Adaptive Predistortion for High Power Amplifier by Exact Model Matching Approach

Yuanming Ding*, Bingnan Pei*, Itthisek Nilkhamhang** and Akira Sano**

*Department of Information Engineering, Dalian University, Liaoning 116622, China
(Tel: +86-411-87402461; Fax: +86-411-87402461; Email:dingymdl1@yahoo.co.jp)
**Department of System Design Engineering, Keio University, Yokohama 223-8522, Japan
(Tel: +81-45-566-1730; Fax: +81-45-566-1720; Email:art@contr.sd.keio.ac.jp and sano@sd.keio.ac.jp)

Abstract: In this paper, a new time-domain adaptive predistortion scheme is proposed to compensate for the 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 used 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. In numerical example, the effectiveness of the proposed method is confirmed and compared with the identification method based on PSMWM.

Keywords: High Power Amplifier, Predistortion, Wiener-Hammerstein Model, Exact Model Matching

1. Introduction

Orthogonal frequency division multiplexing (OFDM) has been used in the digital terrestrial television broadcasting, and the potentials of OFDM have received much attention in the development of the fourth generation mobile communication systems in recent years [1], [2]. However, the pursuit of high power efficiency in OFDM communication systems generally results in that high power amplifiers (HPA) in transmitter often operate near saturation regions. This means that the input-output relation of HPA involves nonlinearity. The 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.

Normally, distortions in HPA include both nonlinear distortion caused by memoryless nonlinearity and linear distortion introduced by linear dynamics. To compensate for such distortions, appropriate model description for HPA is essentially needed. Moreover, adaptive predistortion techniques are desired to compensate for the uncertain nonlinearity caused by aging and temperature variations. For nonlinear HPA preceded by a linear dynamics, predistorters based on a Volterra series model [3] or power series model have been studied [4]. Nevertheless it is difficult to implement the schemes in a real time manner due to their large number of kernels under estimation and their computational complexity [3]. Furthermore, the convergence of the so-called two-stage estimation method is very time consumptive since all the parameters of the Wiener model and its inverse should be estimated iteratively [4]. To overcome such compensation problems, a more efficient compensation method based on adaptive identification has been proposed in [5] under the assumption that the Wiener model can describe the linear dynamics followed by the nonlinearity of the 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 HPA followed by a dynamical distortion, a model matching-based adaptive compensation algorithm has been developed in the time domain [6], [7]. For HPA expressed by the Wiener-Hammerstein model (WHM), identification-based compensation schemes have also been studied in the frequency-domain and time-domain [8], [9]. In [8], the parameters of the nonlinear element and linear dynamics are obtained iteratively in a bootstrap manner. Moreover, 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. [9] utilizes a third-order Volterra series model (VSM) to construct a predistorter (PD) of the HPA with linear dynamics. However, the computation is complex [10]. To overcome the above problems, identification-based adaptive predistortion compensation is also proposed in [10], where a complex WHM is used to describe input-output relationship of HPA with linear dynamics and inverse of the WHM is approximated by power series model with memory (PSMWM). Then PD to the HPA can be realized by using the copy of the estimated PSMWM and the computation complexity is decreased greatly.

The purpose of this paper is to investigate a new approach to the linearized compensation of nonlinear amplifier in OFDM systems. The generalized Wiener-Hammerstein model (WHM) of HPA is considered, and we propose an adaptive predistortion method. In this method, the power series model with memory (PSMWM) is used to directly construct a linearized compensator (PD) of the WHM based on the Exact Model Matching (EMM). The effectiveness of the proposed predistortion method is validated and compared with the identification method by numerical simulation for 64QAM-OFDM systems.

