Iterative Algorithm for Channel Re-Estimation and Data Recovery in Nonlinearly Distorted OFDM Systems

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Abstract: This paper presents a new algorithm for the nonlinear distortion cancellation and channel re-estimation in an iterative manner for the OFDM transmission systems. Whereas in practical OFDM systems, where nonlinear amplifiers are used in the transmitter, data as well as pilot symbols are nonlinearly distorted. As perfect channel state information is often assumed in many papers, the effect of the nonlinear distortion of the pilot symbols is usually not accounted for, and the data symbols are considered only. However, as the pilot symbols are used to obtain the channel state information, the distortion caused to pilot symbols by the nonlinear amplification is of the great importance, and for this reason this effect should be taken into account. To address this issue, in this paper, an efficient algorithm will be introduced for joint data recovery and channel re-estimation in an iterative manner for OFDM transmission system. This algorithm iteratively estimates the nonlinear distortion due to nonlinear high power amplifier of the transmitter and then it uses it to compensate for this nonlinear distortion of the data and the pilot symbols, which are subsequently used for subsequent and more precise channel re-estimation. As is shown in this paper, the proposed algorithm can be used to reduce nonlinear distortions even in situations when highly nonlinear amplifiers are applied.

Keywords: OFDM, iterative receiver, channel re-estimaiton, PAPR, nonlinear distortion

1 Introduction

The demands for high data rate transmission over multipath radio channels have increased rapidly. To fulfill this requirement, the utilization of multi-carrier-based transmission techniques seems to be an inevitable solution. In former methods, the signals received through the multipath channel suffer from severe intersymbol interference (ISI) since the delay spread becomes much larger than the symbol duration. In order to overcome this fact, the Orthogonal Frequency Division Multiplex (OFDM) transmission scheme, with very promising potential, is justifiably one major candidate for Beyond 3G and 4G wireless communication systems [1]. OFDM-based transmission systems are characterized by a large number of benefits in comparison with traditional schemes. Among others, easy time invariant multi-path channel equalization has received a great amount of interest recently. On the other hand, the high Peak-to-average power ratio (PAPR) of the OFDM signal makes it very sensitive to nonlinear amplification, which results in a high Bit Error Rate (BER) penalty, as well as to enormous out-of-band radiation. These effects have harmful impact on the overall OFDM transmission system performance, and therefore strict requirements to mitigate these effects must be taken.

High sensitivity to nonlinear amplification has greatly limited the practical applications of OFDM transmission systems. In order to alleviate this fact, many approaches based on different techniques have been introduced. The conventional solution is to back-off the operating point of the nonlinear amplifier, but this approach results in a significant power efficiency penalty. Alternative approaches for OFDM performance improvement are realized by the application of other usually computationally demanding methods of the PAPR reduction at the transmitter side, e.g. by the active constellation extension [2], tone reservation [3] or selected mapping [4]. Another well known and promising solution for reducing the BER of nonlinearly distorted multicarrier systems is to use nonlinear detection at the receiver side. The first contribution to this topic was proposed by Kim and Stuber in [5]. This technique reduces the clipping noise of OFDM symbols by decision-aided reconstruction at the receiver. In [6], Declerq *et al.* proposed reducing the clipping noise in OFDM by introducing a Bayesian interference to the received signal. Finally Chen *et al.* [8] and Tellado *et al.* [9] proposed iterative techniques to estimate and eliminate the clipping noise in OFDM.

However, besides the well-known and investigated BER degradation and out-of-band radiation, OFDM signal sensitivity to nonlinear amplification has in addition another important consequence. The pilot symbols based channel estimation inserts so-called pilot symbols into the transmission signal to carefully select either frequency and/or time domain patterns for the purpose of acquiring almost perfect channel state information (CSI). In the case of nonlinear amplification, the pilot symbols are also nonlinearly distorted and therefore CSI acquired by traditional estimation techniques is inaccurate [10]. As follows from the aforementioned discussion, the joint effect of the nonlinear amplification and the multi-path propagation is inevitably required for the improvement of overall BER performance. Note that most papers assume only linear communication channels and linear channel equalization, and unfortunately the nonlinear distortion resulting from the large OFDM envelope fluctuation is in this case not taken into account.

