Adaptive Predistortion Compensation for Nonlinearity of High Power Amplifiers

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Abstract: In this paper, an adaptive predistortion scheme is proposed to compensate nonlinear distortions caused by high power amplifiers (HPA) in OFDM systems. A complex Wiener-Hammerstein model (WHM) is used to describe input-output relationship of HPA with linear dynamics. The predistorter is directly identified by complex power series model with memory, which is an approximate inverse of the HPA expressed by the WHM. The effectiveness of the proposed adaptive compensation scheme is validated by numerical simulation for 64QAM–OFDM systems.

Keywords: High power amplifiers, predistortion, nonlinearity compensation, adaptive identification.

1. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is to be applied in digital terrestrial television broadcasting in Japan and Europe, and mobile communication systems since it suppresses the multipath fading strongly and utilizes the available bandwidth efficiently [1-2]. However, the OFDM signal is often suffered from the saturation characteristic of high power amplifiers (HPA) in transmitter since it has large instantaneous peak power. As a result, the out-of-band signal emission and in-band signal distortion, which deteriorate the transmission quality greatly, occur in OFDM systems [3]. So, the OFDM systems require linearization of HPA.

Normally, the distortions in HPA include both nonlinear distortion caused by memoryless nonlinearity and linear distortion introduced by linear dynamics. To compensate such distortions, appropriate model description for HPA is essentially needed. Moreover, adaptive predistortion techniques are desired to compensate the uncertain nonlinearity caused by aging and temperature variations. For nonlinear HPA preceded by a linear dynamics, predistorters based on a Volterra series model [4] or power series model have been studied [5]. Nevertheless it is difficult to implement the schemes in a real time way due to their huge number of kernels under estimation and their computational complexity [4]. Furthermore, the convergence of the so-called two-stage estimation method [5] is very time consumptive since all the parameters of the Wiener model and its inverse should be estimated iteratively. To overcome such compensation problems, a more efficient compensation method based on adaptive identification has been proposed in [6] under the assumption that the Wiener model can describe the linear dynamics followed by the nonlinearity of static part of HPA, which is approximated by complex power series with finite number of terms in the baseband domain. Moreover, it can identify the inverse of the Wiener model through a complex Hammerstein model adaptively.

On the other hand, for HPA followed by a dynamical distortion, a model matching-based adaptive compensation algorithm has been developed in the time domain [7]. Moreover, for HPA expressed by the Wiener-Hammerstein model (WHM), an identification-based compensation scheme has also been studied in the frequency-domain, in which the parameters of the nonlinear element and linear dynamics are obtained iteratively in a bootstrap way [8]. The identification for WHM needs a large amount of computation and is done on a frame-by-frame basis, so it takes much time for convergence of iterative procedures. The purpose of this paper is to present a new on-line predistortion compensation method of the HPA based on adaptive identification. In this approach, a complex WHM is used to describe input-output relationship of HPA with linear dynamics. Then inverse of the WHM is approximated by power series model with memory (PSMWM). In adaptive predistortion structure for HPA, the linearization from the input of predistorter

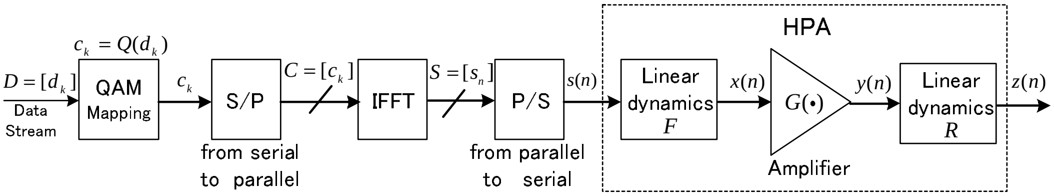


Figure 1: The baseband-equivalent system of QAM–OFDM transmitter

to the HPA output can be realized by using the copy of the estimated PSMWM. The effectiveness of the proposed compensation method is investigated by numerical simulation for 64QAM-OFDM systems.

