ANALYSIS OF NON-LINEAR DISTORTIONS IN MC-CDMA SYSTEMS[1]

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SUMMARY

Multi-carrier code division multiple access (MC-CDMA) is a powerful modulation technique that is being considered in many emerging broadband communication systems. It exploits the advantages of spread spectrum and the advantages of multi-carrier systems, particularly orthogonal frequency division multiplexing (OFDM) technique. However, since it uses OFDM, the MC-CDMA signals are a superposition of many narrow-band signals and, as a result suffer from strong envelope fluctuations which make them very prone to nonlinear effects introduced by high power amplifier (HPA). HPA introduces conversion in both amplitude and phase, that is responsible for increasing bit error rate, which is caused by the loss of orthogonality of both, the spreading sequences and subcarriers used in the downlink scenario. In order to be able design a robust method for the nonlinearity effects cancellation, it is necessary to analyze the effects of nonlinear amplification on the MC-CDMA signals. In this paper we have focused on the signals at the output of the nonlinear distorting device, where we observed two major phenomena, rotation and clouding, and spectral outgrowth. Additionally, we used a Bussgang theorem to represent output signal from the nonlinear distorting device as the sum of the scaled version of the input signal and the distortion term. The frequency domain representation of this distortion term let us express the distortion term as two disjoint sets, that correspond to in-band and out-of-band distortion term, respectively.

Keywords: *MC-CDMA, high power amplifier, nonlinear distortion, analysis, evaluation.*

1. INTRODUCTION

MC-CDMA [4] is modulation technology which combines the advantages of OFDM [13] and code division multiple access (CDMA) to produce a spectrally efficient multi-user radio access system. One of the major disadvantages of multi-carrier (MC) systems based on OFDM is the high sensitivity to nonlinear amplification, which requires large back-off in the transmitter amplifier and, as a consequence, inefficient use of power amplifiers. On the other hand, using low back-offs leads to signal distortion and, as a result, increased performance degradation. Obviously HPAs are a part of almost all communication links and due to the nonlinear nature of the electronic components that they are made of, their conversion characteristics are nonlinear. In addition to amplify the signal, the nonlinear amplifier generates nonlinear distortion in both amplitude and phase and causes the loss of orthogonality in the OFDM-based system, resulting in a higher bit error rate (BER).

Several techniques can be found in the literature to reduce the sensitivity of MC systems to nonlinear amplification. Most common transmitter side solutions include amplifier linearization [1] and peak-to-average power ratio (PAPR) reduction and compensation techniques [2, 3].

The aim of this paper is to analyze the influences of the effects of the nonlinear distortions introduced by HPA in MC-CDMA for mobile communication systems. To do this, we will analyze the signal at the output of the nonlinearity (NL). Synchronous downlink scenario is considered in this paper and therefore orthogonal spreading sequences, such as orthogonal Walsh-Hadamard codes are used to reduce multiple access interference (MAI). Spreading is done in order to distinguish different data streams originating from K different active users. The resulting signal is a sum of these spread users' data symbols and with the increasing number of active users, the signal will suffer from higher PAPR. However, the major contribution of increasing PAPR is caused by the nature of an OFDM modulation, which uses scaled inverse fast Fourier transformation (IFFT). IFFT is applied to represent complex baseband modulated data symbols as a time-domain signal suitable for the further radio channel transmission, reflecting the characteristics of the channel. Prior to the transmission, the signal is radio frequency (RF) upconverted and subsequently power amplified. HPA introduces a nonlinear distortion to the communication link which cause a loss of orthogonality of both the spreading sequences and subcarriers as well, and thus increasing BER. Therefore, it is necessary to analyze its effects in order to be able design a robust method for nonlinearity effects cancellation.

The structure of this paper is as follows. The general system model of an MC-CDMA system is presented and described in more details in section 2. The section 3 summarizes the HPA baseband models, which are most commonly used in communication systems. Subsequently in section 4 an analysis of nonlinearly distorted OFDM-based

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signal is given in order to show the effects of nonlinear amplification and is used in section 5 for its performance evaluation.

