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Improving PA Efficiency by Chaos-Based Spreading in Multicarrier DS-CDMA Systems

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***Abstract*— In this paper, we investigate the effect of spreading sequences on the peak-to-average power ratio (PAPR) in order to improve the power amplifier efficiency of multicarrier direct-sequence code-division multiple access systems. Baseband shaping has been identified to have a key role in reducing PAPR by spreading and we have found that chaos-based spreading sequences give good results as compared with Gold and i.i.d. sequences behaving differently depending on the number of subcarriers.**

I. Introduction

Code-division multiple access (CDMA) is widely used in modern third-generation (3G) cellular systems. Recently, there has been a great interest in using multicarrier (MC) modulation combined with CDMA in order to explore diversity and interference suppression and to support high data rate services over hostile radio channels.

MC-CDMA systems employ both orthogonal frequency division multiplexing (OFDM) and CDMA. Multicarrier direct-sequence CDMA (MC-DS-CDMA) combines time-domain spreading and multicarrier modulation by allowing each user to serial-to-parallel convert and spread over time its input data stream before modulating the orthogonal carriers. MC-DS-CDMA signals are characterized by an high peak-to-average power ratio (PAPR) thus implying a trade-off between linearity and efficiency in the transmitter power amplifier (PA).

A huge number of contributions have been devoted to the solution of the high PAPR problem in MC-DS-CDMA and similar systems. The most part of solutions is based on a deterministic approach (see [1]–[3] and references therein) but also statistical methods have been investigated [4]. In this work we aim at analyzing the effect of spreading sequences on the PAPR level by computer simulations. The key point is that for MC-DS-CDMA systems, spreading chips affect the PAPR if baseband shaping filter is considered. In fact, when each chip extends its influence beyond the chip duration the statistical properties of a sequence may affect the signal envelope.

Chaos-based sequences are able to offer a variety of statistical features that, for example, have been employed widely to reduce interference due to multiple access in asynchronous systems. We here investigate their use for the control and reduction of PAPR in the output signal of each transmitter.

The paper is organized as follows: the MC-DS-CDMA system model is described in section II, chaos-based spreading sequences used in the system are introduced in section III, the system performance merit figures useful for performance evaluation and comparisons are defined in section IV, finally simulation parameters and simulation results and comments are given in section V.

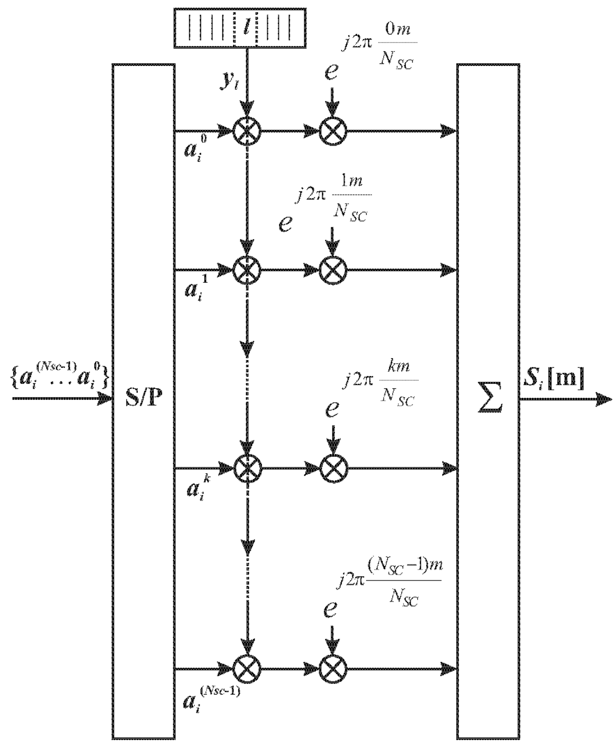

Fig. 1. MC-DS-CDMA baseband transmitter model

II. System model

Since we are evaluating PA performance, we will consider the MC-DS-CDMA transmitter and the uplink scenario.

A. MC-DS-CDMA baseband modulator

Figure 1 shows the baseband transmitter model. Information bits are converted into complex information symbols by means of some constellation mapper. Symbols are then passed through a series-to-parallel (S/P) converter and a *multisymbol* is built from N_{sc} input symbols $a_i^0 ... a_i^k ... a_i^{N_{sc}-1}$ where i denotes the i-th group of N_{sc} symbols at the S/P input.