2. NONLINEAR DISTORTION FOR HPA

Fig. 1 illustrates a simplified block diagram of the baseband equivalent system for QAM–OFDM transmitter. Let the thick line represent the stream of complex data. The d_k is the transmitted data, and c_k ($c_k = Q(d_k) = a_k + jb_k, k = 0, 1, \ldots, K, \ldots, N-1$) is complex QAM (Quadrature Amplitude Modulation) symbol in the k-th subcarrier and a_k, b_k are determined by the QAM mapping. The K is the carriers number and $c_k = 0$ holds for $k \geq K$, i.e., c_k does not carry any information in the carriers. After the serial conversion of the S/P (from serial to parallel), N-point IFFT (inverse fast Fourier transform), and P/S (from parallel to serial), the sampling data $s(n\Delta T)$, which is simply rewritten as $s(n)$, is obtained. In the OFDM system, $s(n)$ can be expressed by

$$\begin{aligned} s(n) &= \sum_{k=-N/2}^{N/2-1} c_k e^{(j2\pi kn/N)} \\ &= \sum_{k=0}^{N-1} c_k e^{(j2\pi k f_0 nT/N)} \\ &= \sum_{k=0}^{N-1} \{a_k cos(2\pi k f_0 n) - b_k sin(2\pi k f_0 n)\} \\ &\quad + j \sum_{k=0}^{N-1} \{a_k sin(2\pi k f_0 n) + b_k cos(2\pi k f_0 n)\} \\ &= u_I(n) + j u_Q(n) \end{aligned} \tag{1}$$

Where, f_0 is the subcarrier frequency interval and the k-th subcarrier frequency is given by $f_k = kf_0$. When the sampling interval is chosen as $\Delta T = 1/Nf_0$, the valid period T for one symbol frame, within which the discrete OFDM signals $\{s(n), n = 0, 1, \ldots, N-1\}$ are generated, becomes to $T = 1/f_0$. The $s_I(n)$ and $s_Q(n)$ are the in-phase and quadrature components of $s(n)$, respectively.

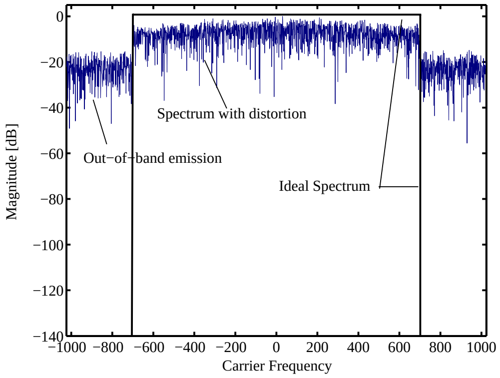


Figure 2: Spectra of OFDM signals

In order to take into account the frequency-dependent distortion due to both pulse shaping filter and electronic circuits, for instance, we adopt a complex Wiener-Hammerstein model (WHM) in Fig. 1. The $F(z^{-1})$ is a linear dynamics as pulse shaping filter [10], and the $G(\cdot)$ is a memoryless nonlinear static element which is followed by a linear dynamics $R(z^{-1})$. The desired OFDM signal $s(n)$ filtered by $F(z^{-1})$ then is input to nonlinear power amplifiers. The distortions occur in the transmitted signal $z(n)$. Moreover, the distortions include both nonlinear distortion caused by memoryless nonlinearity $G(\cdot)$ and linear distortion introduced by linear dynamics like $F(z^{-1})$ and $R(z^{-1})$. The power spectra of the ideal OFDM signal $s(n)$ and the transmitted signal with distortions are plotted in Fig. 2. The high order inter-modulated (IM) products due to the amplitude, phase nonlinearities and the frequency-dependent distortion, yield the severe interferences to detection of the original symbol c_k and cause poor bit error rate (BER) performance. Furthermore the out-of-band leakage is also the undesired interfere to other communication channels. Then the predistor-

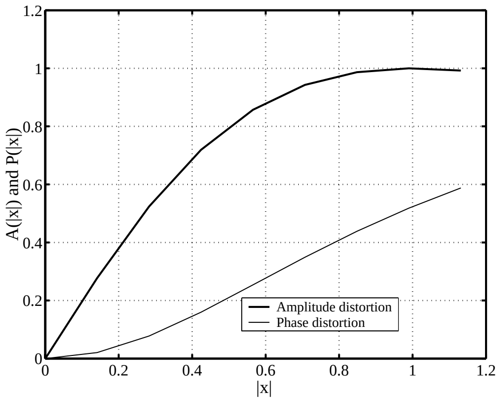


Figure 3: Input-output performance of TWTA described by Saleh model

tion compensation is essential to HPA.

