System performance evaluation of power amplifier behavioural models

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Keywords: APSK modulation, BER, behavioural models, non-linear, power amplifier.

Abstract

Power amplifiers are one of the major sources of non-linearities in a communication system. To compensate the PA non-linear behaviour, techniques such as data pre-distortion together with the implementation of a memoryless model such as Saleh's, Ghorbani's, Rapp's or the Bessel-Fourier, are widely used in the literature. However, the accuracy of these models has been compared and tested by taking into account just the PA behaviour. Hence, the main contribution of this paper consists of comparing the performance of these models at system level by presenting computed and measured BER results.

1 Introduction

Power amplifiers (PAs) are one of the most significant elements in radio telecommunication systems since they are responsible for most of the total power consumption of the chain and one of the major sources of non-linearities [1]. Critically, the efficiency of a power amplifier increases when the amplifier back-off is reduced thereby giving rise to the well-known design trade-off between linearity and power [2]. This trade-off becomes increasingly critical not only for communications systems such as the second-generation digital video broadcasting for satellites (DVB-S2) but for RADAR applications [3].

In order to reduce the non-linearities generated by the PA at saturation, pre-distortion techniques such as signal and data pre-distortion are widely used in the literature [4, 5]. As data pre-distortion does not introduce spectral regrowth, which is quite critical when following standard regulations, this technique is considerably desirable [6]. Most data pre-distortion techniques consist of applying iterative methods which update the pre-distorted constellation points by taking into account the difference between the distorted constellation at the output of the PA and the reference constellation [5, 7]. These techniques usually require a model, which can be memoryless or with memory, to account for the PA behaviour.

The problem regarding behavioural models with memory is that, although they are mainly more accurate, they increase the computational time and complexity of the pre-distortion algorithm, so that is the reason why memoryless models are generally preferred in this case. Some of the most widely used memoryless models in the literature are Saleh's [8], Ghorbani's [9], Rapp's [10] and the Bessel-Fourier [11]. However, the accuracy of these models has been compared and tested in the literature in terms of normalized mean square error (NMSE) and adjacent channel error power ratio (ACEPR), which take into account just the PA behaviour [12, 13]. Hence, the main contribution of this paper consists of comparing the performance of the aforementioned memoryless behavioural models at system level. To this end, computed and measured bit-error-rate (BER) results in additive white Gaussian noise (AWGN) channel and the presence of a solid-state power amplifier (SSPA) are depicted. The modulation chosen for this performance evaluation is the amplitude and phase-shift keying (APSK) since it is much more sensitive to the non-linear behaviour of the PA than the phase-shift keying (PSK) modulation.

2 Overview of widely used behavioural models

The memoryless PA behavioural models exploit experimental characterization of the PA amplitude-to-amplitude modulation (AM/AM) and the amplitude-to-phase modulation (AM/PM), to provide an analytical solution to model the non-linear PA performance.

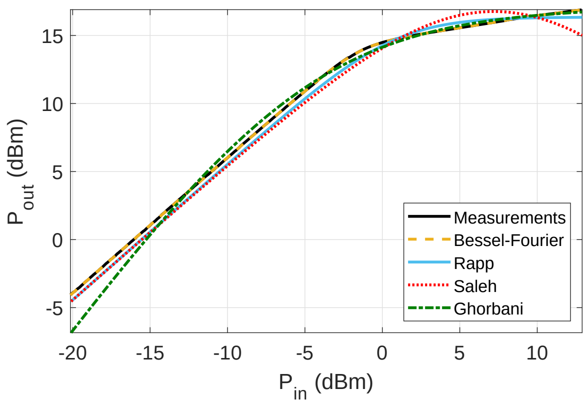

Fig. 1: Measured and computed AM/AM conversion of the power amplifier ZJL-4HG+ by Mini Circuits. The behavioural models applied for the computation were: Bessel-Fourier, Rapp, Saleh and Ghorbani.

