Proceedings of the 6th Nordic Signal Processing Symposium - NORSIG 2004
June 9 - 11, 2004
Espoo, Finland

Design of Predistorters for Power Amplifiers in Future Mobile Communications Systems

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***Abstract*— This paper studies the accuracy and performance of polynomial based predistorters identified using two least-squares (LS) curve fitting methods. The model of the amplifier (PA) to be linearized is obtained from the AM/AM measurement of the Mini-Circuits ZVE-8G PA. In the first method (PD-LS), the predistorter (PD) function is approximated using the inverse function of the PA. The second method (PD-NLS) employs nonlinear LS curve fitting to directly estimate the predistortion function from the desired linearized output of the PD-PA system. We found that the PD-NLS model results in linearized output closer to an ideal limiter. The mean-squared error (MSE) between the linearized output and ideal limiter is employed as a measure of PD model accuracy. The MSE (in log scale) obtained from the PD-NLS model is up to 5.4 dB better than the PD-LS model. The performance of the two PDs with adjacent channel power ratio (ACPR) as performance metric are also evaluated. The PD-NLS model outperforms the PD-LS model by approximately 5 dB at PD order 3. Results also show that the PD-NLS model is able to achieve 26 dB in performance improvement leading to ACPR near 45 dBc with model order as low as 3 while the PD-LS model requires model order as high as 7 to obtain the same performance improvement.**

I. Introduction

The growing demand for higher speed, higher capacity and multi-mode services in today's mobile communications has lead to the development of broadband mobile communications systems such as the 3G and B3G systems. These systems focus on spectral efficiency and hence are likely to employ linear modulation such as QAM at the baseband and multi-carrier modulation such as OFDM or CDMA at the passband. Due to the non-constant envelope and high peak-to-average power ratio of these modulation methods, it is difficult to avoid nonlinear distortion which causes signal distortion and interference to adjacent channel. The conventional method to minimize nonlinear distortion is by backing off the PA. However, backing off the operating point results in reduced power efficiency.

In mobile communication systems, power source at the mobile station (MS) is limited. Therefore, power efficient transmission is important to ensure maximum battery-time of the MS. The PA is known to be the most power consuming component in a transmitter, hence it is desirable to operate the PA as efficient as possible, i.e., near the PA's saturation region. Unfortunately it is at the operating region that the transmitted signal is most susceptible to nonlinear distortion. Therefore, to meet the objective of linear transmission without sacrificing power efficiency, some means to compensate nonlinear distortion are needed. Predistortion is one of the most popular linearization methods.

In this paper, we consider polynomial based PDs for compensating amplitude distortion. A simplified amplitude PD was proposed in [1], where the PD modelled with a polynomial was identified based on the inverse function of the PA. Least-squares (LS) estimation was used to identify the parameters. Here, instead of approximating the PD model from the inverse function of the PA, we propose direct extraction of the PD model using nonlinear LS curve fitting. In our approach, the PD model is identified based directly on the desired linearized output.

The objective of this paper is to evaluate the accuracy of the two above PDs, for linearizing the Mini-Circuit ZVE-8G PA. The evaluation of PD model accuracy will be based on the MSE between the PD-PA output and the desired ideal limiter. However, the AM/AM characteristic alone is not sufficient in illustrating the performance of the PDs. Therefore, we also investigate the improvement in adjacent channel power ratio (ACPR) provided by the two PDs. For this purpose, a two-tone signal is used as excitation signal to the system.

The paper is organized as follows. The system model will be presented in Section II. In Section III, our proposed PD model identification using nonlinear LS estimation will be introduced. In order to keep the paper self-contained, the PD identification in [1] will also be reviewed in the same section. Section IV presents the simulation results followed by conclusions in Section V.

II. System model

The PA characteristic in our simulation was obtained from fitting a set of AM/AM measurement data of the Mini-Circuits ZVE8G power amplifier obtained in [2] to the Cann's limiter model [3] given by

$$f(|x|) = \frac{G|x|}{(1+(\frac{G|x|}{K_a})^s)^{\frac{1}{s}}}, \tag{1}$$

where G is the small signal voltage gain of the amplifier, K_a is the saturated output voltage, s is a parameter that controls the

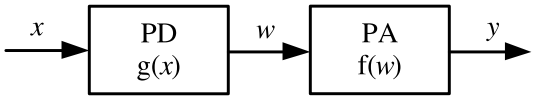


Fig. 1. System model

smoothness of the transition form linear to nonlinear region and $|x|$ is the amplitude of the input signal.