In simulation, memoryless nonlinearity of a typical traveling wave tube amplifier (TWTA) is often expressed by the input-output model called Saleh. Then the output of the nonlinear TWTA is described by

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

Where, $A(|x(n)|)$ and $P(|x(n)|)$ represent the amplitude nonlinearity (AM–AM conversion) and phase nonlinearity (AM–PM conversion) of the TWTA (also named as amplitude AM–AM and phase AM–PM distortion), respectively. The memoryless distortions are characterized by the relations as [9]

$$A(|x(n)|) = \frac{\alpha_a |x|}{1+\beta_a |x|^2} \tag{3}$$

$$P(|x(n)|) = \frac{\alpha_p |x|^2}{1+\beta_p |x|^2} \tag{4}$$

Here, the output amplitude is normalized by its saturated magnitude. The distortions of amplitude and phase for the input magnitude are illustrated in Fig. 3. The most popular index for the nonlinearity of HPA is the back-off (BO). The output back-off (OBO) is defined by

$$OBO = 10 \log \frac{P_{o,sat}}{P_o} \tag{5}$$

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

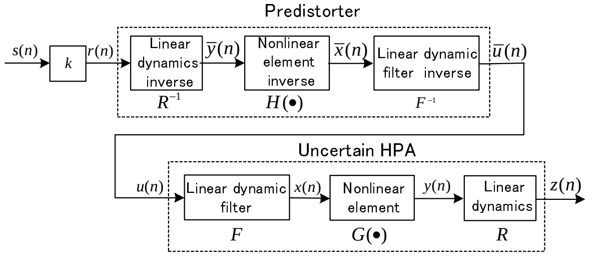


Figure 4: Predistortion structure for the HPA expressed by WHM

In this paper, the Saleh model will be applied to examine the validity of the proposed adaptive predistortion scheme. On the other hand, the complex power series model with finite terms can be approximate memoryless nonlinearity $G(\cdot)$ of HPA, which is described by

$$\begin{aligned} \hat{y}(n) &= \hat{G}(x(n)) \\ &= \hat{g}_1 x(n) + \hat{g}_3 |x(n)|^2 x(n) + \cdots + \hat{g}_{2L_g+1} |x(n)|^{2L_g} x(n) \\ &= \sum_{l=0}^{L_g} \hat{g}_{2l+1} |x(n)|^{2l} x(n) \end{aligned} \tag{6}$$

where we have interests in components within the fundamental frequency range and then take only odd-order terms [11-12]. The $(2L_g+1)$ is a model order and the $\hat{g}_{2l+1}$ is a complex number.

3. PREDISTORTION COMPENSATION OF HPA

3.1 Predistortion Structure of HPA

In order to compensate the nonlinear distortion and linear distortion of HPA with dynamics, predistortion method is discussed in this paper. The predistortion structure for the HPA expressed by WHM is shown in Fig. 4. Here, the $R^{-1}(z^{-1})$, $H(\cdot)$ and $F^{-1}(z^{-1})$ denote inverses of the $R(z^{-1})$, $G(\cdot)$ and $F(z^{-1})$ respectively, and the k is a nominal linear gain. To implement the predistorter, it is required to identify the unknown $R^{-1}(z^{-1})$, $H(\cdot)$ and $F^{-1}(z^{-1})$ adaptively, further to update the parameters by their newest estimates. When $R(z^{-1}) \cdot \hat{R}^{-1}(z^{-1}) = 1$, $G(\hat{H}(r(n))) = r(n)$ and $F(z^{-1}) \cdot \hat{F}^{-1}(z^{-1}) = 1$ are satisfied and maintained in an adaptive manner, the linearization from the predistorter input $r(n)$ to the HPA output $z(n)$ can be realized even if the nonlinearity of HPA is uncertain and changeable.

