Behavioural Models for Distributed Arrays of High Performance Doherty Power Amplifiers

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***Abstract*—Behavioral models are intended as high level mathematical descriptions which require less computational effort to simulate behavior compared to physical or circuit level equivalent models. When designed and dimensioned properly they are well suited to concise characterization of power amplifiers under different operating conditions. In this paper we compare the relative performance of several behavioral models for modelling an asymmetric Doherty power amplifier for their use in distributed arrays.**

Keywords—Asymmetric Doherty, power amplifier, behavioral model

I. INTRODUCTION

As the demands on cellular network capacity increase, new technologies such as massive-MIMO and beamforming are being proposed to meet the demands on performance. 5G wireless network specifications require improved power consumption, however the requirement for multiple RF transceiver chains will require a considerable design effort to ensure they maintain linear performance. Power amplifier (PA) architectures like asymmetric Doherty have been shown to provide higher power efficiency without the need for greater digital processing hardware. Having a distributed array of 128 of these PAs will require design and planning for the digital hardware providing the respective signals.

A large body of work has been previously undertaken to enable the characterization of PA architectures. Behavioural modelling studies have targeted a reduction in the number of model coefficients [1], [2]. As computational power has improved, and the fundamental characteristics of high efficiency power amplifier architectures have become more complex, an accurate description of the PA behaviour is now of great importance for the design of arrays of distributed PAs. Systems which enable massive-MIMO and beamforming antennas require a large amount of processing power in order to compensate the many paths simultaneously leading to the array of antennas. As a result of device variations, component tolerances and temperature differences between PAs a separate model is ideally required for each path. The ability to accurately represent the behaviour of each branch of these systems, especially in terms of their nonlinear PA behaviour can be extremely time consuming and overcomplicated if the correct modelling strategy is not used.

The remainder of the paper is arranged as follows. In Section II, the underlying theory behind Asymmetric Doherty power amplifiers (DPA) is set out and the non-ideal effects specific to asymmetric Doherty operation are identified. Section III sets out a set of behavioral models which are used to model dynamic nonlinear systems such as high efficiency PAs. The experimental results for an extensive set of tests on the respective models are compared in Section IV. Finally, the conclusions from this work are presented.

II. HIGH EFFICIENCY ASYMMETERIC DOHERTY PA

The first distinction that must be made is the difference in the operation of symmertrical and asymmetrical Doherty PAs.

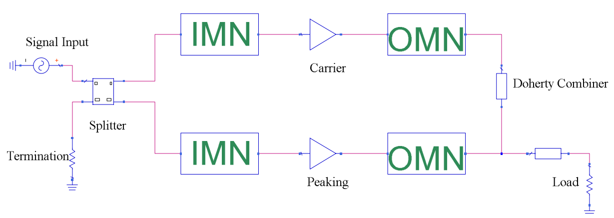

Fig. 1. Doherty Power Amplifer setup

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Fig. 1, indicates the organization of a Doherty power amplifier and its components. Firstly, an analogue splitter that provides the input signal into two different paths according to a predetermined ratio. In literature, this design parameter that determines the activation of gate biasing for the auxiliary amplifier and is commonly termed as α and operates in between 0≤α ≤1 [3], [7].

$$\alpha = P_{linear}/P_{max} \tag{1}$$

Where P_{linear} is maximum linear output power of main PA and P_{max} maximum output power of main PA. Additionally, considering Doherty operation it is possible to infer that the maximum output power of main PA is proportional to the total output power of Doherty PA (P_{total})

As a, result, output back-off (*OBO*) level can be determined as,

$$OBO = 20 \cdot log10(1/\alpha) \tag{2}$$

For a symmetrical amplifier α = 0.5, meaning a back-off level of 6.020 dB from the maximum power output point of the Doherty power amplifier. A case of an asymmetrical division of α = 0.25 yields an OBO of 12.04 dB. [3] In comparison to symmetrical Doherty power amplifier that provides 6 dB back-off limit, an asymmetrical Doherty power amplifier has an extended region of back-off. Thus, allowing higher efficiency at higher back-off levels for modern communication signals such as LTE or WCDMA with higher levels of PAPR [3], [4], [5], [6].

