TIME-DOMAIN ADAPTIVE PREDISTORTION FOR NONLINEAR AMPLIFIERS

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ABSTRACT

This paper is concerned with a new time-domain adaptive predistortion scheme for compensating nonlinearity of high power amplifiers (HPA) in OFDM systems. A complex Wiener-Hammerstein model (WHM) is adopted to describe the input-output relationship of unknown HPA with linear dynamics, and a power series model with memory (PSMWM) is proposed to approximate the HPA expressed by WHM. By using the PSMWM, the compensation input to HPA is calculated in a real-time manner so that the linearization from the predistorter input to the HPA output can be attained even if the nonlinear input-output relation of HPA is uncertain and changeable. The effectiveness of the proposed predistortion method is validated by numerical simulation for 64QAM–OFDM systems.

1. INTRODUCTION

The pursuit of high power efficiency in orthogonal frequency division multiplexing (OFDM) communication systems generally results in that a high power amplifiers (HPA) in transmitter often operates near saturation regions. The saturation characteristics of HPA cause the out-of-band leakage of signal power and in-band distortion of signal waveform, which usually degrade the transmission quality seriously. Thus, linearized compensation of HPA is a very important task in OFDM systems applications.

Some predistortion methods have been developed to compensate the nonlinear distortion of amplifiers. Unfortunately, many ordinary look-up table (LUT) methods need large storage and their convergences are slow [1]. The inverse modeling approach based on the Volterra series analysis has also been proposed to give a predistortion scheme for the static nonlinearity of HPA [2]. Furthermore, data-based learning techniques of neural network [3] and support vector machine approach [4] are also utilized to solve the nonlinear predistortion in the time domain. However, the previous approaches do not consider linear dynamics in HPA.

For nonlinear HPA with linear dynamics, Volterra series model (VSM) based predistortion was proposed [5], its on-line implementation is rather difficult because of the computational complexity. To overcome such problems, a more efficient compensation method based on adaptive identification has been proposed in [6], where the predistorter (PD) is identified as an inverse of complex Wiener model of HPA by using real data calculation.

The purpose of this paper is to propose a new time-domain adaptive predistortion scheme for compensating distortions of HPA expressed by a Wiener-Hammerstein model. For this HPA, a predistortion method based on adaptive identification has been proposed in [7], where inverse of the HPA is approximated by power series model with memory (PSMWM) and a PD of the HPA is realized by using a copy of the estimated PSMWM. In this paper, we give the adaptive predistorter directly by using other approximation PSMWM of the HPA, unlike the above identification method, which need to identify the inverse of the HPA.

2. MODEL OF HPA

2.1. Nonlinear distortion for HPA

We consider the HPA used in the transmitter of OFDM systems [6]. The predistortion scheme is performed in baseband-equivalent system, in which the baseband OFDM signal can be expressed by

$$s(n) = \sum_{k=-N}^{k=N-1} c_k e^{j2\pi kn/N} = s_I(n) + js_Q(n) \tag{1}$$

Here, N is the IFFT size, and c_k is the information symbol which is expressed as $c_k = a_k + jb_k (0 \leq k < K)$ where $a_k, b_k \in \{\pm1, \pm3, \pm5, \pm7\}$ in the 64QAM–OFDM case. K is the carrier number and $c_k = 0$ holds for $k \geq K$, i.e., c_k does not carry any information in the carriers. $s_I(n)$ and $s_Q(n)$ are the in-phase and quadrature components respectively.

The nonlinearity $G(\cdot)$ of HPA without memory is often expressed by using the amplitude distortion (AM–AM conversion) $A(|x(n)|)$ and phase distortion (AM–PM conversion) $P(|x(n)|)$, as

$$y(n) = G(x(n)) = A(|x(n)|)e^{j\{\angle x(n) + P(|x(n)|)\}} \tag{2}$$

where $x(n)$ and $y(n)$ represent the input and output of memoryless HPA, respectively. For example, a typical traveling wave tube amplifier (TWTA) is widely used in simulation, and the memoryless distortions can be characterized by the following Saleh's model [8].

$$A(|x(n)|) = \frac{2|x|}{1+|x|^2}, \quad P(|x(n)|) = \frac{\pi}{3}\frac{|x|^2}{1+|x|^2} \tag{3}$$

Here, the output amplitude is normalized by its saturated magnitude. The most popular index for the nonlinearity of HPA is the output back-off (OBO) which is defined by

$$OBO = 10 \log \frac{P_{o,sat}}{P_o} \tag{4}$$

where P_o denotes the mean output power of HPA and $P_{o,sat}$ represents the maximum output power of HPA in the saturation zone.