3.2 Adaptive Realization of Predistorter

In this section, the problem is to construct predistorter of HPA based on adaptive identification. Fig.5

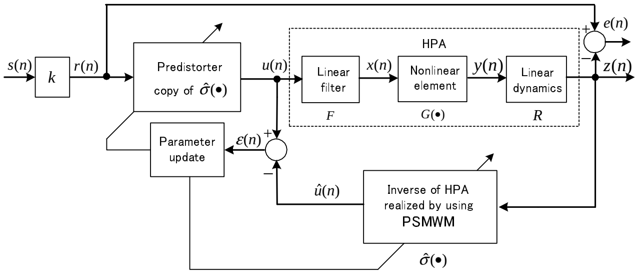


Figure 5: An adaptive identification structure for predistorter of HPA

shows an adaptive identification structure for predistorter of HPA expressed by WHM. Here, the predistorter is modeled by using a power series model with memory (PSMWM) as Eq. (8).

$$\hat{u}(n) = \hat{\sigma}(z(n)) \tag{7}$$

$$= \sum_{m=0}^{L_p} \sum_{l=0}^{L_h} \hat{h}_{2l+1,m}(n)|z(n-m)|^{2l} z(n-m) \tag{8}$$

Where, the L_p represents memory length and the $(2L_h+1)$ is order of model. The $\hat{h}_{2l+1,m}(n)$ are complex coefficients. We use this PSMWM to identfy directly the inverse of HPA. When $\hat{u}(n)$ approximates $u(n)$, by using the copy of estimated PSMWM $\hat{\sigma}(\cdot)$, the linearization from the input $s(n)$ to the output $z(n)$ can be realized. That is $z(n)$ approximates $ks(n)$.

Further, the predistorter output $\hat{u}(n)$ in Eq. (8) can be rewritten in a compact form.

$$\hat{u}(n) = \boldsymbol{\psi}^{\mathrm{H}}(n)\hat{\boldsymbol{\theta}}(n) \tag{9}$$

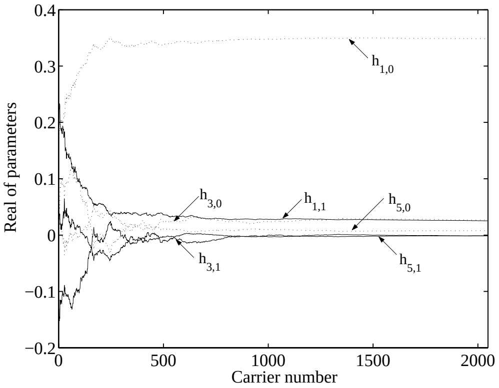
where,

$$\begin{aligned}\hat{\boldsymbol{\theta}}(n) = [&\hat{h}_{1,0}(n), \hat{h}_{3,0}(n), \ldots, \hat{h}_{2L_h+1,0}(n),\\ &\hat{h}_{1,1}(n), \hat{h}_{3,1}(n), \ldots, \hat{h}_{2L_h+1,1}(n), \ldots,\\ &\hat{h}_{1,L_p}(n), \hat{h}_{3,L_p}(n), \ldots, \hat{h}_{2L_h+1,L_p}(n)]^{\mathrm{T}}\end{aligned} \tag{10}$$

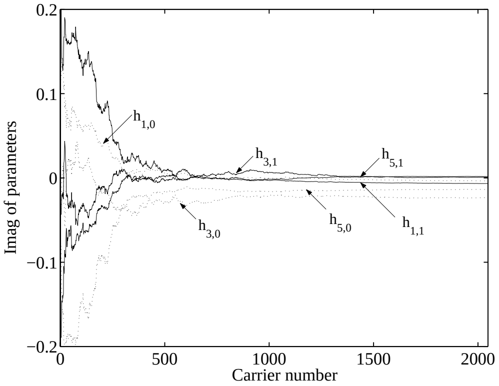
$$\begin{aligned}\boldsymbol{\psi}^{\mathrm{H}}(n) = [&z(n), |z(n)|^2 z(n), \ldots, |z(n)|^{2L_h} z(n),\\ &z(n-1), |z(n-1)|^2 z(n-1), \ldots,\\ &|z(n-1)|^{2L_h} z(n-1), \ldots, z(n-L_p),\\ &\ldots, |z(n-L_p)|^{2L_h} z(n-L_p)]\end{aligned} \tag{11}$$

The superscript H denote the complex conjugate transposition.