The nonlinear equalization introduced in [11] is often described as computationally demanding and the optimal decisions are difficult to implement in practice due to the high degree of complexity. Because of this fact, one needs to find another, simpler approach to combat the joint effect of the nonlinear distortion and multi-path propagation. The promising solution is described in [12], where an algorithm of the nonlinear equalization applied in the OFDM system that estimates separately a linear multi-path channel and transmitted data is introduced.

In this paper, we introduce a similar idea based on the technique introduced in [9] but reformulated for OFDM based transmission systems with imperfect CSI due to the nonlinear distortion. The joint data and pilot symbol recovery is based on the nonlinear noise cancellation that is carried out in an iterative manner. Simulation results show that the proposed scheme reduces significantly the BER degradation of the OFDM systems undergoing nonlinear multi-path propagation.

This paper is organized as follows: The next Section describes the OFDM system model including the basic models of nonlinear high power amplifiers (Subsection 2.1) and the channel model (Subsection 2.2). In the Section 3, the proposed iterative receiver for the iterative nonlinear distortion cancellation and channel re-estimation is introduced, and subsequently, the simulation results are presented in the Section 4. Section 5 contains the conclusion and some considerations concerning future research.

2 OFDM System Model

The block scheme of the investigated OFDM system is presented in Figure 1. As can be observed from the figure, the bits assigned for the transmission are first mapped into the complex-valued vector of QAM constellation points. Then, every $m-th$ block of the mapped symbols is put into parallel streams using the serial to parallel converter, resulting in a $\mathrm{X}_s^m = [\mathrm{X}_0^m, \ldots, \mathrm{X}_{N-1}^m]^{\mathrm{T}}$.

In the next step, the pilot symbols are inserted into the OFDM frame with a uniform distribution among all N sub-carriers using the block-type pilot arrangement (Figure 2). Then, the signal obtained by that approach is OFDM modulated. Since the OFDM signal is the sum of N independent tones with equal bandwidth and the frequency separation $1/T$, the complex baseband OFDM signals are usually generated by using the inverse Fast Fourier transform (IFFT) as follows:

$$x_f^m(n) = IFFT(X_k^m) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k^m \exp\left(\frac{j2\pi kn}{N}\right), \quad (1)$$

where $x_f^m(n)$ is the resultant T/N - spaced discrete-time vector, and m denotes the m-th block of the input symbols.

