PAPR Analytical Characterization and Reduced-PAPR Code Allocation Strategy for MC-CDMA Transmissions

Mr Darshan Thakur, a, Prof Sarita Verma b

aPG Student, Marathwada Institute Of Technology, Aurangabad,

bAssociate Professor, Marathwada Institute Of Technology, Aurangabad.

darshanthakur1985@gmail.com, sarita_verma04@yahoo.com

Abstract: In this paper, an approximate analytical expression for the peak-to-average power ratio (PAPR) of a MultiCarrier Code Division Multiple Access (MC-CDMA) signal is derived. Then, it is demonstrated that the PAPR of a MC-CDMA system employing Walsh-Hadamard (WH) codes can be suitably reduced by resorting to a judicious strategy for the allocation of the spreading signature codes. Eventually, a lowcomplexity implementation of the proposed strategy is presented and the relevant benefits, in terms of peak signal occurrence and robustness against nonlinear distortions, is numerically assessed over conventional random allocation strategy.

Key Words: MC-CDMA, PAPR, WH.

1. INTRODUCTION

MULTI-CARRIER (MC) code-division multiple access (CDMA) is a transmission technique offering many appealing properties, such as robustness against multipath fading channels and flexible multiple access capability [1]. However, any MC signal (including MC-CDMA) experiences a high “peak-to-average power ratio” (PAPR), i.e., the peaks of the instantaneous power are much higher than the average power level. Consequently, the signal reveals vulnerable to nonlinear distortions induced by the high power amplifier (HPA) of the transmitter which entail both signal-to-noise ratio (SNR) degradation and out-of-band emission (OBE) [2]. Such a limiting feature spurred a massive research effort aimed at devising efficient techniques for PAPR reduction in MC signals. A comprehensive survey of PAPR reduction techniques for orthogonal frequency-division multiplexing (OFDM) is presented in [3], while the OBE issue is addressed in [4]. Some techniques originally devised for OFDM have been successfully demonstrated to be applicable to MC-CDMA, too, such as the partial transmit sequences (PTS) [5] and the selective mapping (SLM) [6] methods. Both the techniques reveal effective, but require also side information at the receiver and additional processing at the transmitter. In the particular case of MC-CDMA systems, the code-spreading stage, which enables multi-user access, has a twofold importance. i) it makes the analytical characterization of the PAPR more involved; ii) it provides an extra degree of freedom in controlling the PAPR, for instance by carefully selecting the code set among those available from the literature, or by suitably modifying an already existing set, or by designing a completely new code set.

Concerning the former issue, several works focusing on the analytical characterization of the PAPR for MC-CDMA signals in a multi-user context and on its dependence on the spreading signature properties (mainly, code auto- and cross-correlations) have appeared in the literature. However, most of them had to face critical difficulties in the analytical evaluation of signal peak power $P_{\text{max}}$ distribution. To this respect, Choi and Hanzo [7] derived an analytical upper-bound of the crest factor (CF) for a MC-CDMA system using complementary (CP) codes, to be employed as a criterion for the selection of the lowest-PAPR code set. However, such a method is applicable to MC-CDMA systems with binary phase shift keying (BPSK) modulation and 2 or 4 codes, only. Furthermore, in [8] it is demonstrated that an accurate estimate of the PAPR for a MC-CDMA signal cannot be achieved by resorting to simplistic upper-bound approaches. So, a more accurate characterization of the PAPR distribution shall be obtained by means of a statistical approach. For instance, a closed-form approximation for the PAPR distribution, based on the level-crossing rate analysis, is derived in [9] for OFDM, but, up to date and to the best of authors’ knowledge, no simple and reliable analytical tool for the evaluation of the PAPR of a MC-CDMA signal is available in the literature.

