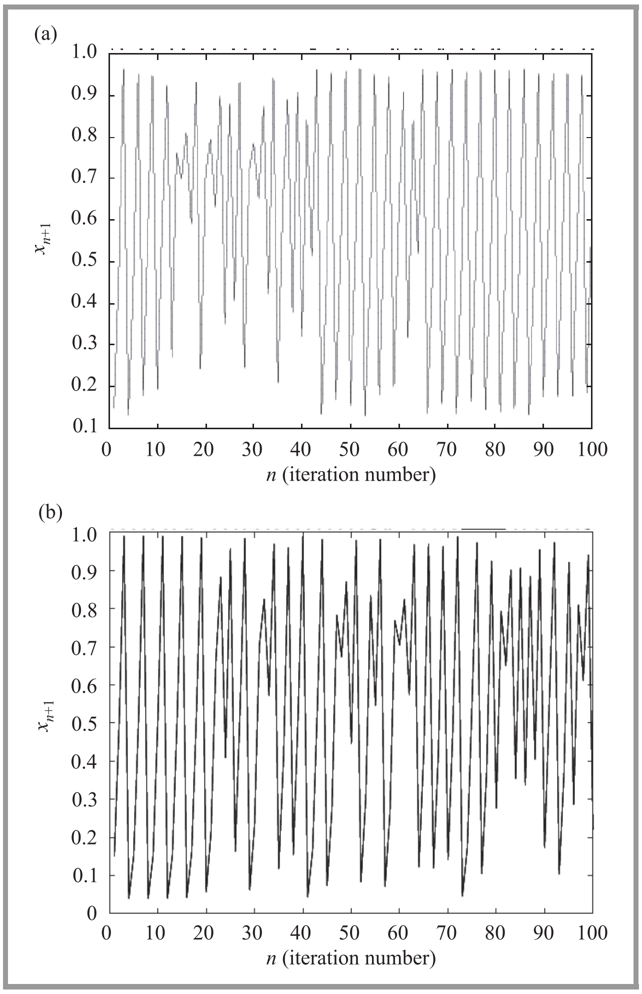

Fig. 4. The logistic map for (a) $\mu = 3.86$ and $x_0 = 0.15$, and (b) $\mu = 3.96$ and $x_0 = 0.15$.

4. Channel Identification Using Chaos

The goal of the equalization techniques is to reduce the effect of the fading and the interference while not enhancing the effect of the noise on the decision of what data symbol was transmitted. Whenever there is a diversity scheme involved, it may involve receiving multiple copies of a signal from time, frequency or antenna diversity, the field of classical diversity theory can be applied. These equalization techniques may be desirable for their simplicity as they involve simple multiplications with each copy of the signal. However, they may not be optimal in a channel with interference in the sense of minimizing the error under some criterion.

Before the equalization, the receiver estimates the channel parameters using a chaotic sequence χ of length N as a training sequence, we assume that the channel is invariant during a time T_p.

The information term is then given by

$$\mathbf{h} = \chi^{-1} r(t). \tag{13}$$

To simplify the formulation, we consider one user in this system, instead of $h_{m,k}$ we use h_k, the same with the equalizer parameters $g_{m,k}$; so $\mathbf{h} = \{h_0, h_1; h_2; \cdots; h_{N-1}\}^T$ and $r(t)$ is the received data from the chaotic sequence transmitted. We suppose that the receiver knows the transmitted chaotic sequence χ by the transmitter based on the model of logistic map Eq. (12). It is shown, from Eq. (13), that the channel parameters can be easily estimated. So the equalization term using equal gain combining (EGC) is given by

$$g_k = \frac{h_k^*}{|\, h_k \,|^2}.$$

The information is then equalized, from Eq. (10) we have:

$$\xi_{inf} = a_m \sum_{k=0}^{N-1} h_k g_k. \tag{14}$$

This technique does not attempt to equalize the effect of the channel distortion in any way. This technique may be desirable for its simplicity as the receiver does not require the estimation of the channel's transfer function. Using this scheme, the decision variable of Eq. (9) is given as

$$\vartheta_0 = \xi_{inf}^{egc} + \beta_{int}^{egc} + \eta^{egc} \tag{15}$$

with $\xi_{inf}^{egc} = a_m$ and $\beta_{int}^{egc} = \sum_{m=1}^{M-1} a_m[k] c_m[k] c_0[k] \cos(\widehat{\theta}_{m,k})$, where the noise can be approximated by a zero-mean Gaussian random with a variance of: $\sigma_\eta^2 = N\frac{N_0}{T_b}$.