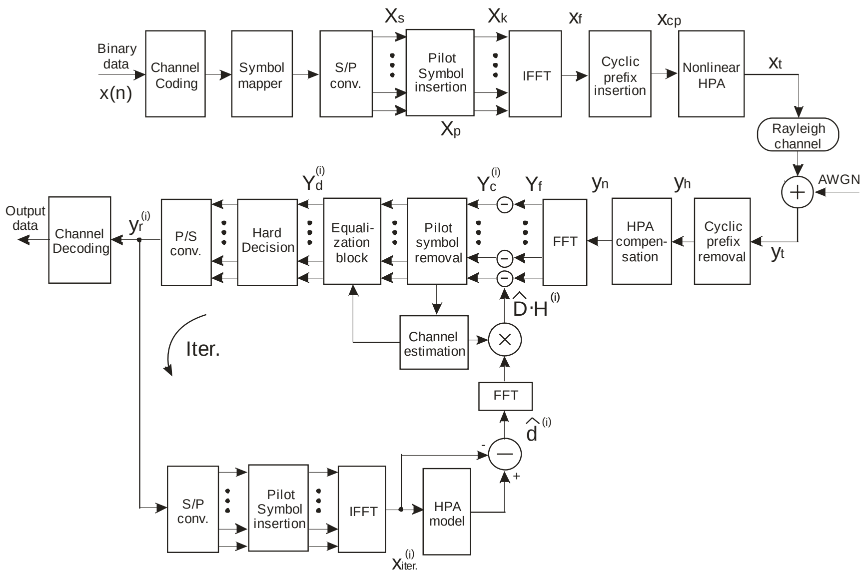

Figure 1
The block scheme of the OFDM system with iterative receiver

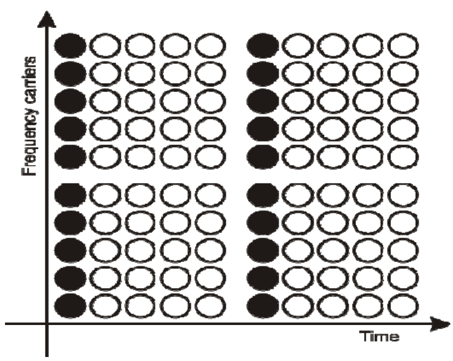

Figure 2
The block type of the pilot symbol arrangement

With the aim to mitigate the ISI introduced by the multi-path propagation of the transmitted signal, a carefully selected cyclic prefix (CP) is used. CP consists of a cyclically extended part of the OFDM symbol over the time interval $[0, T_{CP}]$. Its length is set longer than the delay spread assumed during the signal transmission. The resulting OFDM symbol with CP is afterwards given as

$$x_{cp}(n) = \begin{cases} x_f(N+n), & n = -N_g, -N_g+1, ..., -1 \\ x_f(n), & n = 0, 1, ..., N-1 \end{cases}, \quad (2)$$

where N_g is the length of a guard interval and N is the length of the OFDM symbol. This CP significantly simplifies the design of the equalization circuits because the equalization can be realized as a simple one-tap equalizer, as long as the length of the channel multi-path during the transmission is shorter than the designed CP. Finally, the signal $x_{cp}(n)$ is amplified by a high-power amplifier (HPA).

In this paper, the discrete time indexing $x(n)$ denotes Nyquist rate samples. In order to avoid aliasing and the out-of-band radiation to data bearing tones, the oversampling of the original signal $x(n)$ was implemented in simulations as described in [6].

2.1 Description of HPA Nonlinearity

In this paper, three types of HPA models are used, namely the Saleh model, the Soft Limit model and the Rapp model of nonlinearity. The Saleh model can be described by the following amplitude-to-amplitude modulation (AM/AM) and amplitude-to-phase modulation (AM/PM) characteristics:

$$G(u) = \frac{\kappa_G . u}{1 + \chi_G . u^2}, \quad \Phi(u) = \frac{\kappa_\Phi . u^2}{1 + \chi_\Phi u^2}. \quad (3)$$

In the expression above, we have chosen $\kappa_G = 2, \chi_G = \chi_\Phi = 1$ and $\kappa_\Phi = \pi / 3$. The Saleh model is used to evaluate the performance of a highly nonlinear HPA, which introduces not only amplitude but also phase distortion.

The Rapp model of the HPA is used to model solid state power amplifiers (SSPA) and is described with following AM/AM and AM/PM characteristics:

$$G(u) = \frac{\kappa_G u}{\left(1 + \left(\frac{u_x}{O_{sat}}\right)^{2s}\right)^{\frac{1}{2s}}}, \quad \Phi(u) = 0. \quad (4)$$

And finally, the Soft Limiter of HPA can be described as:

$$G(u) = \begin{cases} u & if \quad u \le 1 \\ 1 & otherwise \end{cases}, \qquad \Phi(u) = 0. \tag{5}$$

The Soft Limiter is used to model the case when pre-distortion is done at the transmitter. The operation point of the HPA is defined by the so-called input back-off (IBO), which corresponds to the ratio between the saturated and average input powers [3].

Let us now analyze the signal at the output of HPA. The following formulation exploits the fact that the OFDM signals with a large number of subcarriers are complex Gaussian distributed. By using the well-known Bussgang theorem [16], the output $y(t)$ of a memory-less nonlinearity with a Gaussian input $x(t)$ can be written as the sum of a scaled input replica of input signal and an uncorrelated distortion term $d(t)$ as

$$y(n) = \alpha.x(n) + d(n), \quad \text{where} \quad \alpha = \frac{R_{xy}(\tau_1)}{R_{xx}(\tau_1)}, \tag{6}$$

where R_{xy} is the cross-correlation function of the signals $x(n)$ and $y(n)$, and R_{xx} is the autocorrelation function of the signal $x(n)$. τ_1 is any possible value of τ, usually $\tau_1 = 0$ is chosen. As can be observed from the Bussgang theorem, the output signal of a nonlinearity with an OFDM-based input signal is equal to a scaled version of the input signal plus an uncorrelated distortion term. The complex scaling term α introduces a uniform attenuation and rotation to the data bearing tones and, therefore, it is responsible for the uniform attenuation and rotation of the signal constellation points. However, this can be easily compensated for at the receiver by introducing a correcting factor $\alpha^* / |\alpha|^2$. On the other hand, the distortion term $d(n)$, also often denoted as nonlinear noise, is responsible for clouding of the constellation and out-of-band radiation and cannot be compensated for by conventional receivers [17].