In the present work, we focus on the downlink transmission, i.e. from base station (BS), to mobile stations (MSs), of a wireless MC-CDMA network, with a twofold aim. i) to derive a manageable closed-form expression of the PAPR distribution for a generic code set, by resorting to a statistical approach, instead of inaccurate upper-bounds. [8] ii) to derive a judicious and low-complexity, code allocation strategy, applicable
to WH codes, which does not require any modification to the transmitter, nor to the receiver, and does not require any additional side information to be sent to the receiver. Based on the analytical PAPR characterization, we derive then a “PAPR metric”, as a function of the auto and cross-correlations of the WH codes, and we demonstrate that it is quasi-monotonically related to the PAPR value, so as to play the role of a “cost function” to be minimized [20]. Furthermore, we derive a low complexity allocation strategy for the spreading signatures, based on an incremental-search algorithm, applicable to the Walsh-Hadamard (WH) set [20], which reduces the PAPR metric and yields improved PAPR performance. The complexity of the proposed search method is also numerically evaluated and compared with that of the exhaustive search approach. Eventually, the benefits provided by the proposed allocation strategy are assessed in terms of statistical distribution of PAPR and signal distortion at the output of the transmitter HPA.

2. SYSTEM DESCRIPTION

Let consider the down-link of a MC-CDMA system connecting the BS to $N_u$ MSs. The $n$th information-bearing symbol $a_n^{(k)}$ of the $k$th user ($1 \leq k \leq N_u$) runs at rate $1/T_u$, and belongs to a $M$–QAM constellation with $E\{a_n^{(k)}\} = 0$, $E[|a_n^{(k)}|^2] \Delta A_1$, $E[|a_n^{(k)}|^4] \Delta A_2$, and $E[|a_n^{(k)}|^4] \Delta A_4$. Any information symbol is copied into $N$ branches (equal to the number of subcarriers), and each of the $N$ replicated symbols is then multiplied by a different chip of the binary spreading sequence $c_m^{(k)} \in \{\pm 1\}$ ($0 \leq m \leq N-1$), which acts as the user’s channel identification signature. The resulting spreading factor, i.e., the number of replicas of each information symbol transmitted on an OFDM block, is thus coincident with the number of subcarriers $N$. The spread data $a_n^{(k)} c_m^{(k)}$ of all the $N_u$ active users are then summed together, and subsequently mapped to the $N$ available subcarriers by IFFT (Inverse Fast Fourier Transform) unit. A cyclic prefix of $L$ samples is inserted at the beginning of each IFFT output block to produce a ($N+L$)-sized block containing the samples.

$$b_i = \frac{1}{\sqrt{N}} \sum_{k=1}^{N_u} \sum_{m=0}^{N-1} a_n^{(k)} c_m^{(k)} e^{j2\pi m l / N}, \quad -L \leq l \leq N-1. \quad (1)$$

A common way of generating continuous-time MC signals consists in resorting to oversampled FFT [22]. Such a method works in the time-discrete domain and is simple yet effective. Its main drawback, however, is that it produces a considerable spreading in the frequency domain. Indeed, without any pulse shaping, the out-of-band PSD components decay slowly according to a “sinc”–shaped function, and even far away from the edge of the nominal bandwidth, the amplitude of the side lobes is still sizeable. As a result, the actual spectral occupancy of the MC signal, and so its sensitivity to the distortions induced by the nonlinear amplifier, gets large and inevitably the system efficiency degrades. A possible approach to skip this limit is to resort to pulse shaping, as for instance through root-raised cosine filtering [23]. That way, the PSD turns out to be more concentrated if compared with conventional shaping, and therefore, the effect of bandwidth expansion due to intermodulation as well as the level of the resultant ISI and ICI are mitigated. According to such an embodiment, the MC-CDMA signal at the output of the transmitter shaping filter results then

$$s(t) = \sum_n \sum_{l=-L}^{N+L} b_i(t-nT_s-lT_c), \quad (2)$$

where $T_c \Delta T_s/(N+L)$ and $T_c$ are the chip and the OFDM block interval, respectively. Also, $g_c(t)$ is a $T_c$-energy root-raised-cosine (RRC) pulse with roll-off $\alpha_c$, and Fourier transform $G_c(f) \Delta \sqrt{T_c}G_n(f)$, where $G_n(f)$ is the Fourier transform of a $T_c$-energy raised-cosine (RC) pulse (“Nyquist pulse”) $g_S(t)$. In the generic $n$th block interval $nT_s - LT_c \leq t < nT_s + NT_c$, the MC-CDMA signal at the output of the transmitter filter can be expressed as