Fig. 1 illustrates the PD-PA cascade system. The PD is represented with a polynomial of degree Q as

$$g(|x|) = \sum_{j=0}^{Q} \beta_j (|x|)^j, \tag{2}$$

where $\boldsymbol{\beta} = [\ \beta_0 \quad \beta_1 \quad \dots \quad \beta_Q\ ]^{\mathrm{T}}$ are the parameters to be identified. The input and output signals of the system are denoted by x and y respectively. The intermediate signal, i.e., the PD output is denoted by w. Details of parameter estimation of the PD will be discussed in the next section.

III. Predistorter identification

A. PD-LS: Approximation with inverse function of PA with LS fitting

The idea in [1] for PD model identification is to simplify the estimation of $g(x)$ in two steps involving linear curve-fitting. First the inverse function of the PA represented by a polynomial $h(y)$ is estimated. Then parameter estimation of $g(x)$ is done by comparing the parameter $g(x)$ to the parameter of the $h(y)$ evaluated at the desired linearized output. Description of the design follows.

In order to identify $g(x)$, we need to first determine the predistorted signal w that will result in the desired linearized output when fed to the PA. Clearly the desired linearized output is Gx and we denote it as

$$y_d = Gx. \tag{3}$$

As illustrated in Figure 2, the predistorted signal w can be determined with the inverse function of the PA. Then y_d can be subtsituted as the argument to obtain w as

$$w = f^{-1}(y_d). \tag{4}$$

To simplify computation, $h(y)$ is approximated using a polynomial of degree Q with parameters $\lambda = [\ \lambda_0 \quad \lambda_1 \quad \dots \quad \lambda_Q\ ]^T$ as

$$h(y) = \sum_{k=0}^{Q} \lambda_k y^k. \tag{5}$$

The parameters of $h(y)$ are identified with LS fitting of the output-input data to (5) as shown in Figure 2. Substituting (5)

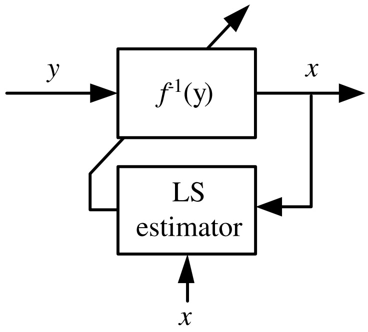


Fig. 2. Identification of inverse function of PA

into (4) and recalling that $w = g(x)$ and $y_d = Gx$, we get

$$\begin{aligned} w &= \sum_{k=0}^{Q} \lambda_k y_d^k \\ g(x) &= \sum_{k=0}^{Q} \lambda_k y_d^k \\ \sum_{j=0}^{Q} \beta_j x^k &= \sum_{k=0}^{Q} \lambda_k y_d^k \\ \sum_{j=0}^{Q} \beta_j x^k &= \sum_{k=0}^{Q} (\lambda_k G^k) x^k. \end{aligned} \tag{6}$$

The last line of (6) indicates that the parameters of the PD is identified as

$$\beta_i = \lambda_i G^i. \tag{7}$$

B. PD-NLS: Estimation with desired linearized output with nonlinear LS fitting

The PD in [1] presented in the previous subsection does not take into account the PA model in the estimation. Instead, only the small signal gain of the PA is utilized in the estimation. It is expected that incorporating the complete PA model into the PD model estimation would yield better result. Therefore, we propose a method to directly extract the PD model from the desired linearized output by means of nonlinear LS curve fitting as shown in Fig. 3.

The PD-PA cascade system output can be expressed as $y = f(g(x))$. Since f is a known function and $g(x)$ is a function of $\boldsymbol{\beta}$, we can rewrite the output as

$$y = F(\boldsymbol{\beta}, x). \tag{8}$$

The nonlinear LS estimator searches for parameter vector $\boldsymbol{\beta}$ that minimizes the following objective function

$$\begin{aligned} \hat{\boldsymbol{\beta}} &= \arg\min_{\boldsymbol{\beta}} \frac{1}{2} \|F(\boldsymbol{\beta}, x) - y_d\|_2^2 \\ &= \frac{1}{2} \arg\min_{\boldsymbol{\beta}} \sum_n (F(\boldsymbol{\beta}, x(n)) - y_d(n))^2. \end{aligned} \tag{9}$$