2.2. Wiener-Hammerstein model for HPA

In order to take into account the frequency-dependent distortion due to linear dynamics, for instance, a frequency-domain Wiener-Hammerstein model has been proposed to describe the input-output

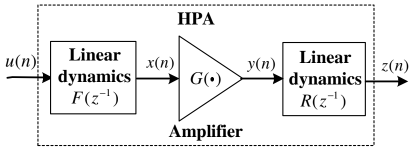


Fig. 1. A complex Wiener-Hammerstein model for HPA

relationship of HPA [9]. In this paper, we adopt a complex Wiener-Hammerstein model (WHM) as shown in Fig. 1, which has a structure similar to [7]. $F(z^{-1})$ is a linear dynamics like a pulse shaping filter, and the $G(\cdot)$ is a nonlinear statics which is followed by a linear dynamics $R(z^{-1})$. Here, we assume that $F(z^{-1}) = f_0 + f_1 z^{-1} + \cdots + f_{n_f} z^{-n_f}$ is a stable FIR filter, and $R(z^{-1}) = z^{-L}N(z^{-1})/D(z^{-1})$ and its inverse are also stable dynamics.

2.3. A power series model with memory

In numerical simulation, the WHM as shown in Fig. 1 will be applied to describe the input-output relationship of an unknown HPA. On the other hand, a power series model with memory (PSMWM) as expressed in (6) is adopted to construct the PD of the HPA, because this PSMWM can approximate the WHM [7].

$$\hat{z}(n) = \hat{\sigma}(u(n-L)) \tag{5}$$

$$= \sum_{m=0}^{L_p}\sum_{l=0}^{L_g} \hat{g}_{2l+1,m}|u(n-m-L)|^{2l}u(n-m-L) \tag{6}$$

where L_p represents the memory length and $(2L_g+1)$ is the model order. $\hat{g}_{2l+1,m}$ are complex coefficients.

3. ADAPTIVE PREDISTORTION FOR HPA

3.1. Adaptive predistortion system

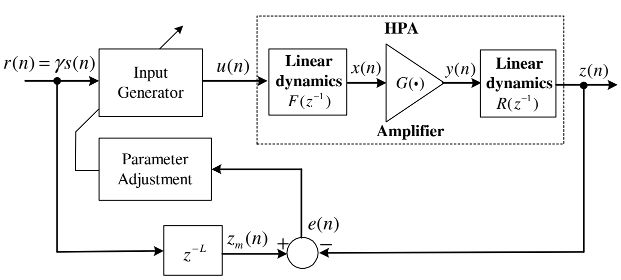


Fig. 2. Time-domain adaptive predistortion system for HPA

The proposed time-domain adaptive predistortion system for the nonlinear HPA is illustrated in Fig. 2, and is executed in the baseband process. Since the desired input-output property is linear, the desired response dynamics is specified as

$$z_m(n) = z^{-L}r(n) = \gamma z^{-L}s(n) \tag{7}$$

where $z_m(n)$ is the desired output of the system, $s(n)$ is the input OFDM signal of the system, and γ is a nominal gain of linear amplifier.

The output error between the desired output and the output of HPA is defined by

$$e(n) = z_m(n) - z(n) \tag{8}$$

If the input $u(n)$ to HPA is generated so that the output of HPA can track perfectly the ideal linear amplifier output $z_m(n)$, then the input generator can perform as a predistorter, that can compensate the nonlinearity of HPA for arbitrary OFDM signal. The purpose of the paper is to generate directly $u(n)$ that realizes the above output tracking even in the presence of uncertainties and changes in the HPA.

3.2. Linearization of HPA

The output error can be obtained by

$$\begin{aligned} e(n+L) &= z_m(n+L) - z(n+L) \\ &= r(n) - \sum_{m=0}^{L_p}\sum_{l=0}^{L_g} \hat{g}_{2l+1,m}|u(n-m)|^{2l}u(n-m) \\ &= \gamma s(n) - \boldsymbol{\zeta}^{\mathrm{H}}(n)\boldsymbol{\theta} \end{aligned} \tag{9}$$

where $\boldsymbol{\zeta}^{\mathrm{H}}(n)$ and $\boldsymbol{\theta}$ are complex vectors defined by

