A NEW PRE-DISTORTION APPROACH TO TWTA COMPENSATION FOR WIRELESS OFDM SYSTEMS

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DOI: 10.36724/2664-066X-2022-8-1-2-6

ABSTRACT

Orthogonal Frequency Division Multiplexing (OFDM) has several desirable attributes which makes it a prime candidate for a number of emerging wireless communication standards. However, one of the major problems posed by OFDM is its high Peak-to-Average-Power ratio (PAPR), which seriously limits the power efficiency of the High Power Amplifier (HPA) because of the nonlinear distortion resulting from high PAPR. The present paper presents a new mixed computational/analytical approach for compensation of this nonlinear distortion for the case in which the HPA is a Traveling Wave Tube Amplifier (TWTA) with time-varying characteristic. TWTAs are used in wireless communication systems when high transmission power is required as in the case of the digital satellite channel. Compared to previous pre-distorter techniques based on LUT (Look-Up Table) or adaptive schemes, our approach relies on the analytical inversion of the Saleh TWTA model in combination with a nonlinear parameter estimation algorithm. This leads to a sparse and yet accurate representation of the pre-distorter, with the capability of tracking efficiently any rapidly time-varying behavior of the TWTA. Computer simulations results illustrate and validate the approach presented.

KEYWORDS: *Orthogonal Frequency Division Multiplexing, OFDM, Traveling Wave Tube Amplifier, TWTA.*

The article is reworked from unpublished 2nd IEEE International Conference on Circuits and Systems for Communications (ICCSC) materials.

I. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) has several desirable attributes, such as high immunity to inter-symbol interference, robustness with respect to multi-path fading, and ability for high data rates, all of which are making OFDM to be incorporated in emerging wireless standards like IEEE 802.11a WLAN and ETSI terrestrial broadcasting. However, one of the major problems posed by OFDM is its high Peak-to-Average-Power Ratio (PAPR), which seriously limits the power efficiency of the High Power Amplifier (HPA) because of the nonlinear distortion caused by high PAPR. This distortion constitutes a source of major concern to the RF system design community. One of the most promising approaches for the mitigation of this nonlinear distortion is to use a Pre-Distorter, applied to the OFDM signal prior to its entry into the HPA. Except for Brajal and Chouly, previous Pre-Distorter-based approaches consisted of: (1) Using a Look-Up Table (LUT) and updating the table via Least Mean Square (LMS)error estimation [1] [2]; (2) two-stage estimation, using Wiener system modeling for the HPA, and Hammerstein system modeling for the pre-distorter [3]; (3) simplified Volterra-based modeling for compensation of the HPA nonlinearity. [4] [5]; and (4) polynomial approximation of this nonlinearity [6]. However, all of these techniques are based on a general approximation form for the nonlinear system, rather than on exploiting specific forms gleaned from physical device considerations.

In the present paper, we describe a new approach to PD (pre-distorter) for TWTA by using the Saleh model for this device and using the exact closed form expression for its inverse represented by means of only four parameters, thus avoiding a larger number of parameters that a generic approx-imation expression (like the polynomial approximation)would require for accurate representation. Brajal and Chouly [9] did present a closed form expression for the inverse for the Saleh model[7] but did not use this inverse in the implementation of their Pre-Distorter for the case of in which the characteristic of the TWTA is time-varying.

We have combined the closed form expression for the inverse of the TWTA characteristic with a sequential nonlinear psrameter estimation algorithm, which allows sparse implementation of the PD and accurate tracking of the the time varying behavior of the TWTA.