Volume 2 • Issue 1

D2

March 2013
The transmitter HPA is a solid-state power amplifier (SSPA) which is modeled as a nonlinear memoryless device with normalized amplitude and phase characteristics [1]

\[ M(\rho) = \rho/(1 - \rho^q)^{1/q}, \quad \Phi(\rho) = 0 \]  

respectively, where \( \rho(t) \Delta h_0 \mid s(t) \mid \) is the instantaneous amplitude of the signal at the HPA input, \( h_0 \) is the input back-off (IBO), and \( q \) is an integer value which controls the smoothness of the transition between the linear and the saturation regions. Since the interest here is on the performance evaluation in the presence of nonlinear distortions caused by the HPA, system performance will be evaluated over a stationary additive white Gaussian noise (AWGN) channel.

3. PAPR ANALYSIS

The PAPR of the signal which enters the HPA, evaluated over the \( n_{th} \) block interval

\[ I_{nT_s-LT_s, nT_s+nT_c} \]

is

\[ \text{PAPR} = P_{\text{max}}/\bar{P}_s, \]  

where \( P_{\text{max}} = \max_{t \in I} \{ \mid s(t) \mid ^2 \} \) is the peak power of \( s(t) \) over \( I \), and \( \bar{P}_s = \int_0^\infty P_s(t) dt / T_s \) is the time-average over \( I \) of the statistical power \( P_s(t) \Delta E[\{ s(t) \}^2] \), which, under the hypothesis \( L << N \), can be approximated as \( \bar{P}_s \approx N_s A_2 \).

3.1 Instantaneous Power

MIMO s Considering the time interval \( J_{nT_s, NT_s+nT_c} \subseteq I \), by replacing (1) into (3), and assuming again \( L << N \), after some algebra (see Appendix A), we obtain

\[ \mid s(t) \mid ^2 \geq \frac{N_s}{N} \sum_{k=1}^{N_s} \sum_{\mu=1}^{N_s} a_n^{(k)} a_n^{(k)} A_{\mu} + \sum_{k=1}^{N_s} \sum_{k'=1}^{N_s} a_n^{(k)} a_n^{(k')} X_{\mu} \mu') e^{j2\pi f_0 T_0} \]  

where

\[ a_n^{(k)} \Delta \sum_{\nu=0}^{\frac{N_s}{2},} i_{\nu}^{(k)} \gamma^{(k)}_{\nu+\mu} X_{\mu} \mu') \Delta \sum_{\nu=0}^{\frac{N_s}{2},} \gamma^{(k)}_{\nu+\nu'} \gamma^{(k')}_{\nu'} \]  

with \( 0 \leq \mu \leq N-1, \ 1 \leq k, \text{and} \ 1 \leq k' \leq N_s \), are the aperiodic auto- and cross-correlation, respectively, of the “modified code” sequence, defined as
4. REDUCED-PAPR CODE ALLOCATION STRATEGY

Derivation of PAPR Metric

Let define now the following metric

\[
\Lambda(C) \triangleq \sum_{k=1}^{N_u} \left[ \sum_{j=1}^{N-1} A_{\mu}^{(i_{j})^2} + \sum_{k \neq k'} \sum_{\mu=1}^{N_u} \left( a_{\mu}^{(i_{j})} A_{\mu}^{(i_{j'})} + X_{\mu}^{(k,k')} \right) \right]
\]  