$$\boldsymbol{\theta} = [g_{1,0}, g_{3,0}, \ldots, g_{2L_g+1,0}, \ldots, g_{2L_g+1,1}, \ldots, g_{2L_g+1,L_p}]^{\mathrm{T}} \tag{10}$$

$$\boldsymbol{\zeta}^{\mathrm{H}}(n) = [\boldsymbol{\zeta}_0^{\mathrm{H}}(n), \boldsymbol{\zeta}_1^{\mathrm{H}}(n), \ldots, \boldsymbol{\zeta}_{L_p}^{\mathrm{H}}(n)] \tag{11}$$

$$\boldsymbol{\zeta}_0^{\mathrm{H}}(n) = [u(n), |u(n)|^2u(n), \ldots, |u(n)|^{2L_g}u(n)] \tag{12}$$

$$\begin{aligned} \boldsymbol{\zeta}_m^{\mathrm{H}}(n) = [&u(n-m), |u(n-m)|^2u(n-m) \\ &, \ldots, |u(n-m)|^{2L_g}u(n-m)] \end{aligned} \tag{13}$$

$$\boldsymbol{\zeta}_m^{\mathrm{H}}(n) = \boldsymbol{\zeta}_0^{\mathrm{H}}(n-m) \quad \text{for} \quad m = 1, \ldots, L_p. \tag{14}$$

Here, the superscript H denotes a conjugate transpose.

The input $u(n)$ which can force $e(n+L)$ into zero is given by a solution of the complex nonlinear equation (15).

$$\sum_{m=0}^{L_p}\sum_{l=0}^{L_g} g_{2l+1,m}|u(n-m)|^{2l}u(n-m) - \gamma s(n) = 0 \tag{15}$$

Thus the input $u(n)$ satisfying equation (15) can attain stable tracking $z(n) \to z_m(n)$, and the linearized compensation for the nonlinearity of HPA can be achieved. The question is how to obtain the solution of (15).

3.3. Adaptive input generator

When the parameters in the model for HPA are uncertain, the coefficients of (15) are also uncertain, so these parameters $\boldsymbol{\theta}$ should be replace by their estimates $\hat{\boldsymbol{\theta}}(n)$. The adaptive algorithm for adjusting the parameters $\hat{\boldsymbol{\theta}}(n)$ employs the RLS method [6, 7].

Then the compensation input $u(n)$ is a solution of the following equation with the estimated coefficients as

$$\begin{aligned} &\hat{g}_{2L_g+1,0}|u(n)|^{2L_g}u(n) + \cdots + \hat{g}_{3,0}|u(n)|^2u(n) + \hat{g}_{1,0}u(n) \\ &= \gamma s(n) - \sum_{m=1}^{L_p}\sum_{l=0}^{L_g} \hat{g}_{2l+1,m}(n)|u(n-m)|^{2l}u(n-m) \end{aligned} \tag{16}$$

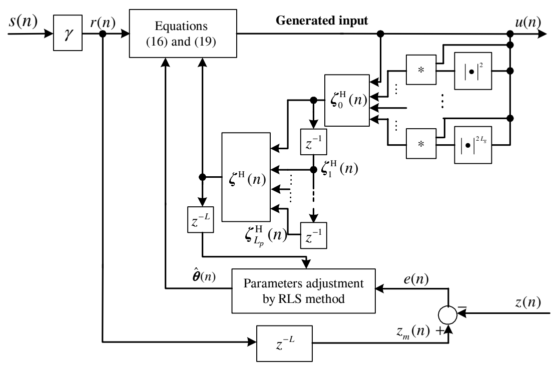


Fig. 3. Structure of adaptive input generator for linearization of HPA

A structure of the adaptive input generator is illustrated in Fig.3. By denoting the nonlinear equation (16) by $f(u_n) = 0$, and denoting its solution by $u_n = u(n) = v_n + jw_n$, $f(u_n)$ is rewritten as

$$f(u_n) = f_1(v_n, w_n) + f_2(v_n, w_n)j \tag{17}$$

where $f_1(v_n, w_n)$ and $f_1(v_n, w_n)$ denote the real and imaginary parts of $f(u_n)$, respectively. The solution of $f(u_n) = 0$ is the same as that of

$$f_1(v_n, w_n) = 0 \qquad f_2(v_n, w_n) = 0 \tag{18}$$

Then by introducing the error index function as

$$S(v_n, w_n) = \frac{1}{2}({f_1}^2(v_n, w_n) + {f_2}^2(v_n, w_n)) \rightarrow min \tag{19}$$

the procedure for solving the complex equation (16) is reduced to the minimization of $S(v_n, w_n)$ with the real variables v_n and w_n.