2.2 Channel Model

The output signal of the transmitter x_t is finally transmitted through the frequency-selective multi-path Rayleigh fading channel with additive white Gaussian noise (AWGN). In our simulations, the transmission channel was modelled as a 4-tapped COST 207 RA (Rural Area) channel [18], with characteristics given in Table 1.

Table 1
The tap coefficients of the COST 207 RA Rayleigh fading channel

Tap number	Delay [μs]	Power [dB]
1	0	-2.408
2	0.2083	-4.408
3	0.4167	-12.41
4	0.625	-22.41

The signal at the receiver antenna can be expressed as:

$$\begin{aligned} y_t(n) &= x_t(n) * h_t(n) + w(n) \\ &= (\alpha \cdot x_t(n) + d(n))h_t(n) + w(n), \end{aligned} \tag{7}$$

where $w(n)$ is the additive white Gaussian noise with zero mean and variance N_0 and $h_t(n)$ is the channel impulse response.

3 Structure of Iterative Receiver

Using the nonlinear amplifier, data symbols as well as pilot symbols are distorted by the nonlinear noise. In a system where the estimated CSI is used, the deterioration of the pilot symbols results in a significant degradation of CSI, and therefore, a less reliable equalization and subsequent data detection. The proposed iterative receiver decreases the nonlinear distortion caused to data and pilot symbols by a nonlinear cancellation, firstly proposed in [12] for clipping noise mitigation, in an iterative manner. Then, using the corrected pilot symbols, which are less distorted by nonlinear noise, the channel is in every iteration re-estimated and used for the more reliable equalization and subsequent data detection. Using this approach, the performance of the iterative receiver operating with the real CSI is significantly improved. The operation of the proposed iterative receiver is described in more detail in the following text.

Following Figure 1 at the receiver side, the CP is removed and the received signal is compensated by the complex scaling term α in a block of HPA compensation, as suggested in [17]. This compensation is realized as the simple channel equalization block set up with the correcting factor $\alpha^* / |\alpha|^2$. The output signal of the block of HPA compensation is sent to the FFT block for OFDM demodulation realizing the following operation:

$$\begin{aligned} Y_f(k) &= FFT\{y(n)\} \qquad k = 0,1,2...,N-1 \\ &= \frac{1}{N}\sum_{n=0}^{N-1} y(n)\exp\left(-\frac{j2\pi kn}{N}\right). \end{aligned} \tag{8}$$

Following the FFT of transmitted signal, the pilot symbols are removed from the received sequence of the data and CSI is estimated in the channel estimation block. Because the pilot symbols, similarly to the data symbols, are subject to the nonlinear amplification, the performance of the channel state estimation is degraded not only by the AWGN noise and channel fluctuations, but also by the nonlinear distortion due to the transmitter HPA.

The estimated CSI is further used in the channel equalization block, which has been implemented utilizing zero forcing method.

After equalization, the obtained signals are converted from the parallel streams to a serial sequence by the parallel-to-serial converter. The QAM constellation points are estimated using the hard decision block.

These hard estimates are subsequently fed into the backward loop of the iterative receiver, the simplified version of which has been firstly used in [6] for the mitigation of the clipping noise.

In the backward loop the nonlinear noise $d(n)$ can be estimated from received vector $y_r(n)$ and further subtracted from the signal $Y_f(k)$, thus decreasing the distortion effect of the nonlinear HPA. Although this estimate of the nonlinear noise denoted as $\hat{d}(n)$ is degraded by the incorrect estimate of the transmitted signal $x(n)$ and by CSI degraded by the channel noise and the nonlinearly distorted pilot symbols, the overall performance will be improved if:

$$E[|d(n)-\hat{d}^{(i)}(n)|^2] < E[|d(n)|^2]. \tag{9}$$

The resulting signal $Y_c^{(i)} = Y_f - \hat{D} = Y_f - FFT(\hat{d})$ will be less distorted by the nonlinear noise, and subsequently decoding will result in a better and more reliable estimate of $y_r(n)$. The symbol (i) denotes the order of the loop in the iterative process, and in this manner it will be used throughout the following text.