2. Model of Nonlinear HPA

We consider the HPA used in the transmitter of OFDM systems. The predistortion scheme is performed in baseband-equivalent system. Fig. 1 illustrates a simplified block di-

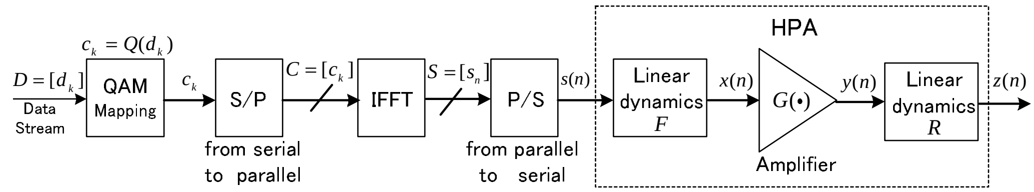


Fig. 1. The baseband-equivalent system of QAM-OFDM transmitter

agram of the baseband-equivalent system for QAM-OFDM transmitter. Let the thick line represent the stream of complex data. d_k is the transmitted data, and c_k ($c_k = Q(d_k) = a_k + jb_k, k = 0, 1, \dots, K$) is complex QAM (Quadrature Amplitude Modulation) symbol in the k-th subcarrier and a_k, b_k are determined by the QAM mapping. 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, the baseband OFDM signal $s(n)$ can be expressed by by the following (1).

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

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, within which the discrete OFDM signals $\{s(n), n = 0, 1, \dots, N-1\}$ are generated, becomes $T = 1/f_0$. $s_I(n)$ and $s_Q(n)$ are the in-phase and quadrature components of $s(n)$, 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

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

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 [11].

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

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

$$OBO = 10 \log \frac{P_{o,sat}}{P_o}. \qquad (4)$$

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.

2.1. Wiener-Hammerstein Model for HPA with Dynamics

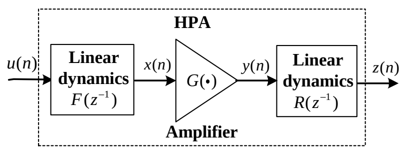


Fig. 2. A complex Wiener-Hammerstein model for HPA

In order to take into account the frequency-dependent distortion due to linear dynamics, for instance, a frequency-domain WHM has been proposed to describe the input-output relationship of HPA [8]. In this paper, we adopt a time-domain WHM as shown in Fig. 2. $F(z^{-1})$ 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 $R(z^{-1}) = N(z^{-1})/D(z^{-1})$ and its inverse are also stable dynamics.

2.2. A Power Series Model with Memory

In this paper, a power series model with memory (PSMWM) as expressed in (6) is adopted to construct the PD, because this PSMWM can approximate the WHM [10].

$$
\begin{aligned}
\hat{z}(n) &= z^{-L}\hat{\sigma}(u(n)), \qquad (5) \\
&= \sum_{m=0}^{L_p}\sum_{l=0}^{L_g} \hat{g}_{2l+1,m}(n)|u(n-m-L)|^{2l}u(n-m-L). \qquad (6)
\end{aligned}
$$

In the PSMWM, L_p represents the memory length, $(2L_g+1)$ is the model order, and L is a delay time of system. u(n) and z(n) are input and output of the WHM, respectively. $\hat{g}_{2l+1,m}(n)$ are complex coefficients.

3. Adaptive predistortion for HPA

3.1. Adaptive predistortion system

The proposed time-domain adaptive predistortion system for the nonlinear HPA is illustrated in Fig. 3, and is executed

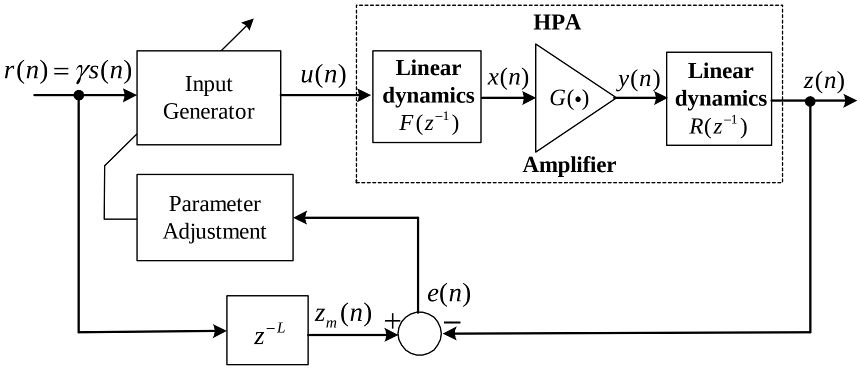


Fig. 3. Time-domain adaptive predistortion system for HPA

in the baseband process. Since the desired input-output property is linear, the desired response dynamics (reference model) 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