2. MC-CDMA SYSTEMS

MC-CDMA type of transmission is an extension of the basic OFDM principle, firstly proposed in [4], which combines and exploits the advantages of spread spectrum principle and OFDM. This technology offers many additional advantages comparing to direct sequence (DS) CDMA (DS-CDMA) [5]. However, it is know that MC systems using OFDM are more sensitive to nonlinear amplification introduced by HPA, than single carrier modulation schemes. OFDM signal usually requires higher back-offs, in order to achieve acceptable performance of the system in the presence of nonlinear HPA. It is caused by the nature of the OFDM signal, which is complex Gaussian distributed with Rayleigh envelope distribution, which results in severe clipping-effects. That means, depending on HPA conversion characteristics, all signal samples with magnitude higher than the saturation level of the amplifier A_{sat}, will be mapped to a point in a circle with radius A_{sat}. This will cause a high degradation of the transmitted signal and spectral outgrowth.

2.1. MC-CDMA system model

The block diagram of an MC-CDMA synchronous downlink transmitter is shown in Fig. 1, where $\mathbf{d}^{(k)} = \{d_1^{(k)}, d_2^{(k)}, \cdots, d_M^{(k)}\}$ denotes M complex data symbols of the k-th user, $k = 1, 2, \cdots, K$, where $K \le L$ is the number of active users and L denotes the spreading factor. After serial-to-parallel conversion, each complex symbol is spread by a sequence $\mathbf{c}^{(k)} = \{c_1^{(k)}, c_2^{(k)}, \cdots, c_L^{(k)}\}$, unique for each user. The resulting chip symbol vector of the length $N = ML$ is element wise summed with $K-1$ other user's chip symbol vectors. Subsequently, the elements of the resulting vector are interleaved in the frequency domain for frequency diversity by using M-input block interleaver of depth L, and once more serial-to-parallel converted. Then the over-sampling is performed in the frequency domain, which is represented by the $N(O-1)$ zero padding of the parallel data vector, where O denotes over-sampling factor. The oversampled input data vector is then fed into the NO-length. The output samples of the IFFT are back converted to its serial form. MC systems usually insert a cyclic prefix (CP) (called guard interval) after every OFDM symbol, in order to simplify the equalizer design at the receiver in the presence of finite-length channel multipath. The CP is simply a periodic extension of the symbol over the interval $[-T_{CP}, 0]$, resulting in symbol of length $[-T_{CP}, T]$, where T_{CP} is the length of the CP and T denotes the length of the OFDM symbol. And finally, the signal is fed into the HPA after RF upconversion and transmitted through the channel to the receiver. At the receiver side, inversion operations are performed, in order to reconstruct original transmitted data stream.

2.2. Pros and cons of an MC-CDMA systems

As it was previously stated, an MC-CDMA implies an OFDM modulator and therefore has the same advantages and/or drawbacks as OFDM system. Though, the OFDM scheme has some considerable advantages, such as its robustness to frequency fading and time dispersion and the possibility to achieve the transmission rates close to capacity, it has some inherent drawbacks. The sensitivity to frequency offset and the sensitivity