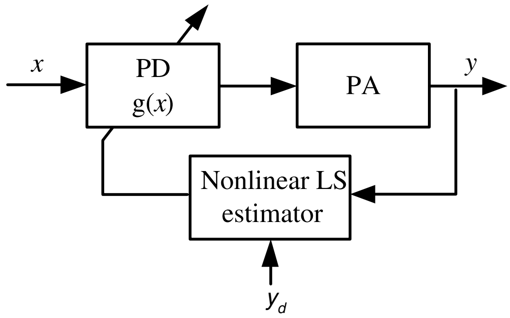


Fig. 3. Identification of PD with nonlinear LS fitting

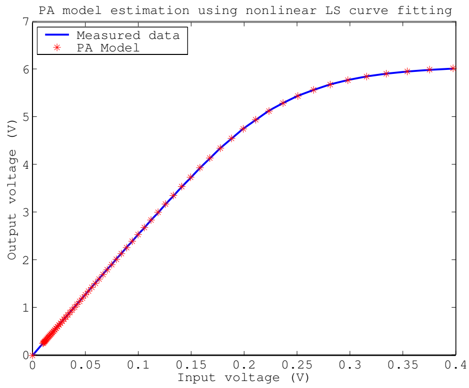
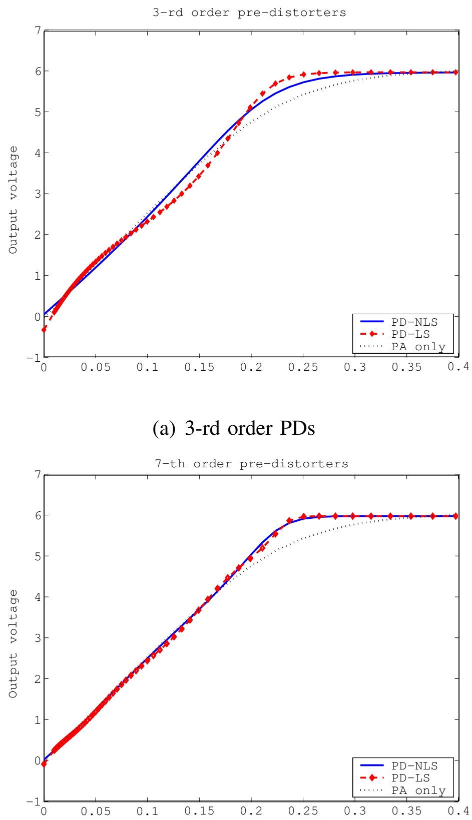


Fig. 4. Cann's model identification using nonlinear LS curve fitting



(a) 3-rd order PDs

(b) 7-th order PDs

Fig. 5. PD-PA responses with PD-NLS and PD-LS

In our simulation the non-linear least-squares curve fitting was implemented with a ready function in Matlab© optimization toolbox, *lsqcurvefit( )*.

In this method, the complexity of finding the PD is expected to be higher compared to the previous method. However, the characteristic change of the PA is also expected to be slow. Therefore, frequent updating of PD parameter in adaptive algorithm is not needed. Furthermore, the PD model can be used as a benchmark for future development of polynomial PDs.

IV. Simulation Results

A. PA model parameters identification

The three parameters of the Cann's model in (1) were identified using nonlinear curve fitting to the AM/AM measurement data obtained in [2]. The AM/AM measurement was done with a single-tone excitation signal at 5 GHz, which is the mid-band frequency of the Mini-Circuit ZVE-8G PA. The parameters of the model identified from the nonlinear curve fitting were $G = 25.49$, $K_a = 6.13$ and $s = 5.06$. The obtained model is shown in Fig. 4.

B. Modelling accuracy

The PD-PA system responses with the PDs modelled with polynomials of order 3 and 7 are shown in Fig. 5. We observed that at order 3, the PD-NLS was already exhibiting a highly linear system response. Although the response of the 3rd order PD-NLS resulted in less compensation to signal compression near saturation region, the PD-LS produced rather large rippling in the response especially in the linear region. At order 7, the PD-NLS showed improvement in compensating signal compression near saturation region while slight ripple is still observed in the response of the PD-LS.

The accuracy of the PD models extracted with the two methods can be examined closer by measuring the MSE between the system response of the PDs and an ideal limiter. At low PD order, the MSE in log scale were found to be in the range of 10^{-3} to 10^{-2} and 10^{-2} to 10^{-1} for the PD-NLS and PD-LS respectively as shown in Fig. 6. The log(MSE) of the PD-NLS was on average lower than that of the PD-LS's and 5.4 dB lower at PD order 3 and 5. This results clearly shows that the PD-NLS system is more accurate in emulating the response of the ideal limiter, indicating that the nonlinear LS curve fitting models more accurately.