5. Theoretical Analysis

5.1. Uplink Transmission

We analyze bit error rate (BER) of the proposed chaotic MC-CDMA system. We have calculated the theoretical BER for the classical equalizer EGC.

Below, some of the theoretical performance results obtained are given:

$$\sigma_{\beta int}^2 = (M-1)\overline{P}_m \text{ (variance of interferences)}$$

and

$$\sigma_\eta^2 = N\,\frac{N_0}{T_b} \text{ (variance of noise).}$$

We have the general form of BER [14] :

$$BER = \frac{1}{2}\text{erfc}\left(\frac{0.5(\sum_{k=0}^{N-1} h_k g_k)^2}{\sigma_{\beta int}^2 + \sigma_\eta^2}\right)^{1/2}. \tag{16}$$

In the case of EGC we have :

$$BER = \frac{1}{2}\text{erfc}\left(\frac{\frac{1}{2}(\sum_{k=0}^{N-1} h_k)^2}{(M-1)\overline{P}_m + N\frac{N_0}{T_b}}\right)^{1/2}. \tag{17}$$

The objective is to find an approximation of $h = \sum_{k=0}^{N-1} h_k$.

In the limiting case of a large number of subcarriers, $\left(\sum_{k=0}^{N-1} h_k\right)$ can be approximated by the law of large number (LLN) to be the constant $NE[h_k]$. The advantage of using the LLN is that it requires low computational complexity. Using the LLN simplifies the expression for the probability of error to [14]:

$$N \text{ is large} \Longrightarrow \gamma_0 = \sum_{k=0}^{N-1} h_k \simeq NE[h_k],$$

$$BER = \frac{1}{2}\text{erfc}\left(\frac{\frac{1}{2}N^2 E^2[h_k]\,T_b}{(M-1)\overline{P}_m T_b + NNN_0}\right)^{1/2},$$

$$BER = \frac{1}{2}\text{erfc}\left(\frac{\frac{\pi}{4}N\,SNR}{(M-1)\,SNR + N}\right)^{1/2}, \tag{18}$$

where N is the number of subcarriers and M is the number of users.

5.2. Downlink Transmission

Transmissions in the downlink, i.e., the transmission from the base station to the terminals through the same channel.

In this section, we'll use the notation of Eq. (8), and we assume perfect phase correction for interference. The generalized decision variable given in Eq. (8), simplifies to

$$\vartheta_0 = a_0[k] \sum_{k=0}^{N-1} h_k g_k + \sum_{m=0}^{M-1}\sum_{k=0}^{N-1} a_m[k] c_m[k] c_0[k] h_k g_k + \eta\,.$$

The used codes are orthogonal and the product, $c_{k,i}c_{k,j}$ is, then, equal to 1 with the probability $1/2$ and -1 with the same probability for $i \neq j$:

$$\begin{aligned}\vartheta_0 &= a_0[i] \sum_{k=0}^{N-1} h_k g_k \\ &\quad + \sum_{m=0}^{M-1} a_m[k] \left(\sum_{k=0}^{N/2-1} h_k g_k - \sum_{k=0}^{N/2-1} h_k g_k\right) + \eta.\end{aligned} \tag{19}$$

6. Performance Analysis

In this section, the approximations for the BER using the LLN is evaluated numerically. Using the expressions for the BER obtained for uplink transmissions in a Rayleigh fading channel, the average BER versus the number of co-channel interferers with a spreading factor $N = 128$ is shown in Fig. 5. To calculate the BER, it is assumed that the local-mean power of each interferer is equal to the local-mean power of the desired signal. The signal-to-noise ratio (SNR), which is assumed to be 10 dB, is defined as

$$SNR = \frac{\overline{p}_0 T_b}{N_0},$$

where $\overline{p}_0$ is the power of each user supposed equal for all users.