II. SYSTEM DESCRIPTION

Fig.1 shows a simplified block diagram for compensation of the HPA nonlinearity for OFDM system. Typically, OFDM signal can be represented as

$$x(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X[k] e^{j2\pi f_k t} \tag{1}$$

where $X[k]$ denotes QAM symbol, N is the number of subcarriers, and f_k is k^{th} subcarrier frequency which can be represented as

$$f_k = k \cdot \frac{1}{NT_s} \tag{2}$$

where T_s is symbol duration of $x(t)$.
By discretizing $x(t)$ at $t = nT_s$, we have the following equation

$$x(n) \equiv x(nT_s) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X[k] e^{\frac{j2\pi kn}{N}} \tag{3}$$

As a HPA model, we use Saleh's well established TWTA model. In this model, AM/AM and AM/PM conversion of TWTA can be represented as [7]

$$u[r] = \frac{\alpha r}{1 + \beta r^2} \tag{4}$$

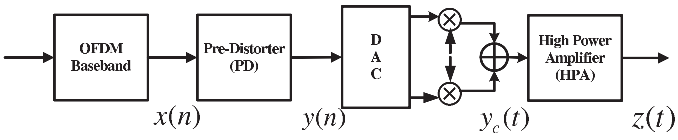

Fig. 1. Simplified OFDM Transmitter with PD and HPA

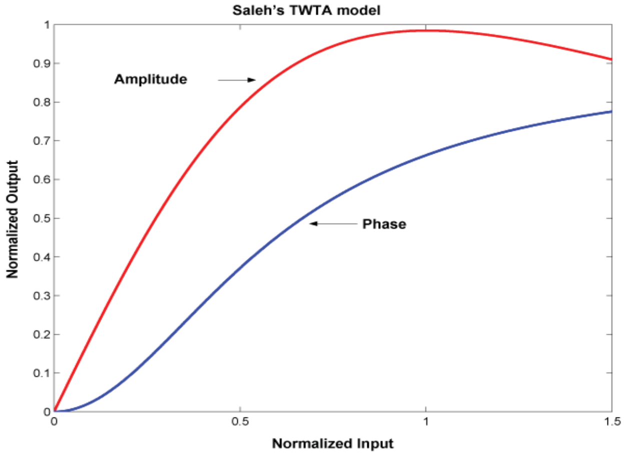

Fig. 2. Nonlinear amplitude and phase transfer function of the Saleh's TWTA model

$$\Phi[r] = \frac{\gamma r^2}{1+\varepsilon r^2} \tag{5}$$

where r is input amplitude of TWTA and $\alpha, \beta, \gamma, \varepsilon$ are four adjustable parameters. The behavior of (4) and (5 is illustrated in Fig.2. In this figure we use $\alpha = 1.9638, \beta = 0.9945, \gamma = 2.5293, \varepsilon = 2.8168$ as in Saleh's original work [7] The output of TWTA without PD can be represented as

$$z(t) = u[r]\cos(\omega_c t + \varphi(t) + \Phi[r]) \tag{6}$$

where $\theta(t)$ is the phase of the input signal.

III. PRE-DISTORTER

Let g and h denote the nonlinear zero memory input output maps of the PD and HPA, and $x(t)$, the input of the PD, $y(t)$, the output of the PD which is also the input to the HPA, and $z(t)$ the output of the HPA as in Fig 1. Then for any given HPA , an ideal pre-distorter is one for which the input-output maps satisfies

$$h[g(x(t))] = k \cdot x(t) \tag{7}$$

where k is a desired pre-specified linear amplification constant. In this paper, we assume $k = 1$.

According to [9], the PD for amplitude compensation which satisfy (7) is

$$q(r) = \frac{\alpha - \sqrt{\alpha^2 - 4r^2\beta}}{2r\beta}, \qquad r \le 1 \tag{8}$$

Also for zero phase distortion, we must have

$$\theta(r) + \Phi(q) = 0 \tag{9}$$

or

$$\theta(r) = -\Phi(q) = -\frac{\gamma(q(r))^2}{1+\varepsilon(q(r))^2} \tag{10}$$

