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Performance of Trellis Coded FPM Systems with High Power Amplifiers Linearization

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***Abstract*—Trellis coding combined with expanded signal sets has been considered in this paper to improve error performance over uncoded modulation. New communications services have created the demand for highly linear high power amplifiers (HPA's). Traveling Wave Tubes Amplifiers (TWTA) continue to offer the best microwave HPA performance in terms of power efficiency, size and cost, but lag behind Solid State Power Amplifiers (SSPA's) in linearity. This paper presents a technique for improving TWTA linearity. The use of pre-distorter (PD) linearization technique is found to provide TWTA performance comparable or superior to conventional SSPA's. The characteristics of the PD scheme is derived based on the extension of Saleh's model for HPA. The analysis results of hybrid modulation scheme derived from combination of frequency and phase shift keying (FSK/PSK) or (FPM) in non-linear channels are presented in this paper.**

***Index Terms*—HPA, Nonlinear distortions, Saleh model, AM/AM and AM/PM, Pre-distortion, FPM scheme.**

I. INTRODUCTION

For wireless communication on fading channels, channel coding is an important tool for improving communication reliability. Trellis coded modulation (TCM) was proposed to achieve significant coding gain without bandwidth expansion by treating coding and modulation as single entity [1].

Power amplifiers (PA's) are vital components in communication system. The linearity of a PA response constitutes an important factor that ensures signal integrity and reliable performance of the communication system. High power amplifiers (HPA) in microwave range suffer from the effects of amplitude modulation to amplitude modulation distortion (AM/AM), and amplitude modulation to phase modulation distortion (AM/PM) [2], during conversions caused by the HPA amplifiers. These distortions can cause intermodulation (IM) distortion, which is undesirable to system designs.The effects of AM/AM and AM/PM distortions can cause the signal distortion that degrade the bit error rate performance of a communication channel to be increased.

A modulation scheme that produces a constant envelope and continuous phase signal set, implemented by multiplexing of two frequency/phase modulated signal of the type *(*FPM), both with the same frequency in each transmission interval [3].

The amplitude and phase modulation distortions are minimized using linearization method. The linearization method requires modeling the characteristics of the amplitude distortion and phase distortion of the HPA. Two types amplifiers are mostly used in communication: TWTA and SSPA. TWTA is most mostly used for high power satellite transmitters. Saleh model [4], has been used to provide the linearization method and applied to measured data from HPA that characterize the distortion caused by the HPA. The measured data provides a performance curve indicating nonlinear distortion.

Saleh model is a mathematical equation that describes the amplitude and phase modulation distortions of the HPA.

The amount of desired linearization is then determined to inversely match the amount of distortion for canceling out the distortion of the HPA. This paper investigates Pre–distorter technique for the linearization of a HPA to mitigate the AM/AM and AM/PM effects in digital communication systems.

The remainder of this paper is organized as follows. In section 2, a description of the proposed system was discussed. In section 3, the non-linear model for a HPA, and pre-distortion scheme were driven. Numerical results were presented in section 4, showing an improvement in the performance of FPM transmission system over the nonlinear channel.

II. SYSTEM MODEL

Fig. 1 illustrates the baseband equivalent functional block diagram of the TC-FPM transmitted signal through HPA using pre-distorter scheme.

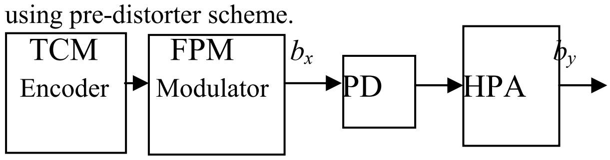

Fig. 1. Simplified TCM-FPM Transmitter through HPA

Let the base-band input signal to HPA be modeled as

$$b_x(\mathrm{t}) = U_x(t)\; e^{j\alpha_x(t)} \tag{1}$$

where $U_x(t) = |\, b_x(t) \,|$

Trellis coding of constant envelope M-ary signals employing frequency and phase modulation (TC-FPM) (e.g., 2FSK/MPSK, 4FSK/MPSK) has been driven by [3] with application to the AWGN channel. The symbols constituting the FPM signal set for the 2FSK/MPSK scheme are defined by

$$b(t) = \left(\sqrt{2/T}\right) \cos\left[\left(2\pi f_c t \pm h \pi t/T\right) - \varphi_i\right]$$
$$\varphi_i \in \{0, 2\pi/M, \ldots, 2(M-1)\pi/M\} \tag{2}$$

where T is the symbol duration, f_c is the carrier frequency, h is modulation index. The two FSK frequencies are defined by :

$(2\pi f_c t + h\pi t/T)$ *and* $(2\pi f_c t - h\pi t/T)$ rad/s. The

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signal space is four dimensional, and was defined in [3].