From Fig. 5, we remark that we have, approximately, the same BER results if we use both codes such as: orthogonal

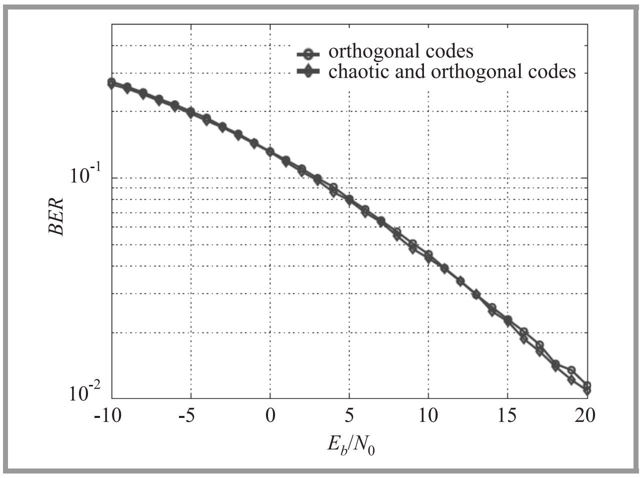

Fig. 5. Simulated BER of equalizers for chaotic MC-CDMA system.

code and chaotic code, comparing to the results obtained if we use only the orthogonal code. This result is very interesting because the use of the chaotic code allows first channel identification and this transmission is more secure than the classical MC-CDMA as combine both the Walsh-Hadamard and the chaotic codes.

7. Conclusion

Channel identification of a digital modulation technique MC-CDMA was proposed. This technique is based on the use of the chaotic sequence as a pilot frame. In fact, the chaotic code given by a nonlinear system (in this paper we have used the logistic map but other chaotic's systems could be used such Hénon map, Róssler map, Lyapunov fractal, Horseshoe map, ...) is known by the transmitter and the receiver. These codes are very sensitive to the initial conditions, so security depends on difficulty in finding these parameters.

The EGC equalization technique was used after the channel identification to correct the channel's distortion. The performance of this technique, gauged by the average bit error rate, was analytically and numerically evaluated. It is demonstrated that the performance of MC-CDMA system employing chaotic binary sequences can be superior to that for conventional codes in terms of bit error probabilities.

References

[1] S. Papadimitriou, T. Bountis, S. Mavaroudi, and A. Bezerianos, "A probabilistic symmetric encryption scheme for very fast secure communications based on chaotic systems of difference equations", *Int. J. Bifurc. Chaos*, vol. 11, pp. 3107–3115, 2001.

[2] N. K. Pareek, V. Patidar, and K. K. Sud, "Discrete chaotic cryptography using external key", *Phys. Lett. A*, vol. 309, pp. 75–82, 2003.

[3] A. T. Parker and K. M. Short, "Reconstructing the keystream from a chaotic encryption scheme", *IEEE Trans. Circ. Syst.*, vol. 48, pp. 624–630, 2001.

[4] V. Stefano and S. Gianluca, "Improving PA efficiency by chaos based spreading in MC/DS-CDMA systems", in *Proc. IEEE ISCAS Conf.*, Kos, Greece, 2006, pp. 1195–1198.

[5] A. Abel and W. Schwarz, "Chaos communication-principles schemes and system analysis", *Proc. IEEE*, vol. 90, no. 5, pp. 691–710, 2002.

[6] S. Kaiser, "Multi-carrier CDMA mobile radio system-analysis and optimization of detection, decoding, and channel estimation", Ph.D. thesis, University of Munich, Germany, 1998.