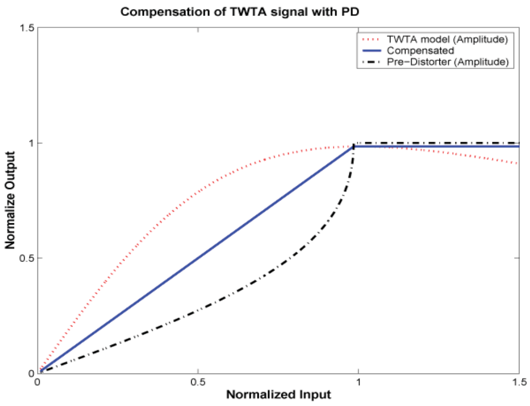

Fig. 3. Amplitude compensation effect of Saleh's TWTA model

If $r > 1$, equation (8) has no solution. In this case, we clip the signal as in Fig 3. This analytical solution (8), (10) was previously obtained by Brajal and Chouly [9]. We now extend this solution to the time-varying as follows.
We express MSE in amplitude as

$$J(\alpha,\beta) = E\left(\frac{\alpha q}{1+\beta q^2} - u\right)^2 \tag{11}$$

Partially differentiating w. r. t. α and equating the result to zero, we get,

$$\frac{\partial J(\alpha,\beta)}{\partial \alpha} = E\left[2\left(\frac{\alpha q}{1+\beta q^2} - u\right)\frac{q}{1+\beta q^2}\right] = 0 \tag{12}$$

$$\alpha E\left(\frac{q^2}{(1+\beta q^2)^2}\right) = E\left(\frac{qu}{1+\beta q^2}\right) \tag{13}$$

Differentiating (11) w. r. t. β and equating the result to 0,

$$\frac{\partial J(\alpha,\beta)}{\partial \beta} = E\left[2\left(\frac{\alpha q}{1+\beta q^2} - u\right)\left(-\frac{\alpha q}{(1+\beta q^2)^2}\right)q^2\right] = 0 \tag{14}$$

$$\alpha E\left(\frac{q^4}{(1+\beta q^2)^3}\right) = E\left(\frac{q^3 u}{(1+\beta q^2)^2}\right) \tag{15}$$

Let's define the following for the sake of simplicity.

$$A(\beta) = E\left(\frac{q^2}{(1+\beta q^2)^2}\right) \tag{16}$$

$$B(\beta) = E\left(\frac{qu}{1+\beta q^2}\right) \tag{17}$$

$$C(\beta) = E\left(\frac{q^4}{(1+\beta q^2)^3}\right) \tag{18}$$

$$D(\beta) = E\left(\frac{q^3 u}{(1+\beta q^2)^2}\right) \tag{19}$$

According to (13), (16) and (17)

$$\alpha = \frac{B(\beta)}{A(\beta)} \tag{20}$$

and according to (15), (18), (19), (20)

$$\frac{B(\beta)}{A(\beta)}C(\beta) = D(\beta) \tag{21}$$

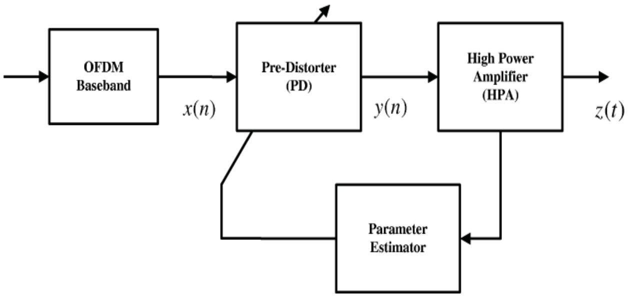

Fig. 4. Block diagram of PD for Time varying HPA

So, the algorithm is: Solve (21) numerically for $\hat{\beta}$, the estimate of β , then replace $\hat{\beta}$ in (20) to obtain $\hat{\alpha}$, the estimate of α. The expectation in (16), (17), (18), (19) can be expressed using following equations

$$A(\beta) = \frac{1}{N} \sum_{n=1}^{N} \frac{q_n^2}{(1+\beta q_n^2)^2} \tag{22}$$

$$B(\beta) = \frac{1}{N} \sum_{n=1}^{N} \frac{q_n u_n}{1+\beta q_n^2} \tag{23}$$

$$C(\beta) = \frac{1}{N} \sum_{n=1}^{N} \frac{q_n^4}{(1+\beta q_n^2)^3} \tag{24}$$

$$D(\beta) = \frac{1}{N} \sum_{n=1}^{N} \frac{q_n^3 u_n}{(1+\beta q_n^2)^2} \tag{25}$$

γ and ε also can be estimated exactly same way as described above.