III. NONLINEARITY EFFECTS ON TCM-FPM SIGNAL

The classical and most often used nonlinear model of power amplifier is Saleh's model [4]. It is a pure nonlinear model for TWTA without memory. The equations define this base-band model of HPA as two modulus dependent *transfer functions* are defined as [6]:

$$A[U_x] = \alpha_a \; U_x \;/\; 1 + \beta_a \, U^2_x$$

$$\Phi[U_x] = \alpha_\Phi \, U_x \;/\; 1 + \beta_\Phi \, U^2_x \qquad (3)$$

where $A[U_x]$ and $\Phi[U_x]$ are the corresponding AM/AM and AM/PM characteristics respectively, both dependent exclusively on U_x, which is the input modulus to HPA.

The values of α_a, β_a , α_Φ and β_Φ are defined in [7]. The corresponding AM/AM and AM/PM curves so scaled are depicted in Fig. 2.

While SSPA's AM/AM and AM/PM can be defined as

$$A[U_x] = \; U_x \;/\; [1 + (U_x / A_{max})^{2p}]^{1/2p}$$

$$\Phi[U_x] = \; 0 \qquad (4)$$

A_{max} is the maximum output amplitude, and p is a constant controls the smoothness of the transition.

$$A_{max} \; = \max \,(\, A[U_x]\,) = \alpha_a \;\, A_s \,/\, 2 \qquad (5)$$

where A_s is the input saturation amplitude equals $1 \,/\, \sqrt{\beta_a}$

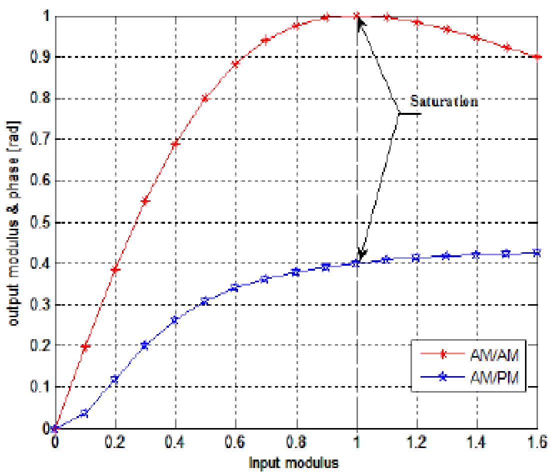

Fig. 2. AM/AM and AM/PM normalized characteristics of the Saleh model For TWTA HPA's

The HPA operation in the region of its nonlinear characteristic causes a nonlinear distortion of a transmitted signal, that subsequently results in increasing the bit error rate (BER), and the out-of-band energy radiation (spectral spreading).

The operating point of HPA is defined by input back-off (*IBO*) parameter which corresponds to the ratio of saturated input power (P_{max}), and the average input power (P_{in}) [6]:

$$IBO_{dB} \;= 10 \log_{10} (\, P_{max} \,/\; P_{in} \,) \qquad (6)$$

The measure of effects due to the nonlinear HPA could be decreased by the selection of relatively high values of *IBO*

The output of HPA defined in Fig. 1, is expressed as

$$b_y = A \;[\; \mathrm{U_x} \;]\; e^{j(\alpha x + \,\Phi[Ux])} \qquad (7)$$

where the input-output functional relation of the HPA has been defined as a *transfer function*. Hence in order to obtain linearization, it may be necessary to estimate a discrete inverse multiplicative function HPA^{-1} [.] such that

$$b_x = b_y \;\; . \;\; \mathrm{HPA}^{-1} \,[U_y] \qquad (8)$$

An alternative expression for the AM/AM distortion in (7), convenient for the theoretical formulation of the linearizer, is obtained by replacing the saturation input amplitude *As* in the expression (3). This gives

$$A[U_x] = A^2{}_s \, \alpha_a \, U_x \;/\; A^2{}_s + \; U^2_x \qquad (9)$$

The theoretical AM/AM inverse transfer function A^{-1}[.]could be determined by solving (9) for $U_x = A \;\{\; A^{-1} \;[U_x]\;\}$

$$[u] = \quad (\; A^2{}_s \, \alpha_a \,/\, 2U \;) \quad \cdot$$

$$\left[1 \; - \sqrt{\; 1 - \quad (\; 2U \,/\;\, A_s \, \alpha_a \,)^2} \;\; \right] \qquad (10)$$

Considering the alternative configurations shown in Fig. 3, where the same input-output function is applied as a pre-distorter [PD] for the linearization of the same HPA. Letting ψ[.] denote the AM/PM characteristic of the PD block.