C. Performance based on ACPR

Spectral regrowth caused by nonlinear transmission is one of the major concerns in communication systems as it causes adjacent channel interference. Thus, the performance of the PDs based on ACPR were evaluated, where ACPR is defined as the ratio of the in-band signal power to the adjacent channel

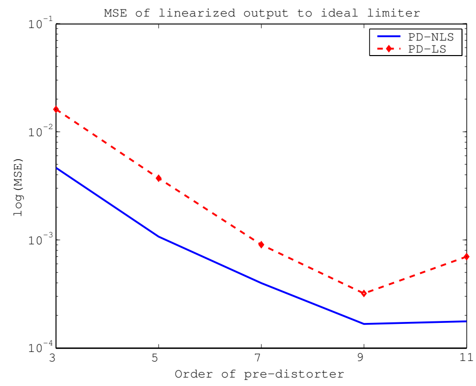


Fig. 6. MSE between linearized output and ideal limiter

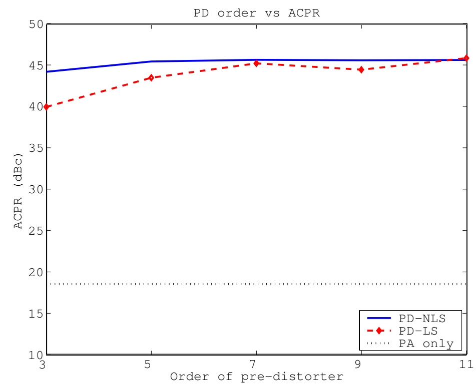


Fig. 7. ACPR with and without PD

signal power.

$$ACPR = 10\log\left(\frac{P_{f_c}}{P_{f_{adj}}}\right), \tag{10}$$

where P_{f_c} and $P_{f_{adj}}$ are the in-band and adjacent channel signal powers, respectively.

For the purpose of performance evaluation, an unmodulated two-tone signal was used as the excitation signal in the simulation. The two tones are chosen at carrier frequency 350 Hz and 450 Hz respectively. Since a memoryless model is considered, a relatively small tone separation of 100 Hz was chosen. The adjacent channel power as a result from the 3-rd order intermodulation distortion (IMD) will be observed at the vicinity of carrier frequency 250 Hz and 550 Hz.

The results of ACPR improvement at OBO = 6 dB are shown in Fig. 7. The performance improvement provided by the 3-rd order PD-NLS was 26 dB, resulting in ACPR = 44.5 dBc as compared ACPR = 18.4 dBc for system without PD. Increasing the order of the PD-NLS caused 1 dB more in improvement resulting in ACPR > 45 dBc. This shows that the nonlinear curve fitting was able to model quite accurately even with polynomial of order as low as 3.

On the other hand, the 3-rd order PD-LS provided an ACPR improvement below 22 dB, resulted in ACPR = 40 dBc. Note that the the PD-NLS outperformed the PD-LS by 4.5 dB in ACPR improvement. The performance of the PD-LS improved as the order of the PD was increased. At order 7, the ACPR improvement was 26.2 dB resulting in ACPR slightly below 45 dBc. This observation tells that the linear LS method used to approximated the PD-LS through the inverse PA model was only able to model accurately with higher order polynomial. The inferior performance of the PD-LS as compared to the PD-NLS, especially at low model order can be explained with model inaccuracy shown in the rippling system response of the PD-LS system as discussed in Subsection IV-B.

V. Conclusions

Two LS estimation methods for identifying an amplitude PD for memoryless nonlinearity of the Mini-Circuits ZVE-8G PA were investigated. The results obtained from evaluating both the modelling accuracy and ACPR performance of the PDs are shown to be in favor of the PD-NLS method. The rippling response seen in the PD-LS system demonstrated the inaccuracy of the PD model obtained through the inverse PA model with linear LS estimation especially at low model order. On the other hand, it was found that the PD-NLS modelled with a 3-rd order polynomial was able to supress the adjacent channel power by 26 dB in a noiseless channel. For the same improvement, the PD-LS need to be modelled with an 7-th order polynomial.

In developing polynomial based PDs, one of the practical limitations is posed by the model order. The model order is affecting the sampling speed required in the A/D and D/A circuits. Although the complexity of the direct model extraction with nonlinear LS curve fitting is higher, the accuracy of the PD model that can obtained with model order as low as 3 is a promising motivation for employing the method. Future work include extension to PD for PA model with memory such as that proposed in [4], and efficient adaptive implementations.

Acknowledgment

The cooperation with Prof. Vainikainen's group within SMARAD and with Peter Jantunen and Gilda Gaméz is gratefully acknowledged.

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