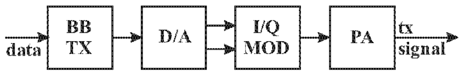

Fig. 2. MC-DS-CDMA complete transmitter model

Each multisymbol element is spreaded using the same N_c-chip spreading sequence with $y_l \in \{-1, 1\}$ denoting the l-th chip and $y_{l+N_c} = y_l$. After this, each chip is multiplied by a *subcarrier*, that is an N_{sc}-point complex exponential $e^{j2\pi \frac{k}{N_{sc}} m}$ where $0 \leq k \leq N_{sc} - 1$ is the symbol index within a multisimbol and m is the discrete-time index. A final sum is performed over all the subcarriers and the complex baseband output sample $S_i[mT_0]$ is produced where T_0 is the baseband sample time. The baseband system is substantially an OFDM system in which symbols are spreaded before performing the N_{sc}-point IFFT. The subcarrier frequency separation Δf is equal to the chip rate f_c, the system bandwidth is $W = N_{sc} f_c$ and the baseband sample rate f_0 is equal to W. Moreover, $T_0 = T_c/N_{sc} = T_S/N_c$ where T_S is the input symbol duration.

From above, the complex baseband modulated signal is $S[mT_0] = \sum_{i=-\infty}^{\infty} S_i[mT_0]$ where

$$S_i[mT_0] = \sum_{l=0}^{N_c-1} \sum_{k=0}^{N_{sc}-1} \frac{y_l a_i^k}{\sqrt{N_c N_{sc}}} e^{j2\pi \frac{k}{N_{sc}} m} \times r_{T_0}(mT_0 - lN_{sc}T_0 - iN_cN_{sc}T_0) \quad (1)$$

with $r_{T_0}(t) = 1$ for $0 \leq t \leq T_0$ and $r_{T_0}(t) = 0$ elsewhere.

B. MC-DS-CDMA transmitter

Figure 2 shows the complete transmitter model. Complex baseband output samples are converted into analog signals by a digital-to-analog (D/A) converter. A pass-band analog signal is formed by an I/Q modulator and passes through the power amplifier (PA) before being sent to the transmitter antenna.

Since we are evaluating PA efficiency in the transmitter, we can avoid to consider guard intervals in the IFFT.

In order to perform simulations, the baseband shaping filtering is performed by an oversample-and-shape operation using an impulse modulator and a raised cosine filter (RCF). From this, the D/A block in figure 2 will not be simulated. The I/Q modulator block can be omitted because the complex baseband approach can be used instead of the passband one.

The complex baseband signal at the PA input is $S(t) = \sum_{m=0}^{\infty} S[mT_0] g(t - mT_0)$ with $g(t)$ being the RCF impulse response. In the simulator, the discrete-time baseband signal is oversampled (the oversampling rate is $R = T_0/T$) giving $S[nT] = \sum_{m=0}^{\infty} S[mT_0] g(nT - mT_0)$. The PA will not be simulated because we are interested in evaluating signal peaks at the PA input.

The basic idea is that when there is an interference between adjacent chips (i.e. using a shaping filter impulse response different than the rectangular one), chip statistics may affect the signal envelope and may lower the high-peaks occurrence.

C. MC-DS-CDMA receiver

Since the signal corresponding to each carrier is spread of a factor N, more than one transmitter is expected to use the same frequencies at the same time while being distinguished by different spreading codes. The receiver is then in charge of decoding a signal that is the superimposition of the contribution of different transmitter. In the following we will assume that the environment is that of a synchronous link so that simple code orthogonality guarantees complete separation between the useful transmitter and the other. This assumption is at least approximately satisfied by commonly used spreading policies and is also approximately satisfied by the use of chaos-based codes as discussed in the next Section.

III. Chaos-based spreading

Chaos-based spreading sequences having an exponential decaying autocorrelation function have revealed the ability to minimize asynchronous interference in DS-CDMA (direct-sequence CDMA) [5] and multicode DS-CDMA systems [6]. Here we try to evaluate the effect of such sequences on the PA performance. The symbols y_l are taken from the quantization of the trajectory of a discrete time chaotic dynamical system.