Newly estimated $y_r^{(i)}$ can be further fed into the feedback of the iterative receiver again, thus increasing the overall performance with every iteration of the iterative receiver.

The outlined iterative process of decreasing the nonlinear noise inflicted by the HPA to the transmitted pilot symbols and the data can be described as follows:

1) From the signal Y_f obtained from the output of FFT, the pilot symbols are extracted. Then, the CSI is obtained in channel estimation block at the pilot symbol positions by performing

$$H_p^{(i)}(k) = \frac{Y_p(k)}{X_p(k)} \quad k = 0,1,...,N-1 \tag{10}$$
$$= \frac{H(k)\cdot X_p(k) + H(k)\cdot D + n}{X_p(k)},$$

where $Y_p(k)$ and $X_p(k)$ are the received and transmitted pilot signals at the $k-th$ pilot symbol position, D is FFT of the nonlinear distortion d inflicted by the nonlinear amplifier, and (i) denotes the iteration number.

2) Using this estimated CSI, the data symbols are equalized by utilizing zero forcing, and hard decisions of the constellation points are made by

$$\overline{X}_n^{(i)} = \min_{\{X\}} |Y_d^{(i)} - \eta_n X|, \quad 0 \le n \le N-1. \tag{11}$$

3) The hard decision of the constellation points are then OFDM modulated by using IFFT:

$$x_{iter.}^{(i)} = \frac{1}{\sqrt{N}} \sum_{n=0}^{N\text{-}1} \overline{X}_n^{(i)} \exp\left(\frac{j2\pi kn}{N}\right), \quad 0 \le k \le N\text{-}1. \tag{12}$$

4) Resulting signal $x_{iter}^{(i)}$ is sent to the model of HPA given by $\mathrm{q}(\cdot)$ as a nonlinear function. Nonlinearly distorted output of the model is then subtracted from its original version, thus creating an estimate of the nonlinear noise $\hat{d}(n)$ inflicted to the data as well as the pilot symbols by the nonlinear HPA:

$$\begin{aligned}\hat{d}^{(i)}(n) &= q(x_{iter.}^{(i)}) - x_{iter.}^{(i)} \\ &= (x_{iter.}^{(i)}(n) + d_{x_{iter}}^{(i)}(n)) - x_{iter.}^{(i)}(n). \\ &= d_{x_{iter}}^{(i)}(n)\end{aligned} \tag{13}$$

5) The nonlinear noise is then transformed into the frequency domain and multiplied by the estimated CSI:

$$\hat{D}^{(i)} \cdot H(k)^{(i)} = FFT(\hat{d}^{(i)}) \cdot H(k)^{(i)}. \tag{14}$$

6) Finally, the resulting signal is subtracted from the output $Y_f(k)$ of FFT, thus decreasing the nonlinear noise in an iterative manner:

$$Y_c^{(i+1)}(k) = Y_f(k) - \hat{D}^{(i)} \cdot H(k)^{(i)}. \tag{15}$$

Then, the iterative process goes back to the step 1, where the pilot symbols are extracted from the data stream and a new process of the obtaining estimate of the CSI and the detection of the data symbol begins, but now less distorted by the nonlinear noise. In our simulations, the maximum number of the examined iterations was set to 7; however, in most of the simulations, the system achieved very good performance in a fewer number of the iterations, and in that case, the results with most important iterations are only shown in the simulation results. Although resulting signals will still be distorted by the nonlinear noise and by the imperfect CSI, which is degraded by a cumulative effect of the imperfect estimate and the nonlinear distortion of the pilot symbols, they will be now much less affected by the nonlinear noise. The resulting data are finally decoded in channel decoding block using the Viterbi decoding algorithm.

4 Simulation Results

The performance results of the OFDM system with the proposed iterative receiver for joint nonlinear distortion cancellation and channel re-estimation have been obtained using Monte Carlo computer simulations. Simulations were performed using 256 and 512 subcarriers with 64-QAM modulation. We considered OFDM transmission system with the Saleh, Soft limit and Rapp models of nonlinear amplifier. Transmitted signals were generated by using 4-multiple oversampling. The CP length was set to 3.33 μs. Subcarrier spacing was set to 18.74 kHz. The summary of all important simulation parameters is given in Table 2.