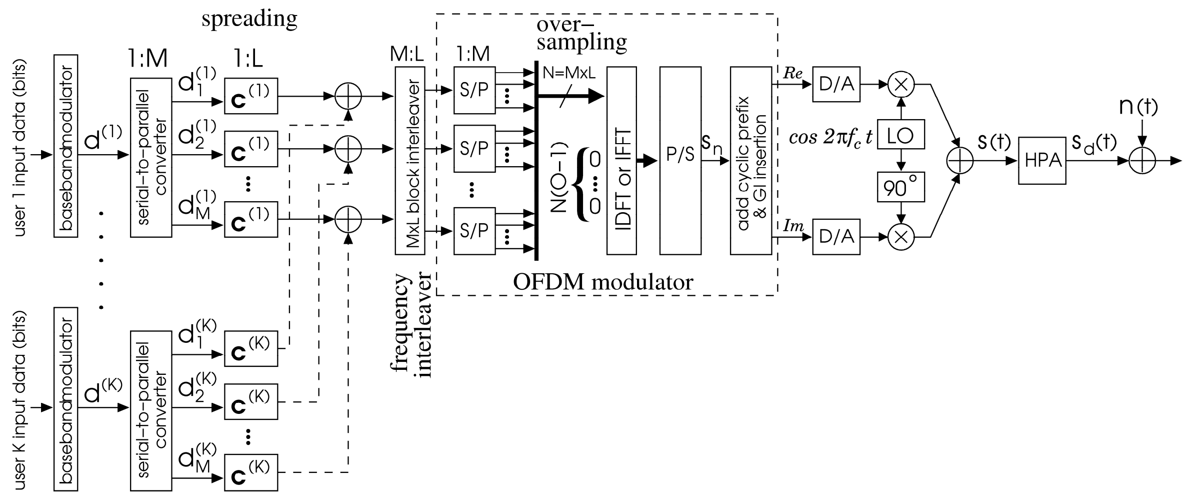

Fig. 1 The block diagram of an MC-CDMA synchronous downlink transmitter.

to nonlinear amplification are pointed out as the major ones. We are specially interested in the sensitivity to nonlinear amplification. The sensitivity to nonlinear amplification results from the fact that, as with other MC schemes, the MC-CDMA signals have strong envelope fluctuations and high PAPR which is a result of superposition of many subcarriers with their overlapping power spectra. This either requires an inefficient use of the HPA otherwise introduces large performance degradation, i.e. increase of both the BER and the out-of-band radiation. Another drawback that is result of large envelope fluctuations is the need of a high-resolution digital-to-analog converter (D/A) at the transmitter and a high-resolution analog-to-digital converter (A/D) operating at high dynamic range at the receiver side.

In the following section we will focus on the baseband modelling of HPA in order to determine its effects in MC systems based on OFDM.

3. HPA NON-LINEAR MODELS

High power amplifiers exist in almost all wireless communication links. Due to various nonlinear electronic components inside them, these power amplifiers are nonlinear devices. Increasing demand of high power efficiency requires high transmit power which causes more nonlinear distortion introduced by HPA. In order to evaluate the entire communication system, it is necessary and crucial to have models that properly characterize HPA characteristics.

Power amplifiers in general exhibit nonlinear distortion in both, amplitude and phase. The amplitude conversion is commonly referred as Amplitude Modulation to Amplitude Modulation (AM/AM) conversion and phase conversion is referred as Amplitude Modulation to Phase Modulation (AM/PM) conversion. This implies that both amplitude and phase of the output signal are affected nonlinearly with the respect to the input signal. Both these conversion characteristics are used to specify characteristics of the given HPA model.

Two major types of power amplifiers are typically used in communication systems, travelling wave tube amplifiers (TWTA) and solid state power amplifiers (SSPA) [6].

3.1. TWTA amplifier

The Saleh model [7] is a widely accepted TWTA model. The output of the amplifier can be expressed as:

$$y(t) = G(|x(t)|)e^{j(\angle x(t)+\Phi(|x(t)|))} \tag{1}$$

where $x(t)$ and $y(t)$ is the input and output signal from the amplifier, respectively. The AM/AM conversion of the Saleh model is given by

AM/AM: $$G(|x(t)|) = \frac{\kappa_G |x(t)|}{1+\chi_G |x(t)|^2} \tag{2}$$

where χ_G is the parameter defining the saturation point of the input and output signal and κ_G is the small signal gain. The AM/PM conversion is given by:

AM/PM: $$\Phi(|x(t)|) = \frac{\kappa_\Phi |x(t)|^2}{1+\chi_\Phi |x(t)|^2} \tag{3}$$

where κ_Φ and χ_Φ are specified to suit the given HPA.