Secondly, the two devices are termed Main/Carrier and Auxiliary/Peaking amplifiers [7]. Since Doherty power amplifier deals with complex envelope signals, the two amplifiers in practice are biased in Class AB and Class C respectively. Thereafter, the two matching networks aside each transistor provides the optimum power transfer into and from the device. As a Doherty combiner two transmission lines, acting as an impedance inverter and a transformer provides non-isolating power summation at the output. Additionally, there exists phase correction lines to compensate for phase variations between the two paths [3], [4], [5], [6], [8].

Apart from difference in gate biasing, symmetrical Doherty amplifier devices are equal in design and have same matching networks on either side. Different classes of operation of two devices leads to a difference in output power levels they produce, hence there is an asymmetry in gain. Additionally, since the auxiliary amplifier is not contributing as expected to the active load modulation operation, carrier amplifier will show an early saturation without reaching its maximum output voltage drive, this leads to a deterioration in linearity. [9] As a solution to this, device manufactures, or design engineers choose a relatively higher power device for the auxiliary path in-order to mitigate this issue [9]. Another technique is to use an uneven power drive for the auxiliary path. Kim et al, has successfully investigated this in [8] and gain asymmetry can be resolved to a good extent. Therefore, a well-designed asymmetrical Doherty power amplifier supersedes a symmetrical design, in addition to other benefits such as higher back-off levels and application adjustable and more efficient operation. Therefore, as a single input and output advanced power amplifier an asymmetrical power amplifier stands as the best choice to be deployed in an array of networked distributed PAs.

III. Models For Asymmetric PAs

A modulated bandpass signal in each model can be written as *x(t)*, where,

$$x(t) = x_1(t) \cdot exp(j\omega_c t) \tag{3}$$

again,

$$x_1(t) = A(t) \cdot exp(j\theta(t)) \tag{4}$$

with $x_1(t)$, denoting the complex envelope of *x(t)*. The discrete form of this signal is subsequently denoted as *x(n)*. [17], [18]

A. AM/AM & AM/PM model

A complex envelope output for the polar form of the AM/AM and AM/PM model can be expressed as,

$$y_1(n) = g[A(n)] \cdot exp(j\{\theta(n) + \phi[A(n)]\}) \tag{5}$$

A polynomial equation can be used as the analytical representation of both the AM/AM and AM/PM transfer characteristics g[A(t)] and ϕ[A(t)] respectively. In this case a power series of specified order is fit to the measured data for each transfer characteristic, yielding two sets of coefficients g[A(t)] and ϕ[A(t)]. [17], [18]

B. Discrete Volterra Series

The second behavioural model that was used in this work for the accurate characterization of the asymmetric Doherty PA uses the discrete form of the baseband complex envelope Volterra series. For an in-depth description of this model the interested reader is referred to [10].

C. Piecewise Volterra Series

The application of piecewise Volterra models to high efficiency power amplifiers has been carried out previously [11], [12], [13], [14]. The use of an instantaneous amplitude or power measurement with a bank of Volterra kernels, one for each region over the operating range of the PA. In this work the objective is to perform a more accurate modelling of the PA response as opposed to minimizing the total number of coefficients used for the model.

A key aspect to the application of these models to power amplifiers is the effective segmentation of the range of operation into different regions of distinctly different behaviour. Two approaches used to identify the different regions are k-means and self-organizing maps.

K-means is a method for data clustering and vector quantization and has been used previously in [13]. It is very fast as the computation required to calculate the figure is computationally efficient. The feature space is divided into k non-overlapping clusters, at the center of each cluster is a point called the centroid. Using the Euclidean distance, all data points are assigned to their nearest centroid. All centroids are iteratively repositioned such that the sum of the distances between the points and the centroid in that region are reduced. This process is repeated until the centroids settle and a minimum movement threshold between iterations is met. A code book or look up table is used by the piecewise model to select the appropriate time series.

Self-organizing maps (SOM) provide an alternative method for clustering data compared to K-means [15]. They can be implemented using an array of adders and multipliers or as a traditional cluster LUT method. The structure of a SOM is similar to a single neuron within a neural network. The main difference to a neural network neuron is the output activation function is now a compete transfer function. As the name of the activation function suggests, the input is compared with many possible outputs. The output which has the strongest correlation to the input is selected as the winner. Additionally, the SOM does not use a bias weight on the input signal.