(9)

where \( C \triangleq \{a_{(i_{1})}^{(i_{1})}, \ldots, a_{(i_{N_u})}^{(i_{N_u})}\} \) is an \( N \times N_u \) array containing a generic subset of \( N_u \) sequences selected among an \( N \)-sized set, and \( a_{(i_{j})}^{(i_{j'})}, \ldots, a_{(i_{N_u})}^{(i_{N_u})} \) is the \( N \)-period spreading code assigned to the \( i_{j}^{th} \) user. Also, by defining the following functions of the codes auto- and cross-correlations

\[
E_{A}^{(i_{j})} \triangleq \sum_{\mu=1}^{N_u} A_{\mu}^{(i_{j})^2} 
\]

(10)

\[
E_{X}^{(i_{j},i_{j'})} \triangleq \sum_{\mu=1}^{N_u} \left( a_{\mu}^{(i_{j})} A_{\mu}^{(i_{j'})} + X_{\mu}^{(k,k')} \right)
\]

(11)

the metric (18) can be rearranged as

\[
\Lambda(C) \triangleq \sum_{k=1}^{N_u} \left[ E_{A}^{(i_{k})} + \sum_{k \neq k'} \sum_{\mu=1}^{N_u} E_{X}^{(i_{k},i_{k'})} \right]
\]

(12)

and, recalling (11), and letting \( A_{4} \approx A_{2}^{2} \), we get

\[
\sigma_{F}^2 \equiv \frac{2}{N^2} A_{4} \Lambda(C)
\]

(13)

Therefore, the CCDF of the PAPR (17) turns out to be (approximately) a function \( \Phi \) of the metric \( \Lambda(C) \)

\[
\overline{F}_{\text{PAPR}}(\text{PAPR}_{0}) \equiv \Phi \left[ C_{\text{PAPR}}^{-} \right]
\]

(14)

and by using the inverse function of the CCDF, \( \overline{F}_{\text{PAPR}}^{-1}(\cdot) \) we end up with the following relationship between the PAPR threshold \( \text{PAPR}_{0} \) and the metric \( \Lambda(C) \)

\[
\text{PAPR}_{0} \equiv \overline{F}_{\text{PAPR}}^{-1} \Phi \left[ C_{\text{PAPR}}^{-} \right]
\]

(15)
5. Numerical Validation of Analytical Findings

Numerical results revealed that the metric for the CG, OG, SK, and SR sets does not appreciably depend on the particular selection of the codes that are assigned to the active users (i.e., the array C). This is not the case of WH codes, wherein both the PAPR and the metrics vary with respect to the code selection C. Such a dependence is clearly evidenced by Fig. 1, which plots the 99th percentile of the PAPR distribution \(\text{PAPR}_0@99\%\) for \(N = 64\) and \(N_u = 32\). Eight different subsets of \(N_u\) codes from the WH set have been considered, and for each subset the corresponding metric has been analytically evaluated according to (18), while the relevant \(\text{PAPR}_0@99\%\) has been evaluated by simulation. The resulting metric-PAPR pair has been plotted as a circular mark, while the dot-dash line is a 2nd order polynomial fitting in a least squares sense that reveals a (quasi) monotonic trend between metric and PAPR. Such a feature suggests an efficient strategy for the allocation of the user signatures aimed at reducing the PAPR in systems employing WH codes. Actually, the problem of choosing a subset of \(N_u\) codes that suitably reduces the PAPR of the aggregate MC-CDMA signal, can be reformulated as finding the array \(\hat{C}_{\Delta}^{(1)} \ldots \hat{C}_{\Delta}^{(N_u)}\) containing the set of codes that minimizes the metric (18). In the sequel, such a procedure will be referred to as “Reduced PAPR Allocation” (RPA) method, whilst the conventional allocation strategy wherein the spreading codes in C are randomly selected will be labeled as “Random Allocation” (RA) method.