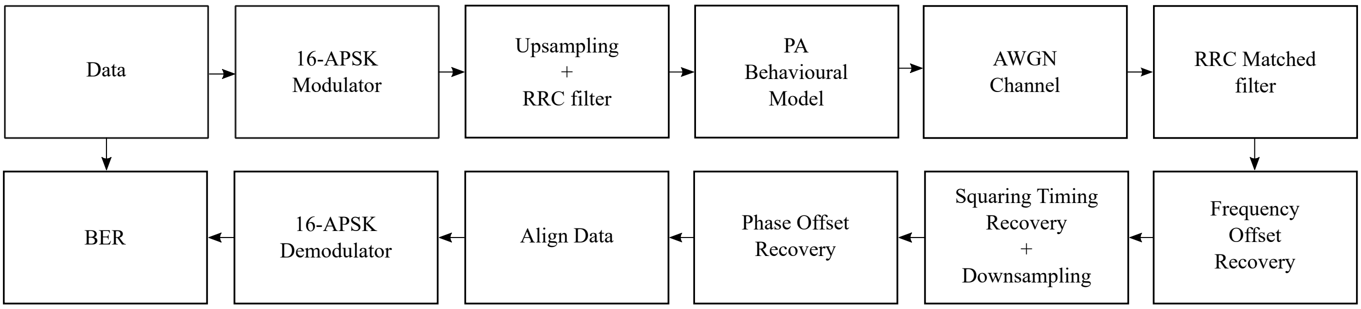

Fig. 2: Block diagram to compute the BER performance for un-coded digital modulations in AWGN channel and the presence of a PA. The AM/AM conversion of the selected PA is depicted in Fig. 1.

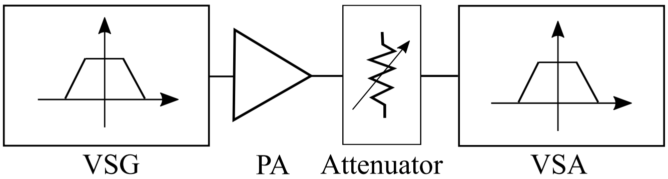

Fig. 3: Block diagram of the experimental set up for measuring the BER performance for un-coded digital modulations and various PA output back-off levels in AWGN channel. The AM/AM conversion of the selected PA is depicted in Fig. 1.

A review of the aforementioned memoryless behavioural models is presented in this section. As the AM/PM conversion of the tested SSPA was negligible, only the AM/AM characterization was considered.

One of the first proposed behavioural models was the one developed by Saleh, who presented a travelling-wave-tube amplifier (TWTA) model that does not estimate the SSPA behaviour with the same acceptable accuracy. The AM/AM envelope characterization proposed by Saleh, $S_{AM/AM}(\rho)$, is the following [8]:

$$S_{AM/AM}(\rho) = \frac{x_0 \rho}{1 + x_1 \rho^2} \tag{1}$$

where ρ refers to the magnitude of the PA input signal and x_0 and x_1 are the only coefficients of the model. Due to the inaccuracies presented by this methodology when modelling SSPAs, Ghorbani proposed the following four-parameter AM/AM characterization [9]:

$$G_{AM/AM}(\rho) = \frac{y_0 \rho^{y_1}}{1 + y_2 \rho^{y_1}} + y_3 \rho \tag{2}$$

$Model$	$Parameters$
$Saleh$	$x_0 = 6.01; x_1 = 190.59$
$Ghorbani$	$y_0 = 130.2; y_1 = 1.6; y_2 = 587.1; y_3 = 0.02$
$Rapp$	$z_0 = 6.71; z_1 = 0.21; z_2 = 1.30$
$Bessel$	$v_0 = 1.93$

Table 1: Estimated parameters to model the measured AM/AM conversion depicted in Fig 1 by applying any of the selected behavioural models.

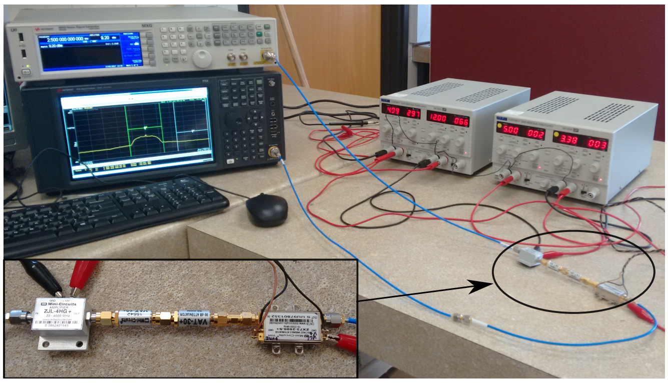

Fig. 4: Experimental set up for measuring the BER performance for un-coded digital modulations and various PA output back-off levels in AWGN channel.

where y_0, y_1, y_2 and y_3 are the coefficients of the model.