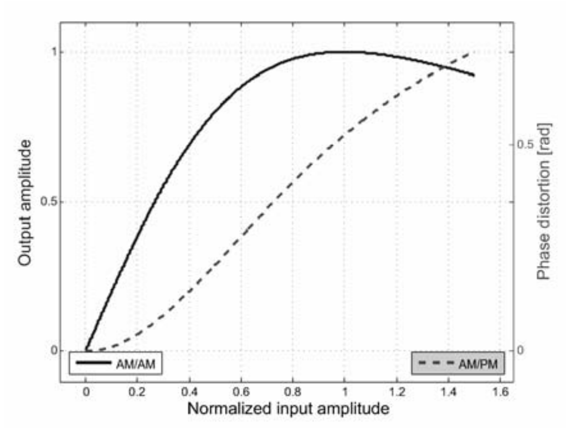

Fig. 2 AM/AM and AM/PM characteristics of the normalized Saleh model.

The AM/AM and AM/PM conversion characteristics are shown graphically in Fig. 2, where $\kappa_G = 2$, $\chi_G = \chi_\Phi = 1$ and $\kappa_\Phi = \pi/3$, which means that both, input and output saturation power are normalized to 1.0.

3.2. SSPA amplifier

SSPA are typically used in mobile communication systems. The Rapp model [8] is a widely accepted model for SSPA. The AM/AM conversion characteristic of this model is given by:

AM/AM: $$G(|x(t)|) = \frac{\kappa_G |x(t)|}{\left(1+\left(\frac{|x(t)|}{A_{sat}}\right)^{2p}\right)^{\frac{1}{2p}}} \tag{4}$$

where p is the smoothness factor which controls the transition from the linear to saturation region. and A_{sat} is the output saturation level. Its AM/PM conversion characteristic is given by:

AM/PM: $$\Phi(|x(t)|) = 0 \tag{5}$$

which implies that the output phase is not affected. Fig. 3 shows an example of the AM/AM characteristic obtained by the Rapp model by setting its parameters to $\kappa_G = A_{sat} = 1$ and $p = 3$.

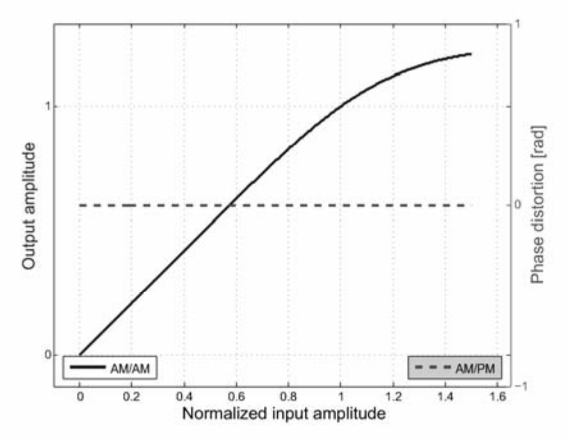

Fig. 3 AM/AM and AM/PM characteristics of the normalized Rapp model

The effect of the nonlinear amplifier depends on the operating point, which position is defined by its back-off. Input back-off (IBO) and output back-off (OBO) are two common parameters to specify the nonlinear distortion. IBO corresponds to the ratio between the saturated and average input power, and is defined as:

$$IBO = 10\log_{10}\frac{P_{\max,in}}{\overline{P_x}} \tag{6}$$

and OBO corresponds to the ratio between the saturated and average output power, defined as:

$$OBO = 10\log_{10}\frac{P_{\max,out}}{\overline{P_y}} \tag{7}$$

The graphical representation of these two parameters is shown in Fig. 4.