For the case of a Pre-distortion, we have [6] :

$$b_{pout} \;=\; A^{-1} \;[\; U_x \,]\; e^{j(\alpha x + \; \psi[Ux])} \qquad (11)$$

$$b_y \;\; = \;\; A \;\; \left[A^{-1} \;[\; U_x \,] \right] \qquad \cdot$$

$$e^{j(\alpha x + \; \psi[Ux] \; + \Phi[A\text{-}1[Ux] \,)} \qquad (12)$$

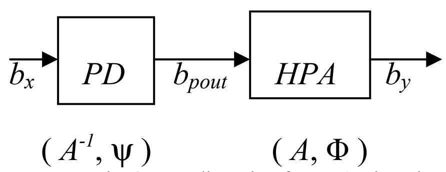

Fig. 3. Pre-distortion for HPA Linearization

The ideal AM/PM correction requires that

$$\psi \;[U_x] = - \; \Phi \;\{\;\; A^{-1}[U_x] \;\;\} \qquad (13)$$

$$b_{pin} = \;\; A \;[\;\; U_x \,]\; e^{j(\alpha x + \; \Phi[Ux])} \qquad (14)$$

$$b_y \;\;\; = \; A^{-1} \;\{ \quad A \;[\;\; U_x \,]\;\} \quad \cdot$$

$$e^{j(\alpha x + \; \Phi[Ux] \; + \psi[A\text{-}1[Ux] \,)} \qquad (15)$$

Pre-distortion linearization idea, as depicted in Fig. 4, can be used to linearize over a wide bandwidth. This is achieved by pre-distortion of the signal prior to amplification with the inverse characteristics of the distortion that will be imposed by the power amplifier. Thus the output of the HPA is a linear function of the input to the predistorter [7]

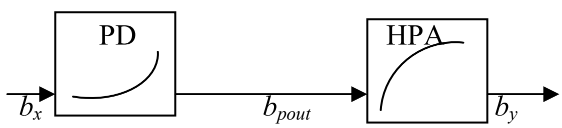

Fig. 4. Basic System Functional Diagram of Pre-distortion Linearization

where the AM/PM correction for Post-distorter case, requires that

$$\psi \;[U] = - \; \Phi \;\{\;\; A^{-1}[U] \;\;\} \qquad (16)$$

A description of the ideal theoretic AM/AM and AM/PM inverse characteristics, valid for the normalized Saleh's HPA model is shown in Fig. 5

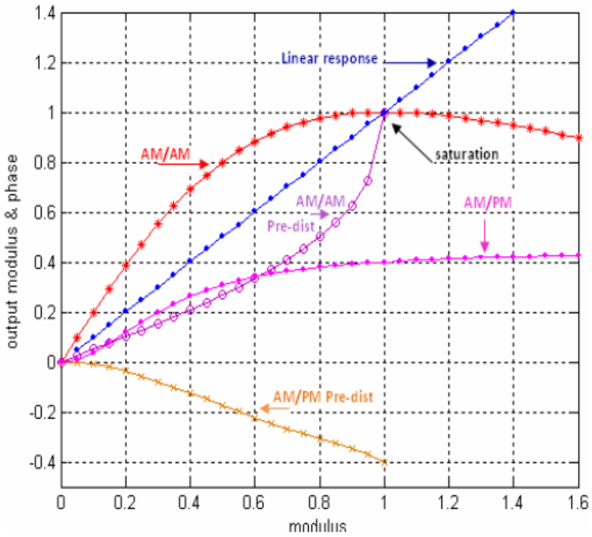

Fig. 5. AM/AM and AM/PM pre-distortion for the Saleh model

IV. Performance Analysis of TCM

An upper bound on the average error probability of conventional TCM over fading channels with coherent detection with ideal channel state information(CSI) is obtained as [8]

$$P_b = \sum_{x,\hat{x} \in c} \sum a(x,\hat{x})\, P(x)\, P(x \rightarrow \hat{x}) \qquad (17)$$

where $a(x,\hat{x})$ is the number of bit errors that occur when the sequence x is transmitted and the sequence $\hat{x} \neq x$ is chosen by the decoder, $P(x)$ is the periori probability of transmitting x, C is the set of all coded sequences, and $P(x \rightarrow \hat{x})$represents the pairwise error probability which is upper bounded by

$$P(x \rightarrow \hat{x}/\rho) \leq \exp\left(-E_s/4N_o\right) \cdot \sum_{i=1}^{L} \rho_i^2 \{x_i-\hat{x}_i\}^2 \qquad (18)$$

$$P(x \rightarrow \hat{x}/\rho) \leq \exp\left(-E_s/4N_o\right) \cdot d_i^2 \{x_i-\hat{x}_i\} \qquad (19)$$