IV. SIMULATION RESULTS AND DISCUSSION

In this section, the validity of proposed predistortion technique for compensation of TWTA nonlinear distortion is demonstrated with computer simulation and presents some discussion about the results. The Additive White Gaussian Noise (AWGN) channels were assumed to clearly observe the effect of nonlinearity and performance improvement by the proposed PD. An OFDM system with 128 subcarrier and 16 QAM is considered. If input amplitude is very high, the HPA operates with highly nonlinear situation. If input amplitude is very small, the HPA operates in very small distortion. In the operation of HPA, relative level of power back off is needed to reduce distortion. However, this power back off is not so desirable. Because, it reduces power efficiency. In our algorithm, compensation solution always exists in the range $r \leq A_0$, where A_0 is maximum output amplitude. So, if input average power is same as A_0^2, we get maximum power efficiency, but highly nonlinear. Thus, we need a criteria to show how much power back off from optimum power efficiency. In the simulations, we define IBO (Input Back-Off) as

$$IBO = 10\log_{10}\left(\frac{A_0^2}{P_{in}}\right) \tag{26}$$

where P_{in} is input average power (average power of baseband OFDM signal). Similarly, we can also define OBO (Output Back-Off) as

$$OBO = 10\log_{10}\left(\frac{A_0^2}{P_{out}}\right) \tag{27}$$

where P_{out} is output average power (average output power of HPA).

A. OFDM, Time invariant TWTA

In this subsection, we present OFDM simulation results with the assumption that parameters $\alpha, \beta, \gamma, \varepsilon$ are time-invariant. Fig 5. shows the difference of signal constellation with and without PD. In Fig. 5, we use IBO = 6 dB.

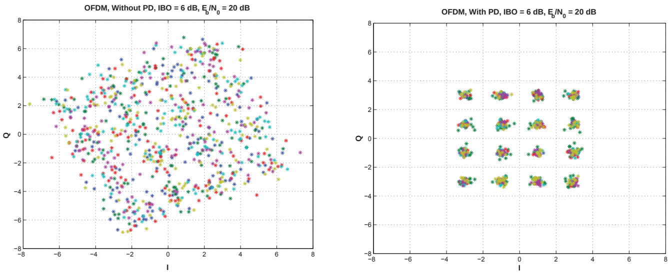

Fig. 5. Received signal constellations of OFDM

The BER performance curve, in Fig. 6, shows that the PD can significantly reduce nonlinear distortion in OFDM system.

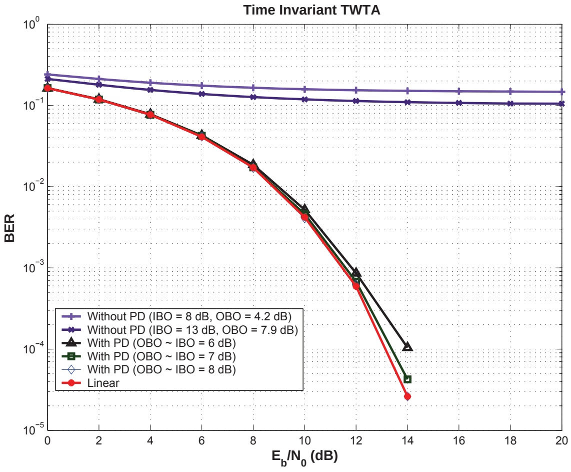

Fig. 6. BER performance of PD in OFDM, with time-invariant HPA

B. OFDM, Time varying TWTA

As we mentioned previously, HPA is time varying system. In this subsection, we assume four parameters $\alpha, \beta, \gamma, \varepsilon$ are time varying, thus we should track the variations of $\alpha, \beta, \gamma, \varepsilon$.

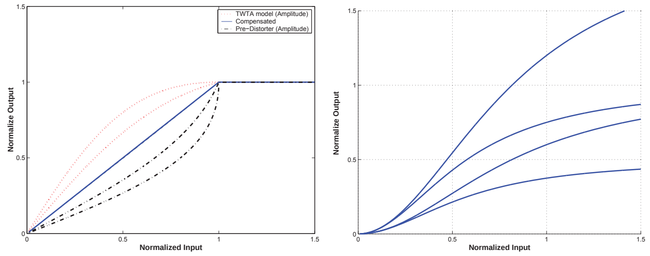

Fig. 7. Some of the examples of amplitude and phase variation

We assume these four parameters change within the following restriction.