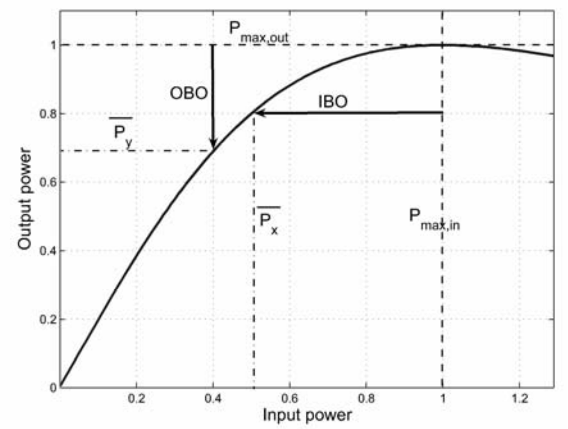

Fig. 4 Graphical representation of IBO and OBO.

4. ANALYSIS

Let us recall to Section 2 and express the baseband transmission signal $x(t)$ of an MC-CDMA symbol as

$$x(t) = \frac{1}{\sqrt{ML}}\underbrace{\sum_{m=1}^{M}\sum_{l=1}^{L}\sum_{k=1}^{K} d_m^{(k)} c_l^{(k)}}_{\mathbf{S}} e^{j2\pi\left\{\frac{M(l-1)+(m-1)}{T_s}\right\}t} \tag{8}$$

where T_s is a symbol period, $0 \le t \le T_s$ and $\mathbf{S} = \{S_1, S_2, \cdots, S_N\}$ represents chip symbol vector of length $N = ML$. The equation (8) can be rewritten to the form

$$x(t) = \frac{1}{\sqrt{N}}\sum_{m=1}^{M}\sum_{l=1}^{L} S_{(m,l)} e^{j2\pi\left\{\frac{M(l-1)+(m-1)}{T_s}\right\}t} \tag{9}$$

where $(m,l) = M(l-1)+(m-1)$. The double sum $\sum_{m,l}$ can be replaced by a single sum $\sum_k$, where summation index $k = M(l-1)+(m-1)$ and thus we obtain

$$x(t) = \frac{1}{\sqrt{N}}\sum_{k=1}^{N} S_k e^{j2\pi\frac{k}{T_s}t} \tag{10}$$

The OFDM symbol duration T_s is determined by the duration of the data symbols T_d as $T_s = N \cdot T_d$. Subsequently, if we sample $x(t)$ at $t = nT$, where $T = T_d / O$ and O is the over-sampling factor we obtain complex samples as

$$x_{n/O} = \frac{1}{\sqrt{N}}\sum_{k=1}^{N} S_k e^{j2\pi kn/ON} \tag{11}$$

for $n = 1, 2, \cdots, ON-1$. Then by zero padding the complex chip symbol vector $\mathbf{S}$ of length N with $N(O-1)$ zeros as

$$\mathbf{S}^{zp} = [S_0, S_1, \cdots, S_{N-1}, \underbrace{0, 0, \cdots .0}_{N(O\text{-}1)}] \tag{12}$$

we can reformulate (11) to

$$x_{n/O} = \frac{1}{\sqrt{N}}\sum_{k=1}^{ON-1} S_k^{zp} e^{j2\pi kn/ON} \tag{13}$$

One of the advantages of an OFDM modulation is its computational simplicity by means of the FFT/IFFT operations, i.e. the equation above can be

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computed using an ON-length scaled IFFT of the zero padded symbol vector $\mathbf{S}$ as

$$x_{n/L} = O\sqrt{N} \cdot IFFT_{ON}\{\mathbf{S}^{zp}\} \quad (14)$$

It can be seen from (14), that the OFDM modulated signal is composed as a superposition of many narrowband signals. If these signals have zero phase shifts, they are added constructively and therefore with N subcarriers used, the peak envelope power will be as large as N times the mean envelope power. In general, the OFDM modulated signal suffers from high envelope fluctuations, which is one of the major disadvantages of the MC systems. The ratio between the instantaneous power of these peaks and the average power of the signal, which is referred as PAPR is too large and it requires the use of power amplifiers which have to operate in linear region. The PAPR is most known metric for envelope fluctuation measurement of MC signals and for MC-CDMA signal generated using (13) can be expressed as:

$$PAPR = \frac{\max\limits_{n=1,\cdots,ON} |x_{n/O}|^2}{E[|x_{n/O}|^2]} \quad (15)$$

where $E[.]$ denotes an expectation operator.