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

$$\boldsymbol{\zeta}^{\mathrm{H}}(n) = [\zeta_0^{\mathrm{H}}(n), \zeta_1^{\mathrm{H}}(n), \ldots, \zeta_{L_p}^{\mathrm{H}}(n)], \tag{11}$$

$$\zeta_0^{\mathrm{H}}(n) = [u(n), |u(n)|^2 u(n), \ldots, |u(n)|^{2L_g}u(n)], \tag{12}$$

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

$$\zeta_m^{\mathrm{H}}(n) = \zeta_0^{\mathrm{H}}(n-m) \quad \text{for} \quad \mathrm{m} = 1, \ldots, \mathrm{L_p}. \tag{14}$$

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].

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

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

A structure of the adaptive input generator is illustrated in Fig.4. 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

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

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.

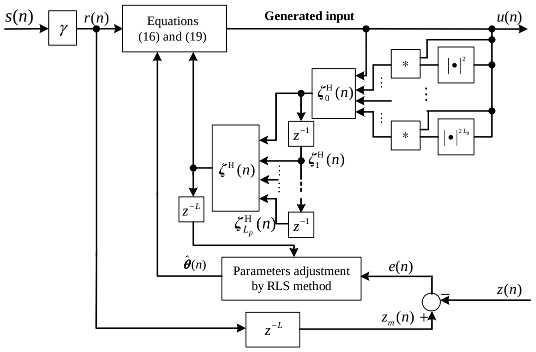
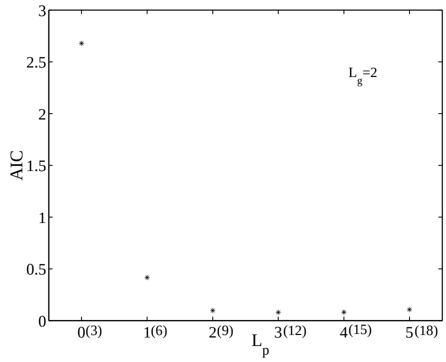
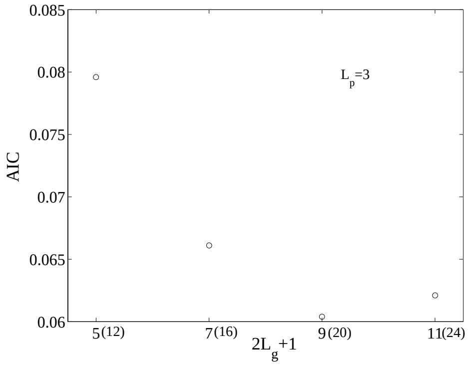


Fig. 4. Structure of adaptive input generator for linearization of HPA



(a) AIC versus L_p



(b) AIC versus $(2L_g + 1)$

Fig. 5. AIC versus model orders

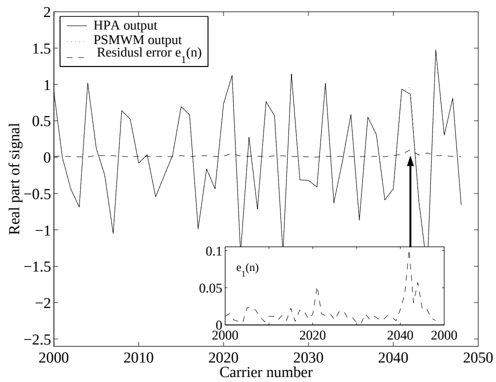


Fig. 6. Residual error between HPA output and model output

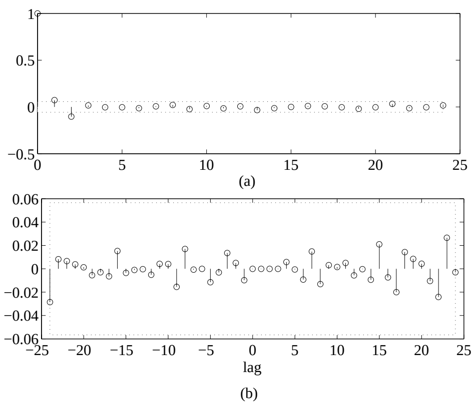


Fig. 7. Correlation function of residuals and cross correlation function between input and residuals from output