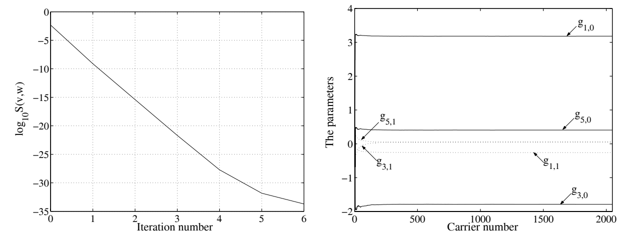
4. NUMERICAL SIMULATION RESULTS

In this section, we investigate the effectiveness of the proposed time-domain adaptive predistortion scheme in simulation studies.

The setup and conditions for the simulation are summarized as follows:

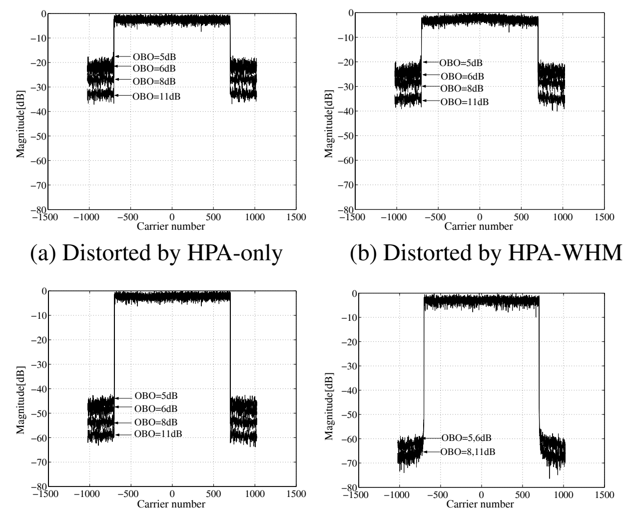
- The FFT size N is 2048 and the carrier number K is 1405.
- HPA has a memoryless $G(\cdot)$ as (3), and linear dynamics $F = [0.8, 0.1]$ and $R = 3.2z^{-1}/(1 + 0.2z^{-1})$.
- In (6), the order and memory length of the PSMWM are chosen as $L_g = 2$ and $L_p = 1$.
- The simple gradient method is adopted to obtain the compensation input $u(n)$, and the initial value of $u(n)$ is always set to zero.

First of all, we show the convergence rate of the minimization of $S(v, w)$ to determine and generate the compensation input $u(n)$. The value of $\log_{10} S(v_n, w_n)$ are plotted versus the iteration number in Fig. 4 (a). It can be noticed that the decreasing rate of $S(v_n, w_n)$ is very fast and the calculation for searching $u(n)$ needs only one iteration. This makes the proposed method feasible.



(a) $\log_{10} S(v, w)$ (b) $\hat{\theta}(n)$

Fig. 4. Decreasing rate of $\log_{10} S(v, w)$ in the iterative procedure for $u(n)$, and convergence of adjustable parameter $\hat{\boldsymbol{\theta}}(n)$



(a) Distorted by HPA-only (b) Distorted by HPA-WHM

(c) Compensated by method in [7] (d) Using proposed method

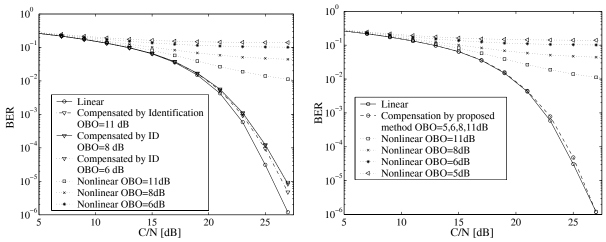
Fig. 5. Power spectra of HPA output

The parameters $\hat{\boldsymbol{\theta}}(n)$ of the input generator are adjusted by RLS method. Fig. 4 (b) shows the convergence behavior of the real part of the parameters $\hat{\boldsymbol{\theta}}(n)$. It can be seen that their convergence can be attained within one symbol length (2048 carrier number).

Next, in order to study the compensation effects for nonlinearity of HPA, we evaluate the performances of out-of-band signal power emission and signal degradation degree. The evaluations use the power spectrum of output $z(n)$ and the BER(Bit Error Rate) of transmitted signal $s(n)$.