where $d_i^2 \{x_i-\hat{x}_i\} = \sum_{i=1}^{L} \rho_i^2 \{x_i-\hat{x}_i\}^2$, ρ is the normalized fading amplitude for ith transmission interval which has a probability density function

$$P_\rho = \rho \exp(-\rho^2/2) \qquad (20)$$

and L is the length of error sequence for which $x_i \neq \hat{x}_i$.
Substituting (19) in (17) yields

$$P_b = \sum_{x,\hat{x} \in c} \sum a(x,\hat{x})\, P(x) \cdot \prod_{i \in \eta} \left[E_s/4N_o \{x_i-\hat{x}_i\}^2 \right]^{-1} \qquad (21)$$

where η defines the set of all i which $x_i \neq \hat{x}_i$

V. Numerical Results for TCM-FPM Schemes

In this section, we have proposed and analyzed the PD linearizer which compensates for arbitrary, invertible, channel nonlinearity in radio systems employing TCM-FPM. Fig. 6, illustrates the performance analysis for a linear TCM-2FSK/4PSK scheme, applying performance comparisons for (TCM-4PSK), and (TCM-2FSK). It is clear to notice the superiority of TCM-FPM over other types of digital modulation schemes.

A performance comparison for TCM-2FSK/4PSK, TCM-2FSK/8PSK and TCM-2FSK/16PSK schemes, are reported in Fig. 7

The performance of the (TCM-2FSK/4PSK) system expressed by bit error probability (P_e) versus E_b / N_o under the case of nonlinearity for different values of *IBO* (*IBO* = 5 dB, *IBO* = 7 dB, and *IBO* = 9 dB), compared with the case of using pre-distorter, are illustrated by Fig. 8.

It can be concluded that it is highly recommended to use PD at the transmitter side in order to suppress the undesirable nonlinearity effects and to get improved bit error performance at the receiver.

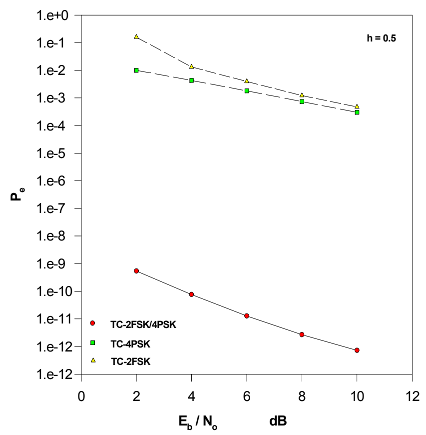

Fig. 6. Performance Comparison for TC- 2FSK/4PSK with TC-4PSK and TC-2FSK Modulation Schemes

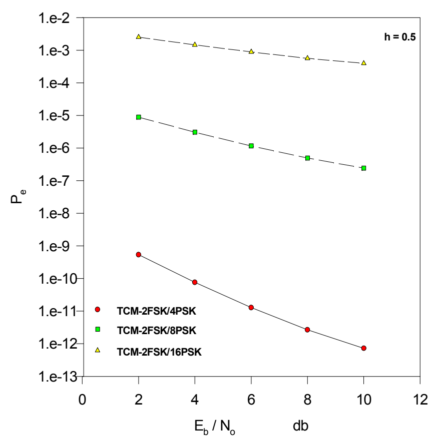

Fig. 7. Performance Comparison for TC-2FSK/4PSK with TC-2FSK/8PSK and TC-2FSK/16PSK Modulation Schemes

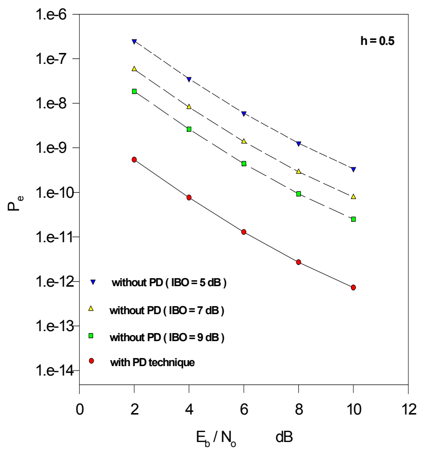

Fig. 8. Performance Analysis for TC- 2FSK/4PSK within different Values of IBO and with Pre-distortion Technique

VI. CONCLUSIONS

In this paper, a spectral efficient modulation scheme has been derived; the FPM signal has a constant envelope and a continuous phase. It has been shown its superiority of the BER performance over MPSK, and MFSK modulation schemes. The effects of nonlinearities (AM/AM and AM/PM) were analyzed. It is shown that these effects can be compensated by using PD technique. From analytical results, it is confirmed that PD system with FPM systems, gives a good BER performance improvements compared to FPM signals without PD.

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