5.1 Search Methods

All the subsequent numerical results have been derived for the down-link of a MC-CDMA system employing 16-QAM and RRC pulses with \(\alpha = 0.125\).

![Figure 1. PAPR @ 99% vs. metric](image)

The PAPR can be effectively reduced by resorting to the “Tree-Search Method” (TSM) which will be demonstrated to bear a much lower complexity with respect to the ESM. The TSM approach, which is pictorially illustrated in Fig. 2, is outlined step by step hereafter, considering \(N_u\) active users to be allocated.

- **Step 1.**

  The signature of user #1 is chosen among the \(N\) available codes by computing the initial metric belonging to a code set having size \(N\), taken \(N_u\) at a time. The number of possible selections of the code vectors composing the array C to be tested with the ESM approach is \(P_{ESM} = N!/[(N_u!(N-N_u)!)]\), which reveals prohibitively large for a practical implementation.

  The PAPR can be effectively reduced by resorting to the “Tree-Search Method” (TSM) which will be demonstrated to bear a much lower complexity with respect to the ESM. The TSM approach, which is pictorially illustrated in Fig. 2, is outlined step by step hereafter, considering \(N_u\) active users to be allocated.

- **Step 1.**

  The signature of user #1 is chosen among the \(N\) available codes by computing the initial metric
\[ \Lambda_i \triangleq \Lambda \Lambda_i \triangleq \Lambda e^{(i)}_A. \]  

Allocate to user #1 that code whose index \( \hat{i}_1 \) minimizes (25)

\[ \Lambda_i \overset{\sim}{=} \min_{\hat{i}_1} A_i \overset{\sim}{.} \]  

- **Step k.**

The signature of user #\( k \) is chosen among the \( N - k + 1 \) available codes by computing the accumulated metric

\[ \Lambda_k \left\{ \ldots, \hat{i}_{k-1}, \hat{i}_k \right\} \triangleq \Lambda \Lambda_k \left\{ \ldots, \hat{i}_{k-1} \right\} + \delta \Lambda_k \left\{ \ldots, \hat{i}_{k-1}, \hat{i}_k \right\} \]  

where, with reference to the tree-diagram in Fig. 2, we defined the “branch metric” at step \( k \) as

\[ \delta \Lambda_k \left\{ \ldots, \hat{i}_{k-1}, \hat{i}_k \right\} = \epsilon^{(i_k)}_X + \sum_{h=1}^{k-1} \epsilon^{(i_{k-1}, i_k)}_X + \sum_{h=1}^{k-1} \epsilon^{(i_k)}_X \]  

Allocate to user #\( k \) that code whose index \( \hat{i}_k \) minimizes (27)

\[ \Lambda_k \left\{ \ldots, \hat{i}_k \right\} \overset{\sim}{=} \min_{\hat{i}_k} A_k \left\{ \ldots, \hat{i}_{k-1}, \hat{i}_k \right\}. \]  

Notice that, since \( \Lambda_k - 1 \) does not depend on \( i_k \), minimization of \( \Lambda_k \) is achieved by minimizing only the branch metric

\[ \delta \Lambda_k \left\{ \ldots, \hat{i}_k \right\} \overset{\sim}{=} \min_{\hat{i}_k} \delta \Lambda_k \left\{ \ldots, \hat{i}_{k-1}, \hat{i}_k \right\}. \]  

By means of such an allocation strategy, we achieve a “local minimum” with respect to subset of the previously allocated codes \( \left\{ \left( \hat{i}_1 \right), \ldots, c^{(i_{k-1})} \right\} \).