In the above setup, only carriers between -702 and 702 have information symbol c_k to be sent, while the carriers in the out-of-band ([-1024, -701], [703, 1023]) have no information. Figs. 5 (a) and (b) illustrate the power spectra of the HPA output $z(n)$ without any compensation in case of different OBO. Fig. 5 (a) is obtained in the absence of linear dynamics, whereas Fig. 5 (b) is obtained in the case with linear dynamics. The spectral gaps between in-band and out-of-band are small due to out-of-band leakage of OFDM signal power, and in-band spectra are not flat due to linear dynamics, so the output $z(n)$ will have many distortions in amplitude and phase.

On the other hand, Figs. 5 (c) and (d) illustrate the power spectra of HPA output $z(n)$ compensated by adaptive predistortion methods in [7] and this paper. In Fig. 5 (c) the spectral gaps can be improved to 42 dB, 45dB, 50dB and 55dB by the adaptive identi-



(a) Compensated by method in [7] (b) Using proposed method

Fig. 6. Bit error rate performance versus CNR

fication method in [7], but in the case using the proposed adaptive predistortion method, the gaps can be improved to 58dB and 62dB as shown in Fig. 5 (d). It can be seen that the spectral shape in the in-band can also be perfectly flat by the adaptive predistortion methods.

Finally, we show the BER performance for CNR (Carrier to Noise Rate) in Fig. 6. The BER of signal transmitted by HPA with linear dynamics are very poor as shown by the dotted-lines. On the other hand, the BER performances compensated by the adaptive predistortion methods can be improved greatly in case of different OBO, and approximate BER performance of signal $s(n)$ transmitted by linear amplifier. Thus, it shows that the signal detection performance can be improved greatly.

5. A COMPARABLE STUDY WITH THE PREVIOUS VOLTERRA-BASED METHOD

For a comparative study, we examine the previous Volterra-based compensation method in [5]. To construct a predistorter of the HPA with linear dynamics, it utilizes a third-order Volterra series model. The inverse system of the HPA can be identified by (20). Then, a predistorter is obtained by using a copy of the estimated inverse system.

$$\hat{u}(n) = \sum_{k=0}^{N_1-1} \hat{h}_k^{(1)}(n) z(n-k) + \sum_{k=0}^{N_3-1}\sum_{l=k}^{N_3-1}\sum_{m=0}^{N_3-1} \hat{h}_{k,l,m}^{(3)}(n) z(n-k) z(n-l) z^*(n-m) \quad (20)$$

where N_1 and N_3 are the memory duration of the first-order and third-order terms, respectively. $\hat{h}_k^{(1)}(n)$ and $\hat{h}_{k,l,m}^{(3)}(n)$ are the discrete time domain Volterra kernels of the first-order and third-order, respectively, and the total number of Volterra kernels (the estimated parameters) can be represented as $K_T = N_1 + (N_3^2(N_3 + 1))/2$. In simulation, we assume that N_1 and N_3 are set to 3, and the other numerical simulation conditions are the same as those in Section 4. So, the total number of Volterra kernels is 21.

Fig. 7 shows the spectra of the output $z(n)$ compensated by the previous Volterra-based method in case of different OBO. The spectral gaps can be improved to 42dB, 46dB, 50dB and 56dB respectively. So, the compensation effects are almost the same as those in Fig. 5 (c). However, for computational complexity, the proposed method is better than the previous Volterra-based method because the number of estimated parameters in the proposed method is 6.

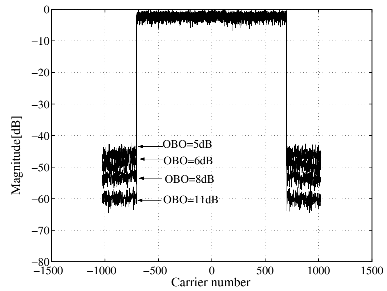


Fig. 7. Spectra of the $z(n)$ compensated by the previous method

6. CONCLUSION

A time-domain adaptive predistortion scheme has been proposed to compensate the nonlinearity of HPA. A Wiener-Hammerstein model is applied for expression of the input-output distortion of HPA with linear dynamics. Different from ordinary approaches, the proposed method gives the adaptive predistorter structure directly, which is not based on the identification of the inverse HPA. The numerical simulation results have validated that the proposed predistortion scheme can attain perfect linearization with fast convergence and less computational complexity, and will be very effective for OFDM systems.

7. REFERENCES

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