Table 2
The summary of the important simulation system parameters

Parameter	**Specification**
Number of subcarriers	256 and 512
Base-band modulation	64-QAM
Frame length	7
Channel model	COST207 RA (Rural Area) 4-tap channel
Noise	AWGN
Cyclic prefix length	3.33 μs, 6.66 μs
Equalization method	Zero forcing
Pilot symbols arrangement	Block-type
Pilot symbols per OFDM symbol	29
Data symbols per OFDM symbol	227
Oversampling factor	4

The simulation results outlined in the Figure 3 correspond to the Soft limit model of nonlinearity with IBO level = 1 dB for the OFDM system with 256 subcarriers and 64 QAM. The top-most curve is the bit-error rate for the coded system using convolution codes with a conventional, non-iterative receiver (e.g. without backward loop depicted in Fig. 1) with zero forcing equalization. The three curves below correspond to the BER after the first, second and third iteration of the iterative algorithm without improvement of CSI in the loops of the iterative receiver. The following three curves correspond to the BER after the first three iterations of the proposed iterative algorithm. Finally, the bottom-most curve is the BER for the linear HPA at the transmitter. The simulation results show that for Soft limit model of the nonlinearity, three and even two iterations are sufficient for the compensation of transmitter nonlinearity. From this figure, it is easily observable that the difference between the ideal, linear BER curve and the BER curve after third iteration of the proposed algorithm is negligible, and the iterative receiver significantly counteracts the nonlinear distortion inflicted to transmission by HPA.

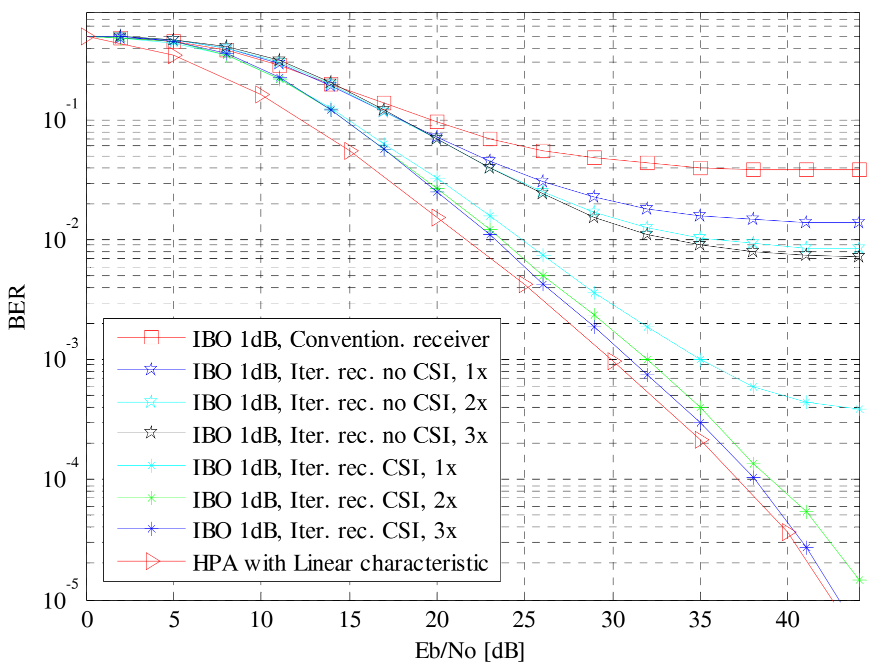

Figure 3
Performance of the iterative algorithm for a Soft Limit nonlinearity model with IBO = 1, 256 subcarriers, 16-QAM

Figure 4 presents the simulation results for the Saleh model of nonlinearity with IBO = 5 dB. The top-most curve corresponds to a typical non-iterative conventional receiver with zero forcing equalization. The 3 subsequent curves (denoted as 'Iter.rec.noCSI' in figure legend) correspond to an iterative receiver without improvement of the CSI with the estimated nonlinear distortion. The next seven curves correspond to the proposed iterative receiver. Their marks in the figure legend, '1x', '2x' and so on, correspond to the number of iterations of the investigated iterative receiver, which resulted in the creation of corresponding BER curves. With every following iteration, the channel is re-estimated and the nonlinear noise is more precisely estimated and then compensated, thus further increasing the performance. As can be seen from Figure 4, after 7 iterations the proposed algorithm can significantly compensate for nonlinear distortion, with a difference of less than 1 dB at BER = 5.10e-5 from the ideal case corresponding to a linear amplifier.