(1) Four parameters change in the following ranges

$$1.01 \le \alpha \le 2, \quad 0.01 \le \beta \le 1, \quad 1.5 \le \gamma, \varepsilon \le 3 \qquad (28)$$

(2) Input output normalization condition, $\beta = \alpha - 1$.
(3) Saturation condition, signal is clipped above 1, as in Fig 7.

The reason, we choose above restriction in amplitude is to maintain normalization condition in both input and output and saturation condition in the above range, even if the amplitude is changed. These restriction are just for convenience of representation, so, in real system, even if above condition does not hold, our algorithm works well. Table 1 shows errors after tracking $\alpha, \beta, \gamma, \varepsilon$ using our algorithm. We used following equations to get the results of Table 1.

$$Error(\alpha) = \frac{|\alpha - \hat{\alpha}|}{|\alpha_{max} - \alpha_{min}|}, \quad Error(\beta) = \frac{|\beta - \hat{\beta}|}{|\beta_{max} - \beta_{min}|}$$

$$Error(\gamma) = \frac{|\gamma - \hat{\gamma}|}{|\gamma_{max} - \gamma_{min}|}, \quad Error(\varepsilon) = \frac{|\varepsilon - \hat{\varepsilon}|}{|\varepsilon_{max} - \varepsilon_{min}|}$$

Table 1. Error of parameters

Step size	Error (α)	Error (β)	Error (γ)	Error (ε)
0.1	1.02×10^{-2}	2.74×10^{-2}	6.3×10^{-3}	1.72×10^{-2}
0.01	9.67×10^{-4}	2.5×10^{-3}	6.04×10^{-4}	1.7×10^{-3}
0.001	9.49×10^{-5}	2.54×10^{-4}	6.18×10^{-5}	1.69×10^{-4}

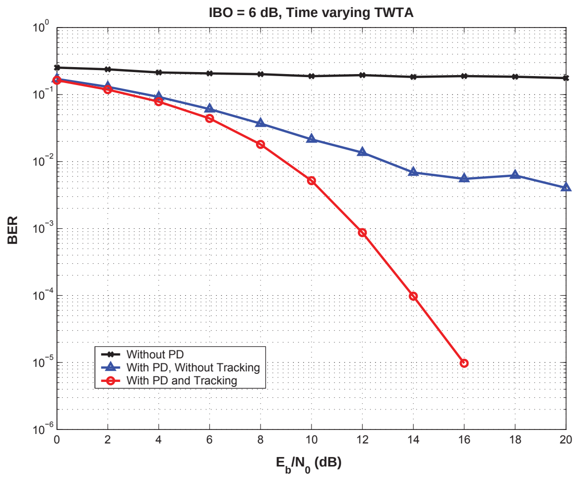

Fig. 8. BER performance of PD in OFDM, with Time varying HPA, IBO = 6 dB

We get the results of Table 1, using only two training sequences, calculating 1000 times and averaging the results. The results of Table 1 shows that only two training sequences are enough for our algorithm. This indicates that our algorithm is vary fast and has little delay.

The BER performance of PD in OFDM with time-varying HPA is shown in Fig.8. In this curve, we assume step size = 0.01. As we can see in Fig.8 that if we don't track the variation of HPA, the performance is much worse compared with the case of tracking. The simulation results clearly show that our algorithm works well and is therefore very promising technique.

V. CONCLUSION

We presented a model-based pre-distortion approach for eliminating or mitigating nonlinear distorion in time-varying TWTA ampplifier used in OFDM-based wireless communications. The approach uses a closed form inverse of the Saleh model of TWTA, with very few parameters required in the representation of the inverse. This sparse and yet accurate representation enables the tracking the time-varying behavior of the TWTA. These properties have been demonstrated by computer simulations.

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