Formally speaking we will assume that a state-update function $M : [0, 1] \mapsto [0, 1]$ exists giving rise to the trajectory $x_{k+1} = M(x_k)$ starting from an initial condition x_0.

An initial condition x_l^0 is drawn independently and the corresponding trajectory $x_l^0, \dots, x_l^{N-1}$ is then passed through a quantization function $\mathcal{Q} : [0, 1] \mapsto \mathbb{C}$, mapping the state space into a finite complex alphabet and yielding $y_l^k = \mathcal{Q}(x_l^k)$. In particular we will assume that the quantization yields $y_l^k \in \{-1, +1\}$ so to deal with binary spreading sequences.

Moreover, we will mainly concentrate on a particular family of maps within the class of the so-called PWAM (*PieceWise-Affine Markov*) maps [7] that are well-known to give the degrees of freedom needed to obtain the statistical behaviors in which we are interested. Figure 3 shows such a family of PWAM maps for which $\mathbf{E}[y_i y_j] = \lambda^{j-i}$ if $i < j$ and $\mathbf{E}[y_i y_j y_k y_l] = \lambda^{j-i+l-k}$ if $i \leq j \leq k \leq l$. The antipodal sequences at the quantizer output are charachterized by an exponential decaying second- and fourth-order correlations with the rate of decay λ that may be set arbitrarily to any number in $]-1, 1[$.

Since the above expressions for second- and fourth-order correlation can be generalized to any-order, setting $\lambda = 0$ we are able to produce perfectly binary, uniform, independently identical distributed (i.i.d.) random variables because $\mathbf{E}[y_i y_j] = \delta_{j-i}$, $\mathbf{E}[y_i y_j y_k y_l] = \delta_{j-i+l-k}$, and so on.

In the following, chaos-based codes will be compared with the reference i.i.d. case ($\lambda = 0$) and the more classical Gold codes [8] as far as the efficiency of the PA is concerned.

It is worth to mention that, as far as multiple-access interference is concerned, their optimality has been widely demonstrated in the asynchronous environment, while in the synchronous case their approximate orthogonality is analogous to what is obtained for Gold sequences. In fact, thanks to the exponentially vanishing autocorrelation, two independently

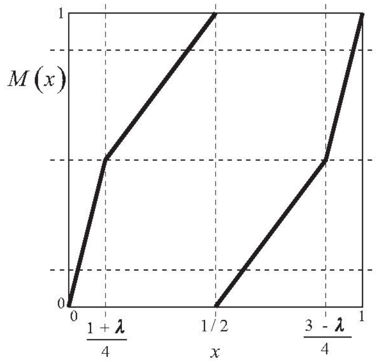

Fig. 3. PWAM family of maps. Statistical features depend on parameter λ.

generated chaos-based sequences have a cross correlation whose average is null and whose variance is $\sigma^2_{cross,chaos} = \frac{1}{N}[1+2\sum_{j=1}^{N-1}(1-\frac{j}{N})\lambda^{2j}]$ As a comparison, Gold sequences feature a cross correlation that, if $N = 2^n - 1$ with n odd, assumes the three values $c_1 = -1/N$, $c_2 = (-1-2^{(n+1)/2})/N$, $c_3 = (2^{(n+1)/2} - 1)/N$. The first value is assumed approximately for one-half of the possible case, while the other two equally share the other half. With this the approximate variance of the cross-correlation between two Gold sequences may be estimated as $\sigma^2_{cross,Gold} = 1/2c_1^2 + 1/4c_2^2 + 1/4c_3^2 = \frac{1}{N}(1+\frac{2}{N})$ that features the same asymptotic trend as $\sigma^2_{cross,chaos}$ for $N \to \infty$, coincides with it for $\lambda = 0$ and is not very far from it since $|\lambda| < 1$. Should this level of performance be deemed insufficient, a subset of truly orthogonal sequences can be sieved starting from a larger set of chaos-based sequences, each of them featuring the proper auto-correlation profile.