Notice that Eq. (9) is linearity about the unknown parameters $\hat{\boldsymbol{\theta}}(n)$. Minimizing the error variable $\varepsilon(n)$, which is given by $\varepsilon(n) = u(n) - \hat{u}(n)$, will yield the parameter estimates $\hat{\boldsymbol{\theta}}(n)$ by using the following least mean square (LMS) algorithm.



(a) Real part



(b) Imaginary part

Figure 6: Estimated parameters of predistorter for the WHM

$$\hat{\boldsymbol{\theta}}(n) = \hat{\boldsymbol{\theta}}(n-1) + \boldsymbol{\Gamma}\boldsymbol{\psi}(n-1)\varepsilon(n) \tag{12}$$

$$\varepsilon(n) = \frac{u(n) - \boldsymbol{\psi}^{\mathrm{H}}(n-1)\hat{\boldsymbol{\theta}}(n-1)}{1 + \boldsymbol{\psi}^{\mathrm{H}}(n-1)\boldsymbol{\Gamma}\boldsymbol{\psi}(n-1)} \tag{13}$$

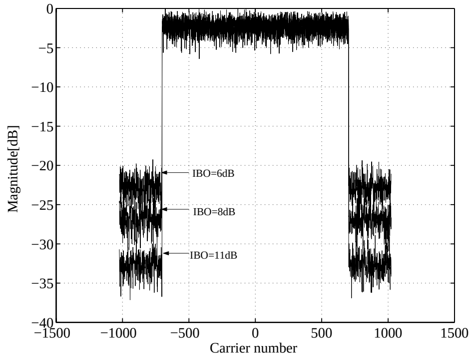
Where, $\boldsymbol{\Gamma}$ is diagonal matrix and it satisfies $\boldsymbol{\Gamma} = \boldsymbol{\Gamma}^{\mathrm{H}} > 0$.

4. NUMERICAL SIMULATION

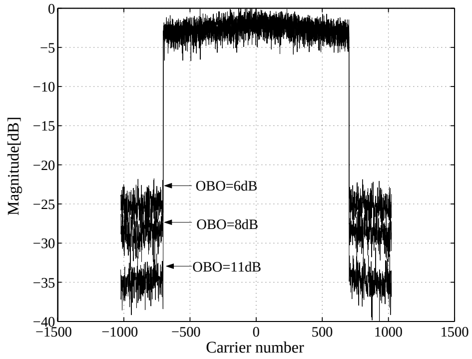
In the simulation, the source symbols $c_k = a_k + jb_k$ are the 64QAM signals, where $a_k, b_k \in \{\pm1, \pm3, \pm5, \pm7\}$. The simulation conditions for the OFDM systems are given as follows: The carrier number is $K = 1405$, the carrier frequency interval is $f_0 = 4$ [kHz], and the FFT size is $N = 2048$.

For the true uncertain HPA, we set memoryless nonlinearities as: $A(|x(n)|) = \frac{2|x|}{1+|x|^2}$ and $P(|x(n)|) = \frac{\pi}{3}\frac{|x|^2}{1+|x|^2}$, and the linear dynamics as: $F(z^{-1}) = 0.8+0.1z^{-1}$ and $R(z^{-1}) = \frac{2}{1+0.2z^{-1}}$. Here, all the parameters are unknown. In PSMWM to identification, we set $L_h = 2$ and $L_p = 1$.