In the literature we can find some other methods for envelope fluctuation measurement of MC signals, such as the cubic metric (CM) [14] and the variance of the instantaneous power (VIP) [15]. The CM method relies on the fact that the major distortion is caused by the third-order intermodulation product and the motivation of VIP metric is to reduce the envelope fluctuations.

To study the effects of nonlinear distortions in MC-CDMA scheme, we will focus on the signal at the output of the nonlinear device. Fig. 5 shows a signal constellation of original and received symbols, where we assumed that 16-QAM and Saleh model operating at 10dB IBO were used. The power spectrum density functions (PSD) of the signal at the input and the output of the nonlinear transmitter is presented in Fig. 6. Here, Saleh model with the parameters specified in Section 3.1 and different IBOs is used.

From the Fig. 5 we can observe two major effects of nonlinear distortion on signal constellation: rotation, which is caused by AM/PM conversion and clouding (conversion from a single point to a cloud of points), which is a result of the probabilistic distribution of the OFDM signal. Let us recall, that an OFDM signal suffers from large envelope fluctuations and therefore, the signals with different amplitudes will be affected by the nonlinearity differently, following the probabilistic distribution of the OFDM signal that can be seen in the Fig. 5.

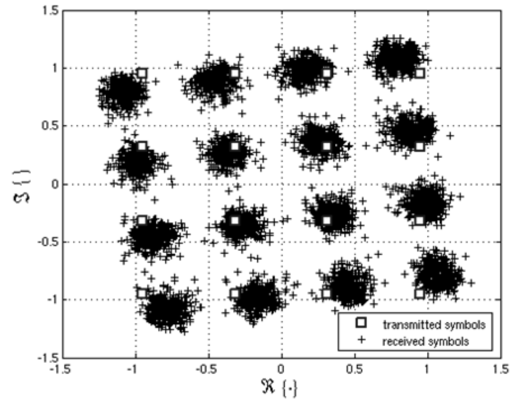

Fig. 5 Original and received signal constellation.

Now we can apply a Bussgang theorem [9] and the result of [3] to represent output signal $y(t)$ of a memoryless nonlinearity as the sum of scaled version of the input signal $x(t)$ and the distortion term $d(t)$, which is uncorrelated with the input signal ($R_{xd} = 0$) as:

$$y(t) = \alpha x(t) + d(t) \quad (16)$$

where $\alpha = R_{xy}(\tau_1)/R_{xx}(\tau_1)$ is the complex valued factor of the proportionality. R_{xy} denotes cross-correlation function of input and output signal and R_{xx} denotes autocorrelation function of the input signal. τ_1 is any value of τ, but we usually choose $\tau_1 = 0$. The scaling factor α is responsible for the attenuation and rotation of the constellation (see Fig. 5), which can be easily compensated at the receiver by introducing correction factor $\alpha^*/|\alpha|^2$. However, the distortion term, which is responsible for both the clouding and the out-of-band radiation can not be compensated and therefore the methods for nonlinear effects cancellation have to be developed and applied.

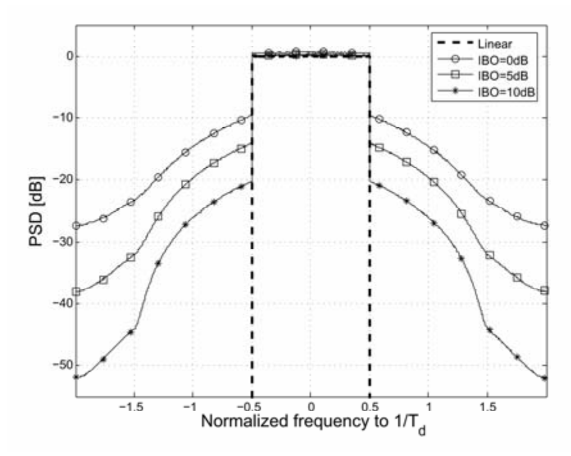

Fig. 6 PSD of the signal at the input and the output of the nonlinearity.