IV. System performance merit figures

An important performance figure for PAs is their efficiency, i.e. the ratio between the power they deliver to the load and the power they drain from supply. When amplified signals do not have a constant envelope such both power terms vary in time and efficiency is customarily measured as the ratio between the two averages, i.e. $\eta = \langle P_{out}\rangle / \langle P_{DD}\rangle$ [9]. Assuming that the PA is always working very close to linearity, the output power is proportional to the input power times the square of its small-signal gain, i.e. $P_{out} = \nu^2 |S(t)|^2$ and, on the average, $\langle P_{out}\rangle = \nu^2 \langle |S(t)|^2\rangle$. Since $PAPR = \max\{|S(t)|^2\}/\langle |S(t)|^2\rangle$ we get $\eta = [1/PAPR]\,\nu^2 \max\{|S(t)|^2\}/\langle P_{DD}\rangle$ that highlights how, when the small-signal gain, the maximum input power and the average absorbed power are fixed, the efficiency is inversely proportional to PAPR. From this, an efficiency *gain* can be defined between two systems A and B

$$G_\eta = \frac{\overline{\eta}_B}{\overline{\eta}_A} - 1 = \frac{PAPR_A}{PAPR_B} - 1 \qquad (2)$$

Considering the exact PAPR in the definition of efficiency may be unrealistic since, theoretically, a very high peak in the signal affects such a measure even if it appears in the signal with an extremely low probability. To cope with this,

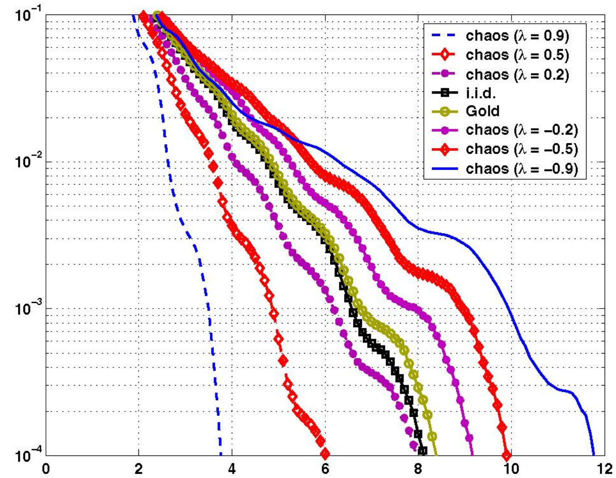

Fig. 4. Simulation results: $CCDF(IAPR)$ curves for a DS-CDMA system (64-QAM) using different families of spreading sequences.

we consider the istantaneous-to-average power ratio (IAPR) $IAPR(t) = |S(t)|^2 / \langle |S(t)|^2\rangle$ and characterize it from a statistical point of view. In fact, following an established path we determine the IAPR complementary cumulative distribution function (CCDF) that is the function $F(x)$ that gives the probability $\Pr\{IAPR > x\}$. Once that this curve is known we may substitute the classical PAPR definition $PAPR = max\{IAPR(t)\} = min\{x|F(x) = 0\}$ with the more realistic estimation $PAPR = min\{x|F(x) < \varepsilon\}$ with ε a certain tolerance assessing the maximum probability of an event that is considered rare enough to be negligible for the functionality of the system. The level of ε may be dictated by higher-level considerations such as the maximum amount of peaks that may be distorted in amplification without impairing proper reception, the maximum frequency of overcurrent in the amplifier, etc. According to this definition, using the reference CCDF value, one can consider the correspondent $IAPR$ values as reference PAPR values and calculate the efficiency gain.

V. Simulation results

A set of Matlab™ routines have been written in order to implement a MC-DS-CDMA system. We have choosen a raised cosine filter impulse response extended over 6 symbol intervals (here *symbol* means the sample before oversampling) with a rolloff factor of 0.22 and an oversampling ratio equal to 8. In order to evaluate the information symbols influence on the IAPR statistics, 64-QAM and BPSK constellation mappers have been selected and systems with a different but small number of subcarriers have been evaluated. Information symbols are generated randomly. The spreading factor have been set to 128 in order to enhance statistical behaviors of spreading sequences without increasing N_c too much. The reference CCDF value for the efficiency gain calculation has been selected to be 10^{-3}.

Figure 4 reports CCDF curves when only 1 subcarrier is present (this system reduces to the DS-CDMA case).