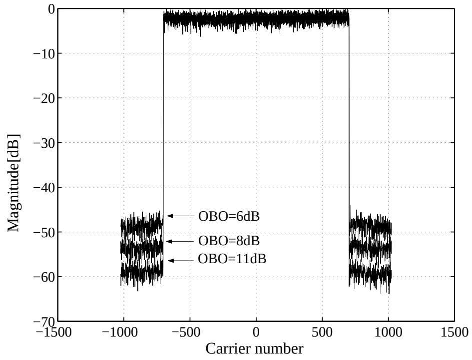
Fig. 6 illustrates convergence profile of predistorter parameters estimated by LMS. From these fig-



(a) No compensation and without dynamics



(b) No compensation and with dynamics



(c) Compensation with proposed predistortion

Figure 7: Spectra of the output $z(n)$

ures, it is clear that the parameters converge within less than one symbol interval.

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 caused by distortions in HPA. 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, the only carriers between -702 and 702 have information to be sent, while the carriers in the out-of-band ($[-1024,\ -701]$, $[703,\ 1023]$) have no information. As stated in section 2, the

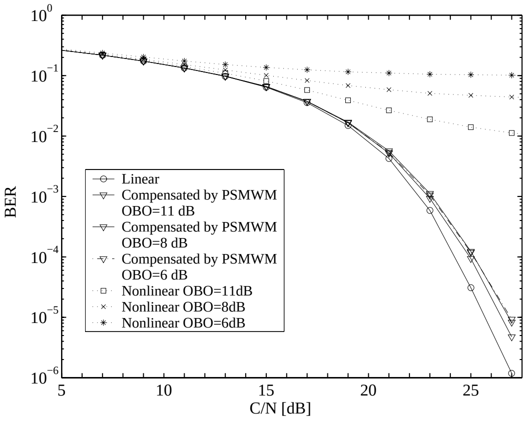


Figure 8: Bit error rate performance

instantaneous power of the baseband OFDM signal changes excessively, then the signal is affected by the nonlinearity of HPA and the power spectrum of the output of HPA has leakage and spread to the outside of carrier signal band. Figs. 7 (a) and (b) illustrate the power spectra of the HPA output $z(n)$ without any compensation under case of different OBO. The Fig. 7(a) is obtained in the absence of the linear dynamics, whereas Fig. 7 (b) is obtained in the case with the linear dynamics. The spectral gaps between in-band and out-of-band are small, and in-band spectra are not flat, so the output $z(n)$ will have much distortion in amplitude and phase.

On the other hand, the power spectra of the predistorted HPA output $z(n)$ is shown Fig. 7 (c), in which the spectral gaps can be improved to 45dB, 50dB and 55dB respectively. The spectral shape in the in-band can also be perfectly flat by the proposed adaptive predistortion compensation.

The BER performance for CN (Carrier to Noise) is shown Fig. 8. The BER of signal transmitted by nonlinear HPA with dynamics are very poor as dot-lines. On the other hand, the BER performances compensated by the proposed adaptive predistortion can be improved greatly in case of different OBO, and its approximate BER performance of signal $s(n)$ transmitted lineally. So it shows that the signal detection performance can be improved greatly.

The proposed method can be also applied to compensate nonlinear HPA expressed by Wiener model (as $R(z^{-1}) = 1$), Hammerstein model (as $F(z^{-1}) = 1$), or model without any dynamics (as $R(z^{-1}) = 1$ and $F(z^{-1}) = 1$). Moreover, compensation effects are almost the same as those in Fig. 7(c) and Fig.8.

3. CONCLUSION

In this paper, the HPA with dynamics is described by general complex Wiener-Hammerstein model. Then a complex power series model with memory model is identified to construct the inverse of HPA. We have presented the adaptive predistortion structure for the HPA, where predistorter is realized easily. Moreover, it can compensate the distortions adaptively even if HPA has uncertainty and its nonlinearity is changeable. In the proposed methods, only a little of parameters are required to be estimated and the computational complexity is decreased, compared with the Volterra-based compensation method. In the numerical simulation for 64QAM-OFDM systems, the results of experiment have shown that the out-of-band signal power emission is suppressed and the BER performance of transmitted signal is improved greatly.

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