- **Step N_u.**

The signature of user #\( N_u \) is chosen among the \( N - N_u + 1 \) still available codes by computing the total accumulated metric

\[ \Lambda_{N_u} \left\{ \ldots, \hat{i}_{N_u-1}, \hat{i}_{N_u} \right\} \triangleq \Lambda \Lambda_{N_u-1} \left\{ \ldots, \hat{i}_{N_u-1} \right\} + \delta \Lambda_{N_u} \left\{ \ldots, \hat{i}_{N_u-1}, \hat{i}_{N_u} \right\} \]  

Allocate to user #\( N_u \) that code whose index \( \hat{i}_{N_u} \) minimizes (31)

\[ \Lambda_{N_u} \left\{ \ldots, \hat{i}_{N_u} \right\} \overset{\sim}{=} \min_{\hat{i}_{N_u}} A_{N_u} \left\{ \ldots, \hat{i}_{N_u-1}, \hat{i}_{N_u} \right\}. \]
By recalling (28) and by including all the selected code vectors into the array \( \hat{C} \), the total accumulated metric (32) at the end of the minimization procedure can be rewritten as

\[
\Lambda_{N_u} \hat{C} = \sum_{k=1}^{N_u} \Lambda_k \left( e_{X}^{(i_k)} + \sum_{k' = k}^{N_u} e_{X}^{(i_k, i_{k'})} \right) = \Lambda \hat{C},
\]

which is an (almost) minimized version of the metric (21).

The computational burden of the reduced-complexity tree-search procedure outlined above can be expressed as the total number of tests to be performed during the minimum metric computation, which is \( N \) at the first step, \( N - 1 \) at the second one, and so forth. Moreover, when allocating a number of users \( N_u > N/2 \), the TSM algorithm reveals faster if used in the reverse order, i.e., starting from the whole code set and by decrementing the number of codes from \( N \) down to \( N_u \) by discarding those having the maximum branch metrics. By using such an expedient, the actual complexity of the proposed allocation method turns out

\[
P_{TSM} = \begin{cases} 
\sum_{k=0}^{N_u-1} (N-k) & \text{for } 0 < N_u \leq N/2 \\
\sum_{k=N_u}^{N-1} (N-k) & \text{for } N/2 < N_u < N 
\end{cases}
\]

Figure 3. CCDF of the PAPR for 16-QAM, \( N = 64, N_u = 32 \): CG (top) and OG (bottom).

The maximum complexity reduction is achieved at half system load (\( N_u = N/2 \)), when \( P_{ESM} \sim 10^{18} \) and \( P_{TSM} \sim 10^{9} \), while for \( N_u = 1 \) or \( N_u = N - 1 \), the two algorithms have the same complexity \( P_{ESM} = P_{TSM} = N \).

6. Numerical Results

Dis numerical results have been obtained with the same system configuration previously described in sub-section IV-B. Figure 3 compares the analytical approximate expression of the PAPR CCDF (17) (solid line) with computer simulations (dashed line), for CG set (top chart) and OG set (bottom chart), with \( N = 64 \) and \( N_u = 32 \). Clearly, due to the simplifications used in the analytical characterization of the signal, numerical results differ somehow from simulation data. However, the discrepancy between theory and simulations is about \( \pm 1 \) dB thus demonstrating a rather satisfactory accuracy of the analytical method. Figure 4 compares the simulated CCDFs of the PAPR, for seven RA realizations (dashed lines) and for the RPA method (solid lines).
line), with \( N = 64 \) and \( N_u = 8 \). As apparent, when using the WH set, the RPA provides significant PAPR reductions with respect to the “blind” RA approach. In particular, PAPR reductions vary from 1 to 5 dB, at crossing probability \( 10^{-2} \). Figure 5 compares the simulated values of \( PAPR_{99\%} \) versus \( N_u \), for various code sets and \( N_u = 64 \). For the WH set, RPA, AOA (Ascending Order Allocation) and DOA

Figure 4. CCDF of the PAPR (7 RA realizations and RPA method) for 16-QAM, WH, \( N = 64 \), and \( N_u = 8 \).