In order to determine the out-of-band radiation which is a part of the overall distortion term introduced by nonlinear amplification, we will take a look at the frequency domain representation of the distortion term $d(t)$, i.e. $\mathbf{D}=[D_0,\cdots,D_{ON-1}]$. This quantity can be expressed as

$$\mathbf{D}=\mathbf{D}^{(in)}+\mathbf{D}^{(out)} \tag{17}$$

where $\mathbf{D}^{(in)}=[D_0^{(in)},\cdots,D_{ON-1}^{(in)}]$ and $\mathbf{D}^{(out)}=[D_0^{(out)},\cdots,D_{ON-1}^{(out)}]$ represent the in-band and out-of-band distortion, respectively. $\mathbf{D}^{(in)}$ is the part of distortion that increases the BER at the receiver, while $\mathbf{D}^{(out)}$ is, directly, the out-of-band radiation, which disturbs the adjacent frequency bands. The spectral outgrowth is the leakage of signal power to the other frequencies outside its bandwidth. This is a source of cross-talk to the nearby channels. This leakage of power is because of the intermodulation products, which fall outside the spectrum of the signal. It is necessary to keep this spectral leakage under a special level.

5. EVALUATION

Various methods can be found in the literature to evaluate performance improvement of the method that deals with nonlinear effects cancellation in OFDM-based system. They can be divided into two main groups; either they evaluate the effects of in-band distortion, or out-of-band distortion. In [10], some methods commonly referred as „IQ signal analysis" methods are defined, particularly System Target Error (STE), Error Vector Magnitude (EVM), Modulation Error Ratio (MER) and some others. In the following we will take a closer look at some of them. Additionally PSD function is used to evaluate effects of out-of-band radiation.

5.1. IQ Analysis

5.1.1. System target error (STE)

When OFDM-based signal undergoes nonlinear amplification, as it is in case of HPA, then its signal constellation will be rotated and a clouded, as seen in Fig. 5. The displacement of the centres of the clouds in a constellation diagram from their ideal symbols point reduces the noise immunity of the system. In general, STE gives a global indication about overall distortion, however, if we assure a noiseless environment and eliminate all other distortion sources, except the nonlinear one, then it can be used to measure the effects of nonlinear distortion term.

Let us assume a 16-QAM baseband modulation scheme, as in Fig. 7. Then the distance d_i for each of the M symbol points in a constellation diagram between ideal symbol point I_n and the point corresponding to the mean of the cloud of this particular symbol point is computed. Then the quantity $\mathbf{d}_i$ for $i=1,2,\cdots,M$ is called Target Error Vector (TEV) and is shown in Fig. 7.

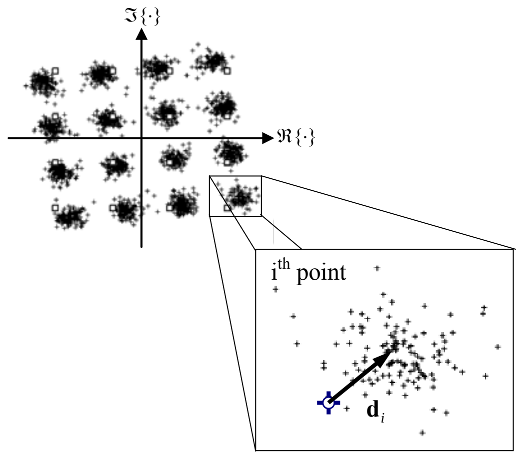

Fig. 7 Definition of Target Error Vector (TEV).