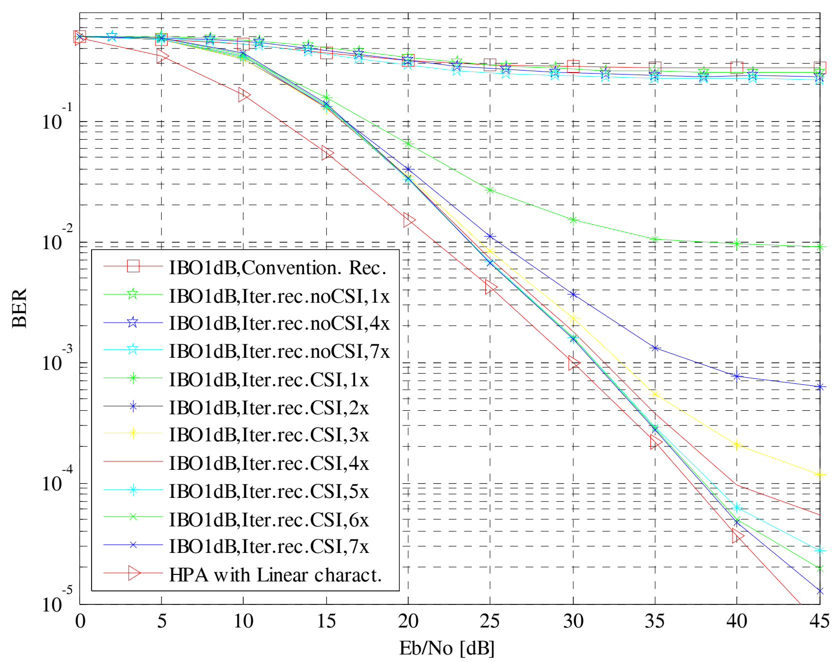

Figure 4

Performance of the iterative algorithm for the Saleh nonlinearity model with IBO = 1, 256 subcarriers, 16-QAM

In the case of the Rapp model of nonlinearity (Figure 5) with severe nonlinear distortions (IBO=1dB), the proposed iterative algorithm of the nonlinear noise cancellation and channel re-estimation provides a significant BER performance improvement (from $3*10^{-1}$ to $4*10^{-5}$ at E_b/N_0 = 40 dB), and in four or five iterations counteracts the nonlinear distortion almost completely.

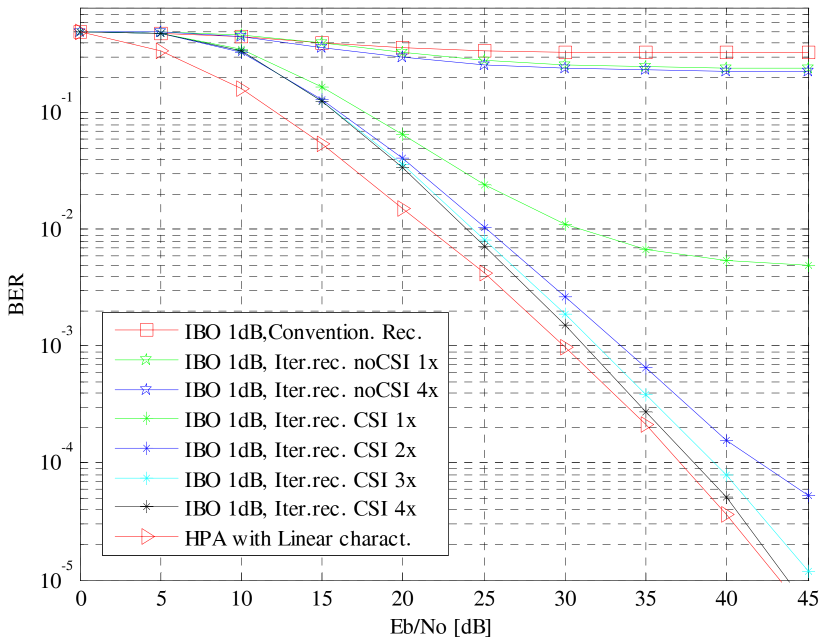

Figure 5

Performance of the iterative algorithm for the Rapp model of nonlinearity with IBO = 1, for OFDM system with 256 subcarriers, 16-QAM modulation