Rapp presented another SSPA model but only for AM/AM, as Rapp suggested that AM/PM conversion is usually small enough to be neglected. The AM/AM equation proposed by Rapp is given by [14]:

$$R_{AM/AM}(\rho) = \frac{z_0 \rho}{\left(1 + \left(\frac{z_0 \rho}{z_1}\right)^{2 z_2}\right)^{\frac{1}{2 z_2}}} \tag{3}$$

where z_0, z_1, z_2 are the model coefficients.

The last model considered here is the Bessel-Fourier, which consists on a series expansion approximation based on the Bessel function of the first kind $J(\cdot)$. The AM/AM envelope characterization in this case is the following [11]:

$$B_{AM/AM}(\rho) = \sum_{m=1}^{M} v_m J_1(v_0 m \rho) \tag{4}$$

where M is the number of terms of the Bessel series, v_m refers to the m-th coefficient and v_0 is another coefficient. The main advantage of this model compared to the previous ones is that it is extensible, in the sense that more coefficients may be added for improved model accuracy.

The measured AM/AM conversion of the tested PA and the curve fits to this data using the aforementioned behavioural

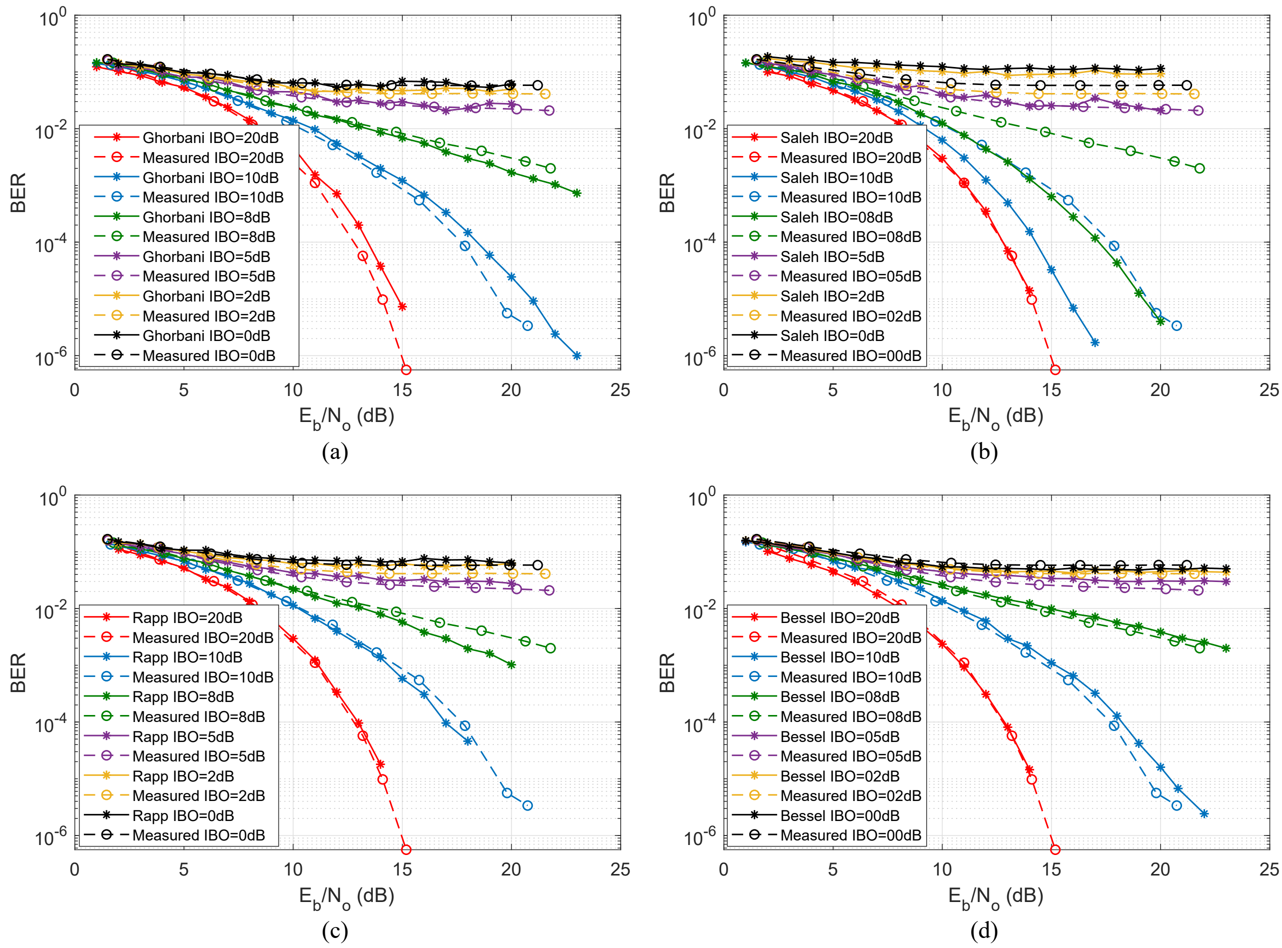

Fig. 5: Comparison between computed and measured BER for un-coded 16-APSK in AWGN channel and the presence of the power amplifier ZJL-4HG+. Parameters used: up-sampling factor = 8, filter roll-off = 0.5 and $\gamma_{in} = 2.5$. Behavioural models applied: (a) Ghorbani; (b) Saleh; (c) Rapp; (d) Bessel-Fourier.

models are depicted in Fig. 1. This figure shows that: the Saleh model only fits accurately the truly linear region while the Ghorbani model does not fit that region properly; the Rapp model fluctuates in the transition between the two regions, linear and saturation; and the Bessel-Fourier model fits accurately the entire curve. The value of the parameters required to characterize every model are presented in Table 1. In the case of the Bessel-Fourier method, the number of total coefficients was 16 and only the value of the parameter v_0 is shown in the table as the other 15 coefficients were expressed in terms of v_0 [15]. Furthermore, an improvement of the Bessel-Fourier model accuracy at high power levels was achieved by applying the methodology proposed in [16].
The behavioural models introduced in this section together with the coefficients presented in Table 1 will be the ones applied to estimate the BER performance in the following section.

3 Testbed description and results

The performance comparison of these behavioural models together with a description of the testbed used are introduced in this section.

Fig. 2 shows the block diagram used to compute the BER performance for different input back-off (IBO) levels and energy per bit to noise power spectral density (E_b/N_o) ratios. The tasks of the first four blocks at the top left part of the figure are: generating the data to be transmitted; applying the 16-APSK modulation; filtering and amplifying the signal by using any of the behavioural models described in the previous section. The AWGN block variance can be adjusted to modify the value of the E_b/N_o for a fixed IBO level. The rest of the blocks are used for match filtering, frequency and phase recoveries, time synchronization, data alignment, demodulation and BER estimation.