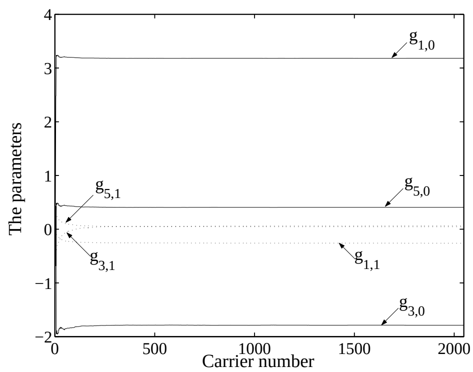


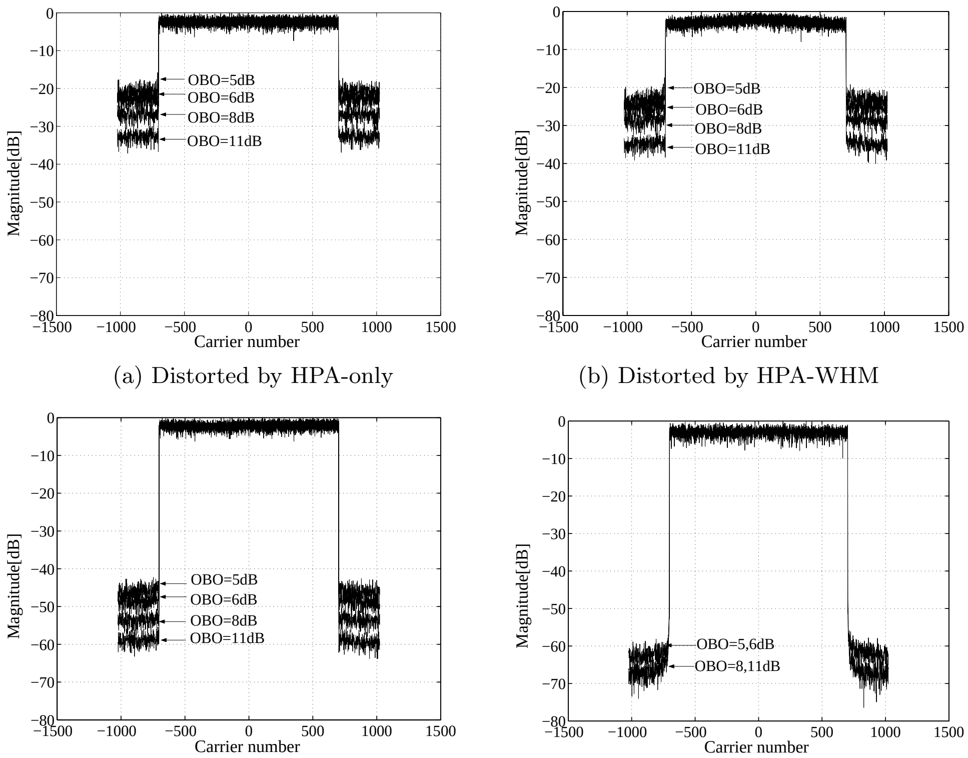
Fig. 8. Convergence of adjustable parameter $\hat{\boldsymbol{\theta}}(n)$

4. Numerical Simulation

In this section, we investigate the effectiveness of the proposed adaptive predistortion scheme in simulation studies. The setup and conditions for the simulation are summarized as follows:

- The source symbols $c_k = a_k + jb_k$ are the 64QAM signals, where $a_k, b_k \in \{\pm 1, \pm 3, \pm 5, \pm 7\}$, the FFT size N is 2048, the carrier number K is 1405 and the carrier frequency interval is $f_0 = 4$ kHz.
- HPA has a memoryless $G(\cdot)$ as (3), and linear dynamics $F = [0.8, 0.1]$ and $R = 3.2z^{-1}/(1 + 0.2z^{-1})$. Here, all the parameters are unknown.
- In PSMWM (6), the memory length L_p and parameter L_g for determining model order are chosen as 3 and 2 by AIC (Akaike's Information Criterion).
- L is set to 1 and γ change with different OBO value in the reference model (7).
- 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 need to determine model orders L_p and L_g in (6) by using AIC. Figs. 5 (a) and (b) show the value of AIC versus L_p and L_g, respectively. At horizontal axis, the number in this parenthesis represent parameter number and it is named as n_1. The AIC is defined as: $\ln[(1+2n_1/N)*V]$, where V is summation of the square error $e_1(n)$ and the $e_1(n)$ is residual error between the HPA output and model output $(e_1(n) = z(n) - \hat{z}(n))$. From Fig. 5 (a), it can be noticed



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

(c) Compensated by method in [10] (d) Using proposed method in this paper

Fig. 10. Power spectra of HPA output

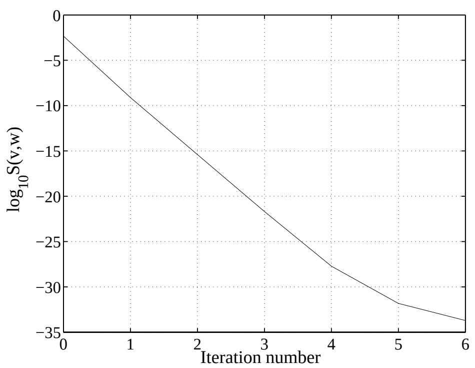


Fig. 9. Decreasing rate of $\log_{10} S(v_n, w_n)$ in the iterative procedure for $u(n)$

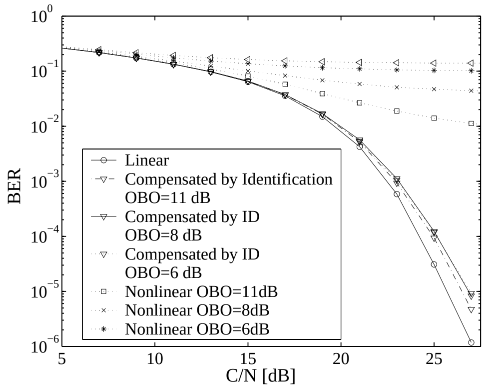
that AIC has a minimum when L_p is 3. Then L_p is set to 3 in the following numerical simulation. In Fig. 5 (b), the AIC value does not much change with L_g. In order to reduce the number of model parameters, the model order in PSMWM is chosen as 5, i.e. L_g is 2.

In the above setup, the validation of PSMWM is examined. Fig. 6 shows $e_1(n)$. It can be seen that the model output $\hat{z}(n)$ approximates the output $z(n)$ of HPA. The correlation function of the residuals and cross correlation function between the input and residuals from output are plotted in Fig. 7, where the dotted-line denotes the 99% confidence interval. From Fig. 7, it is clear that the residual is almost random and is independent for input $u(n)$. The parameters $\hat{\boldsymbol{\theta}}(n)$ of the input generator are adjusted by RLS method. Fig. 8 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). Fig. 9 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. 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.

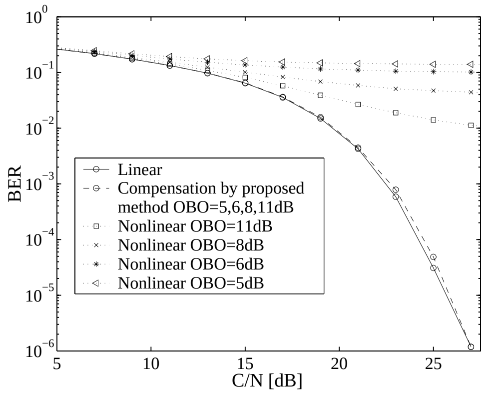
Next, in order to study the compensation effects for nonlinearity of HPA, we evaluate the performances of out-of-band signal power emission and signal degradation degree. The evaluations use the power spectrum of output $z(n)$ and the BER(Bit Error Rate) of transmitted signal $s(n)$.