Figure 6 presents the results for the nonlinearly distorted OFDM system with 512 subcarriers and 64-QAM modulation with the Saleh model of nonlinearity with IBO = 5 dB. The top-most curve is BER for the conventional, non-iterative receiver, e.g. a receiver without backward loop for nonlinear noise cancellation and channel re-estimation. As in the previous figures, the iterative algorithm improves the BER significantly. From the figure, it is easily observable that the difference between the ideal linear BER curve and the BER curve after the fourth iteration of the proposed algorithm is negligible, and the investigated iterative receiver can be used effectively for the compensation of nonlinear distortion inflicted to data and pilot symbols by nonlinear HPA. This would allow for the utilization of HPA in their nonlinear part of characteristic, thus resulting in more efficient energy consumption of OFDM transmitters.

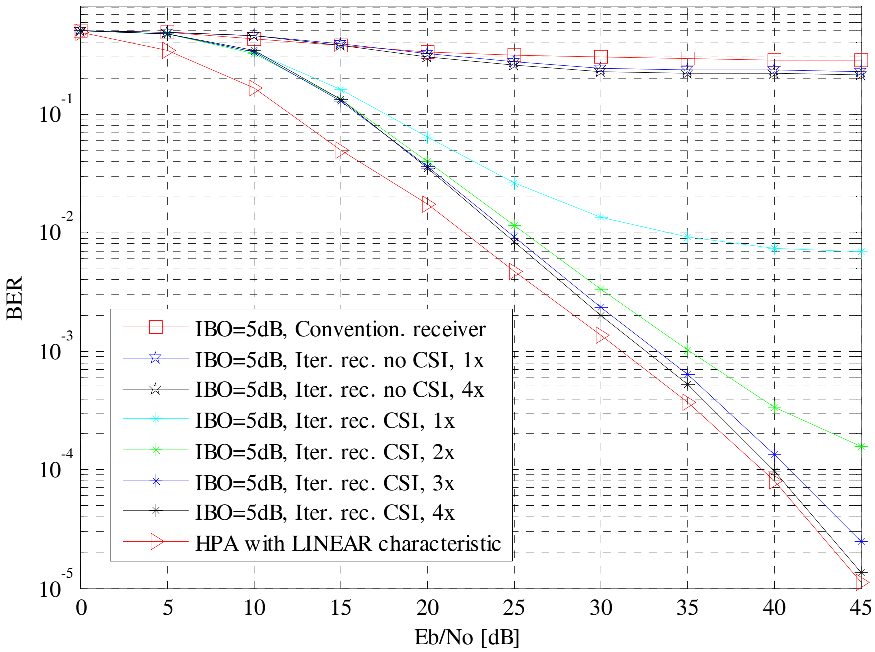

Figure 6
Performance of the iterative algorithm for the Saleh model of nonlinearity model with IBO = 10, 512 subcarriers, 64-QAM

Conclusion

In this paper, the iterative algorithm for nonlinear noise estimation and subsequent noise cancellation and channel re-estimation is introduced. This algorithm estimates nonlinear distortion inflicted on data as well as pilot symbols, and subsequently uses it for data recovery and channel re-estimation in an iterative manner. With every following iteration, the data symbols and CSI are less distorted by the nonlinear noise, which results in a more reliable detection and improved BER performance. The application of the proposed algorithm in nonlinearly distorted OFDM symbols improves BER significantly for all tested models of the nonlinear HPA. The presented results have shown that each iteration of the presented algorithm improved the BER performance until the nonlinear distortion was significantly negligible. For the Saleh model of the HPA with 512 subcarriers and 64-QAM, the first iteration of the proposed algorithm improved BER from $3.10e^{-1}$ to $7.10e^{-3}$ at E_b/N_0 = 45 dB. The next iteration provided additional gain. The results have shown that the proposed algorithm can be used effectively to reduce the nonlinear distortion of the OFDM symbols with the real CSI obtained through pilot symbol channel estimations.

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