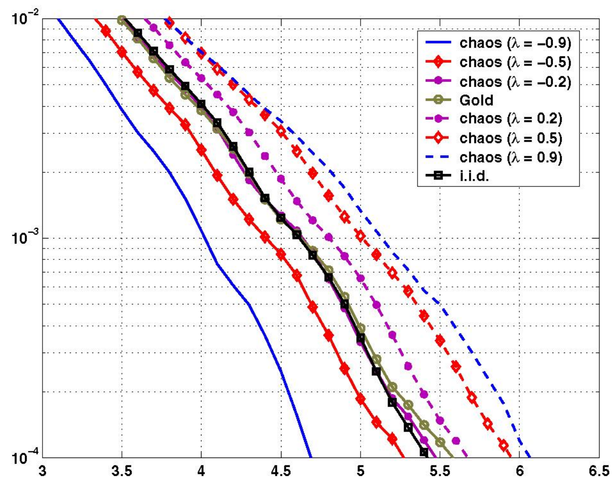

Fig. 5. Simulation results: $CCDF(IAPR)$ curves for a MC-DS-CDMA system (2 subcarriers, 64-QAM).

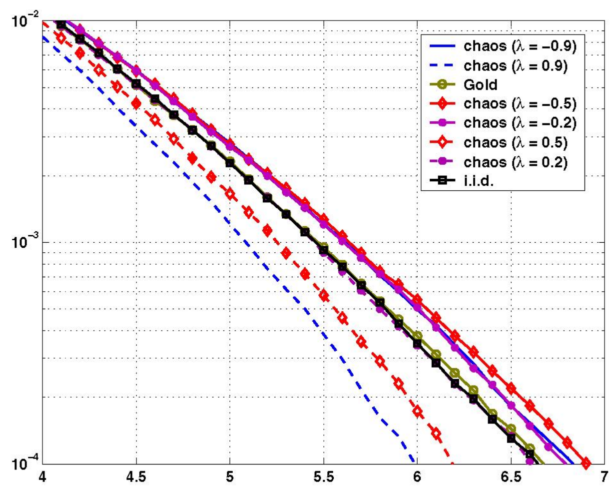

Fig. 6. Simulation results: $CCDF(IAPR)$ curves for a MC-DS-CDMA system (3 subcarriers, 64-QAM).

Spreading sequences with higly positive correlation result in a substantial IAPR reduction. Chaotic sequences with $\lambda = 0.9$ give 88% efficiency gain as compared with i.i.d. sequences. Gold sequences behave like i.i.d. in all our simulations, hence we will use i.i.d. sequences as a reference for efficiency gain estimation. Figure 5 shows CCDF curves when 2 subcarriers are considered. In this case, the result is opposite with respect to the DS-CDMA case. Spreading sequences with higly negative correlation result in IAPR reduction. Figure 6 curves behave like those in figure 4 but the efficiency gain is 10% for chaotic sequences with $\lambda = 0.9$. When an higher number of subcarriers is considered, all CCDF curves tend to the i.i.d. curve and no substantial improvement exists for PA efficiency. In the BPSK modulation case, behaviors are exactly the same even if the IAPR level is lower than that of 64-QAM.
Table I reports the efficiency gain estimations (percentage) for all the cases of interest.

From above, highly positive correlations results in PA efficiency improvement when an odd number of subcarriers is considered. On the contrary, highly negative correlations give an improvement with an even number of subcarriers.

TABLE I

PA EFFICIENCY GAIN $G_\eta\%$ WITH RESPECT TO I.I.D. SEQUENCES

Seq.	1 subc	2 subc	3 subc
chaos ($\lambda = -0.9$)	-33.33	15	-1.79
chaos ($\lambda = -0.5$)	-26.67	4.55	-1.79
chaos ($\lambda = -0.2$)	-16.46	0	-1.79
Gold	-2.94	0	0
chaos ($\lambda = 0.2$)	6.45	-4.17	0
chaos ($\lambda = 0.5$)	37.5	-8	3.77
chaos ($\lambda = 0.9$)	88.57	-9.8	10

VI. CONCLUSION

In this paper, we investigate the effect of spreading sequences on the peak-to-average power ratio (PAPR) in order to improve the PA efficiency of MC-DS-CDMA systems. Baseband shaping has been identified to have a key role in reducing PAPR by spreading and we have found that chaos-based spreading sequences behave differently depending on the number of subcarriers and give good results as compared with Gold and i.i.d. sequences.

ACKNOWLEDGMENT

The authors would like to thank Andrea Ronchiato for his contribution.

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