Figure 5. PAPR @ 99% vs. \( N_u \) (simulations) for MC-CDMA with 16-QAM, \( N = 64 \), and various code sets

(Descending Order Allocation) methods, consisting in assigning the WH codes in ascending and in descending order\(^6\), respectively, and one RA realization have been considered. As apparent, the WH set greatly benefits from the use of the MPA strategy and yields the best PAPR performance among all the considered code sets, for loading conditions greater than 10\(^7\). On the other hand, numerical results obtained by simulations confirmed that the CG, OG, SK, and SR sets have only a minimal sensitivity with respect to the actual selection of the codes. Therefore, using allocation strategies different from the RPA, the PAPR performance would remain practically the same as that depicted in Fig. 5. Furthermore, as apparent from the figure, all these sets exhibit a very similar behavior with respect to the load \( N_u \). The PAPR reduction obtained (especially in the WH case) by the use of the RPA strategy reveals extremely beneficial in the presence of a
transmit HPA which induces nonlinear distortions. Numerical results presented in the following have been obtained by computer simulations and refer to the case of SSPA (4) with $q = 10$, and output back-off $OBO$.

![Spectrum of MC-CDMA at HPA output](image1)

Figure 6. Spectrum of MC-CDMA at HPA output, with 16-QAM, $N = 64, N_u = 32$, $OBO = 5$ dB: various allocations of WH (top), various code sets (bottom).

Figure 6 presents the power spectral density (PSD) of a MC-CDMA signal evaluated after the HPA, for $N = 64, N_u = 32$ and $OBO = 5$ dB. The chart on the upper side of Fig. 6 shows the spectrum at the HPA output for a WH set, obtained with different allocation strategies. The beneficial reduction of the out-of-band emissions provided by the RPA strategy is clearly apparent. The undistorted spectrum at the HPA input is also plotted as a dotted line for the sake of reference. The chart on the lower side of Fig. 6 compares the spectrum at the HPA output for a WH set, obtained with RPA strategy, and the spectra of the CG, OG, SK, and SR sets (which actually have almost all coincident plots). The graph demonstrates that the use of RPA strategy renders the out-of-band emissions of the WH set lower than those of the other codes (which do not benefit from MPA strategy). Another typical performance metric for nonlinear distortions is the Total Degradation (TD), evaluated at a specified value of BER as the sum (in decibels) of the OBO at HPA output and the loss due to the nonlinear distortion incurred in the average energy per bit-to-noise spectral density.
ratio $\frac{\varepsilon_0}{N_0}$. Figure 7 plots the average TD as a function of the OBO at BER = $10^{-4}$, for a system employing WH codes, with $N = 256$ and $N_u = 32$, over a transmission channel including the HPA followed by AWGN. Codes are allocated using RA (triangular marks) and RPA (circular marks) strategies. The (ideal) linear amplifier performance is also plotted as a straight dashed line. As apparent, RPA yields a 2 dB gain for both the TD and the OBO, with respect to RA.

7. Conclusion
In this paper we have derived an approximate analytical expression for the PAPR of a MC-CDMA signal, and we assessed its accuracy for different code sets. After, we have illustrated the RPA method based on a proper allocation of the users’ signatures to minimize the PAPR of the transmitted signal and, accordingly, to improve transmission system performance over nonlinear channels. The proposed RPA strategy is effective on an unmodified WH spreading code set and does not require modifications of the transmitter. In a typical packet-based mobile communication scenario, wherein the users continuously get in and out from the network, by resorting to the TSM implementation of RPA strategy, the admission of a new user involves an additional low-complexity step only. The latter simply consists in the selection of the code signature based upon the evaluation of the branch metric over the not-yet-allocated signatures, without any additional side information to be sent. Simulation results demonstrated that, when using WH codes, the RPA remarkably boosts link performance in terms of PAPR distribution, TD and OBO, over conventional RA strategy. Finally, as an added-value feature, the proposed code allocation strategy can be effectively used with other PAPR-limiting techniques, for boosting system performance.

REFERENCES