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. 10 (a) and (b) illustrate the power spectra of the HPA output $z(n)$ without any compensation in case of different OBO. Fig. 10 (a) is obtained in the absence of linear dynamics, whereas Fig. 10 (b) is obtained in the case with linear dynamics. In Figs. 10 (a) and (b), 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. 10 (c) and (d) illustrate the power



(a) Compensated by method in [10]



(b) Using proposed method

Fig. 11. Bit error rate performance versus CNR

spectra of HPA output $z(n)$ compensated by adaptive predistortion methods in [10] and this paper. In Fig. 10 (c) the spectral gaps can be improved to 42 dB, 45dB, 50dB and 55dB by the adaptive identification method in [10], but in the case using the proposed adaptive predistortion method, the gaps can be improved to 58dB and 62dB as shown in Fig. 10 (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. 11. 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 signal detection performance can be improved greatly.

5. Conclusion

An adaptive predistortion scheme has been proposed to compensate for 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 based on EMM, 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, the out-of-band signal power emission is suppressed and the BER performance of transmitted signal is improved greatly. The proposed predistortion method will be very effective for OFDM systems.

References

[1] Y. Wu, E. Pliszka, B. Caron, P. Bouchard, and G. Chouinard, “Comparison of terrestrial DTV transmission system: the ATSC 8-VSB, the DVB-T COFDM, and the ISDB-T BST-OFDM,” *IEEE Trans. Broadcasting*, vol. 46, no. 2, pp. 101–113, 2000.

[2] J. Chuang and N. Sollenberger, “Beyond 3G: Wideband wireless data access based on OFDM and dynamic packet assignment,” *IEEE Commun. Mag.*, vol. 38, no. 7, pp. 78–87, 2000.

[3] S. Chang, E. J. Powers, and J. Chung, “A compensation scheme for nonliear distortion in OFDM systems,” *Proc. GLOBECOM*, pp.736–740, 2000.

[4] H. W. Kang, Y. S. Cho, and D. H. Youn, “On compensating nonlinear distortions of an OFDM system using an efficient adaptive predistorter,” *IEEE Trans. Commun.*, vol. 47, no. 4, pp. 522–526, 1999.

[5] Y. Ding, L. Sun, and A. Sano, “Adaptive nonlinearity predistortion schemes with application to OFDM system,” *2003 IEEE Conference on Control Applications*, Istanbul, Turkey, pp. 1130–1135, June 2003.

[6] Y. Ding, H. Ohmori, and A. Sano, “Time-domain adaptive compensation for nonlinear distortion of high power amplifiers,” *2003 Amer. Contr. Conference*, Denver, USA, pp. 356–361,June 2003.

[7] Y. Ding, L. Sun, and A. Sano, “Time-domain adaptive compensation algorithm for distortion of nonlinear amplifiers,” *IEEJ Trans. EIS*, vol. 124, no. 3, pp. 861-869, 2004.

[8] L. Sun, Y. Ding, and A. Sano, “Identification-based predistortio6 scheme for high power amplifier,” *IEICE Trans. Fundamentals*, vol.E86-A, no.4, pp.874–881, 2003.

[9] C. S. Eun and E. J. Powers, “A new Volterra predistorter based on the indirect learning architecture,” *IEEE Trans. Signal Processing*, vol. 45, no. 1, pp. 223–227, 1997.

[10] Y. Ding, H. Ohmori, and A. Sano, “Adaptive predistortion compensation for nonlinearity of high power amplifiers,” *Proc. 2003 International Conference on Control, Automation and Systems*, Gyeongju, Korea, pp. 122-127, Oct. 2003.

[11] A. A. M. Saleh, “Frequency-Independent and Frequency-Dependent Nonlinear Models of TWT Amplifiers,” *IEEE Trans. Commun.*, vol.COM-29, no.11, pp.1715–1720 1981.