The experimental set-up employed for measuring the BER is introduced in Fig. 3 and a picture of the set-up is depicted in Fig. 4. The models of the vector signal generator (VSG) and the vector signal analyzer (VSA) were MXG N5182B and PXA N9030B, respectively, both by Keysight Technologies. The amplifier was the one characterized in Fig. 1 and the model of the variable attenuator was ZX73-2500+ by Mini Circuits. In order to generate the analogue signal to be transmitted by the VSG, the filtered symbols at the output of the RRC filter are converted to I16 format and recorded to a binary file. The different E_b/N_o values can be achieved by the use of the variable attenuator. The measured data is recorded back to a binary file to be processed by the receiving blocks included in the block diagram depicted in Fig. 2.

The comparison between computed and measured BER for un-coded 16-APSK in AWGN channel and the presence of a SSPA, which has been characterized by the different behavioural models described in the previous section, is depicted in Fig. 5. As observed in this figure, the BER results computed by applying the four different behavioural models are overall in good agreement with the conclusions extracted from Fig 1: the Ghorbani model does not model accurately the non-linearities when the PA operates in the linear region (eg. IBO = 20dB and IBO = 10dB); the Saleh model is highly accurate when the PA output signal is completely linear (eg. IBO = 20dB); the Rapp model is less accurate when the PA operates in the area between the linear and the high saturation regions (eg. IBO = 8dB); and the Bessel-Fourier model seems to model properly the PA behaviour in all operating regions.

After taking everything into consideration, we could conclude saying that the selection of the behavioural model will depend on the used PAs and the system level specifications. The type of application will determine the operating region where the behavioural model has to be significantly accurate and the number of coefficients that can be used without considerable impact in the complexity and computational time of the system.

4 Conclusion

The accuracy of four memoryless behavioural models, Saleh's, Ghorbani's, Rapp's and the Bessel-Fourier method, has been compared at system level by presenting computed and measured BER results in AWGN channel and the presence of a SSPA.

The results showed that the accuracy of the behavioural models varied depending on the PA operating region. Hence, the type of application and system specifications may be crucial aspects for the proper model selection.

Acknowledgements

This work has been supported by European Commission funded project DORADA (grant agreement no 610691). The authors would like to acknowledge COST Action IC1301 WiPE Wireless Power Transmission for Sustainable Electronics and EPSRC EP/P025129/1.

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