[7] S. Safi, M. Frikel, M. M'Saad, and A. Zeroual, "Blind impulse response identification of frequency radio channels: application to BRAN a channel", *Int. J. Sig. Proc.*, vol. 4, no. 1, pp. 201–206, 2007.

[8] S. Safi and A. Zeroual, "Blind parametric identification of linear stochastic non-Gaussian FIR systems higher order cumulants", *Int. J. Syst. Sci.*, vol. 35, no. 15, pp. 855–867, 2004.

[9] W. Xingang, M. Zhana, G. Xiaofeng, L. Heng, and L. Ying-Cheng, "Spread-spectrum communication using binary spatiotemporal chaotic codes", *Phys. Lett. A*, vol. 334, pp. 30–36, 2005.

[10] "Broadband Radio Access Networks (BRAN); High Performance Radio Logical Area Network (HIPERLAN) Type 2: Requirements and architectures for wireless broadband access", ETSI, TR 101 031 V2.2.1 (1999–01).

[11] "Broadband Radio Access Networks (BRAN); HIPERLAN Type 2; Physical (PHY) layer", ETSI, TS 101 475 V1.3.1 (2001–12).

[12] F. Horlin, S. De Rore, E. Lopez-Estraviz, F. Naessens, and L. Van der Perre, "Impact of frequency offsets and IQ imbalance on MC-CDMA reception based on channel tracking", *IEEE J. Select. Areas Commun.*, vol. 24, no. 6, pp. 1179–1188, 2006.

[13] K. Fazel and L. Papke, "On the performance of convolutionnally-coded CDMA/OFDM for mobile communication system", in *Proc. IEEE Int. Symp. Pers. Ind. Mob. Radio Commun. PIMRC'93*, Berlin, Germany, 1993, pp. 468–472.

[14] N. Yee, J. M. G. Linnartz, and G. Fettweis, "Multi-carrier-CDMA in indoor wireless networks", in *Proc. IEEE Int. Symp. Pers. Ind. Mob. Radio Commun. PIMRC'93*, Yokohama, Japan, 1993, pp. 109–113.

[15] J. M. G. Linnartz, "Performance analysis of synchronous MC-CDMA in mobile Rayleigh channel with both delay and Doppler spreads", *IEEE Trans. Veh. Technol.*, vol. 50, no. 6, 2001, pp. 1375–1387.

[16] M. Frikel, B. Targui, M. M'Saad, and F. Hamon, "Bit error rate analysis of the controlled equalization for MC-CDMA", in *IEEE ICSPC'07 Conf.*, Dubai, United Arab Emirates, 2007.

[17] S. Kaiser, "OFDM-CDMA versus DS-CDMA: performance evaluation for fading channels", in *Proc. IEEE Int. Conf. Commun.*, Seattle, USA, 1995, pp. 1722–1726.

[18] D. Mottier and D. Castelain, "SINR-based channel pre-equalization for uplink multi-carrier CDMA systems", in *Proc. IEEE Int. Symp. Pers. Ind. Mob. Radio Commun. PIMRC'02*, Lisbon, Portugal, 2002, pp. 1488–1492.

[19] S. Azou, G. Burel, and C. Pistre, "A chaotic direct-sequence spread-spectrum system for underwater communication", in *Proc. OCEANS'02 MTS/IEEE Conf.*, Biloxi, USA, 2002, vol. 4, pp. 2409–2415.

[20] C. Ling and S. Li, "Chaotic spreading sequences with multiple access performance better than random sequences", *IEEE Trans. Circ. Syst. I Fund. Theory Appl.*, vol. 47, no. 3, pp. 394–397, 2006.

[21] S. L. Georgoulis and D. G. M. Cruickshank, "Transmitter-based inverse filters for reducing MAI and ISI in CDMA-TDD downlink", *IEEE Trans. Wirel. Commun.*, vol. 3, no. 2, pp. 353–358, 2004.

[22] M. P. Kennedy, R. Rovatti, and G. Setti, "Chaotic electronics in telecommunications", in *Proc. CRC Conf.*, Boca Raton, USA, 2000.

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