The System Target Error Mean (STEM) is then computed as

$$STEM=\frac{1}{M\times S_{rms}}\sum_{i=1}^{M}|\mathbf{d}_i| \tag{18}$$

where S_{rms} is the root mean square amplitude value of the points in the constellation defined as

$$S_{rms}=\sqrt{\frac{1}{N}\sum_{n=1}^{N}|I_n|^2}=\sqrt{E[|I_n|^2]} \tag{19}$$

Additionally, the System Target Error Deviation (STED) is defined as

$$STED=\sqrt{\frac{\sum_{i=1}^{M}|\mathbf{d}_i|^2}{M\times S_{rms}^2}-STEM^2} \tag{20}$$

5.1.2. Error vector magnitude

The EVM is a measure used to quantify the performance improvement of the receiver and especially in our case, the ability to cope with the nonlinear effects cancellation. This method is based on IQ signal analysis, as we used in [11] and therefore an error vector is computed, which is defined as an Euclidean distance between the ideal constellation point I_n and the received constellation point R_n. Then EVM is computed as the ratio between the mean value of the error vectors and the reference power as:

$$EVM=10\log_{10}\left(\frac{E\left[|R_n-I_n|^2\right]}{S_{\max}^2}\right)dB \tag{21}$$

where $S_{\max}$ is the amplitude of the outmost ideal constellation point.

5.1.3. Modulation error ratio

Another measure used to quantify the performance improvement of the receiver is MER, which is closely related to EVM, but is calculated from the average power of the signal.

The MER is computed as the sum of the squares of the magnitudes of the ideal symbol vectors, divided by the sum of the squares of the magnitudes of the symbol error vectors. The result, expressed as a power ratio in dB, is defined as

$$MER = 10\log_{10}\left(\frac{\sum_{n=1}^{N}|I_n|^2}{\sum_{n=1}^{N}|R_n - I_n|^2}\right)dB \qquad (22)$$

5.2. Out-of-band radiation measurement

Out-of-band radiation affects adjacent communication channels, which is undesirable and it is required to keep it under the certain level. EN 300 429 (see Fig. 8) [12] defines spectral mask to specify these levels as a minimum requirement for hardware implementation of the Nyquist filter. In the real systems a spectrum analyser is used to measure out-of-band emissions, while PSD function is used in our simulations. In our simulations the PSD is computed by means of periodogram, as the average of the PSD, computed by FFT, of each transmitted OFDM symbol. Fig. 6 depicts PSD functions of output signal of a nonlinear distorting device represented by a Saleh model with three different IBO values (0, 5, and 10dB). Here we can observe, that higher value of IBO is used, less out-of-band radiation is introduced, but less power efficiency is achieved.

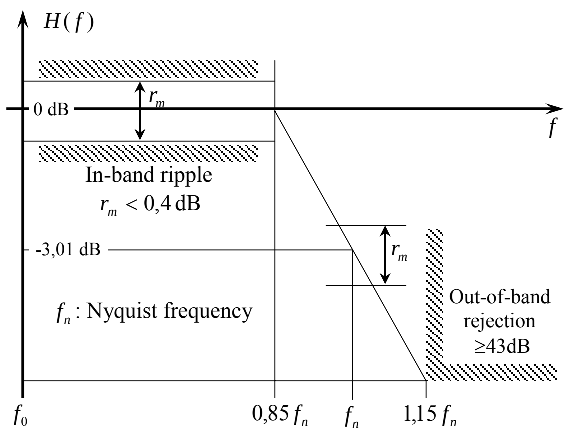

Fig. 8 Spectrum mask for out-of-band emission measurement.

6. CONCLUSIONS

In this paper we analyzed the effects of nonlinear distortions introduced by HPA in MC-CDMA schemes. From the performed analysis we can see that the output signal from a nonlinearly distorting device can be represented as a sum of a scaled input replica and an uncorrelated distortion term. The frequency domain representation of this distortion term yield to a division of a whole distortion term into two disjoint sets, denoted as in-band and out-of-band distortion term. The first of them is the part of distortion that increases the bit error rate at the receiver, while the second one directly corresponds to the out-of-band radiation, which affects adjacent communication channels, which is undesirable and it is required to keep it under the certain level.

To evaluate the effects of nonlinear distortions, some methods were reviewed.

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BIOGRAPHIES

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