IV. Experimental Results

To ensure intended performance of the asymmetric Doherty power amplifier, experimental measurements need to be performed. The device used in this work is an NXP A2I08H040GNR1 and was aimed at FDD LTE for 5G in the sub 1 GHz band for base-station applications. Therefore, the Doherty power amplifier performance has been experimentally validated with LTE test signals and with single tones wherever applicable. The experimental test-bench used to gather the data consisted of: three DC power supplies to supply the gate biasing and drain biasing required for the MMIC power amplifier. A Hameg HMP2030 was programmed to record the DC power supply currents and their voltages. The RF input signal to the DPA was provided by SMU200A Vector Signal Generator from Rohde & Schwarz. At the output of the DPA, an attenuator and a coupler were in place to make sure safety of the measurement equipment. A Rohde & Schwarz NRP power meter was used to measure average output power and FSQ signal analyzer was used to capture the time domain data points from the PA.

Testing was first carried out to ensure the suitability of the PA for operation in the selected frequency range. This entailed confirming it could retain 30 dB of gain across a broad range of frequencies and for a range of different output power levels. Test board indicated an power-added efficiency of 31.5% at an output power of 34.76 dBm which is in good agreement with the device data-sheet. Since this device is rated for 9 Watt output power level the maximum efficiency that can be achieved in practice for lower power levels of operation is marginally compromised [16].

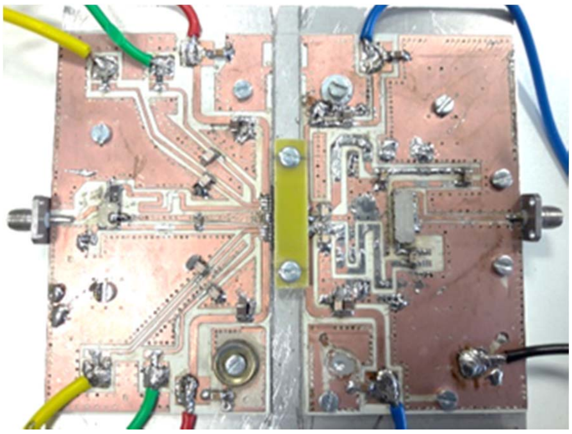

Fig. 2. Fabricated Asymmetrical Doherty Power Amplifier

For accurate characterization of the behaviour of the PA, several experimental tests were conducted to extract the complex envelope of the PA output signal in time domain, using the complex baseband input and output signals. Plotting the AM/AM relationship for the asymmetric Doherty PA using the instantaneous input/output sample pairs, there is a noticeable knee in the plot and spread in the points. (Fig: 4,6,8,9,11) Similarly, as can be seen from the frequency-domain spectra (Fig. 3) for the PA the frequency spreading that occurs is distinct and covers a multiple of the original signal bandwidth. To quantify the quality of the approximation normalized mean square error has been used to compare the relative performance of the four models.

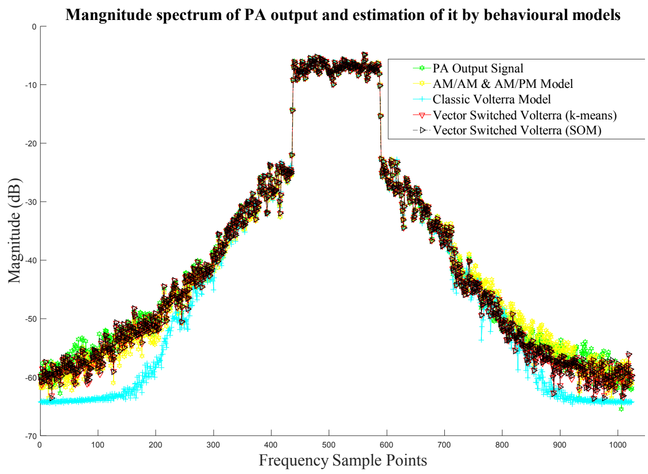

Fig. 3. Comparison of magnitude spectra of the output captured signal with modelled responses from different modelling techniques

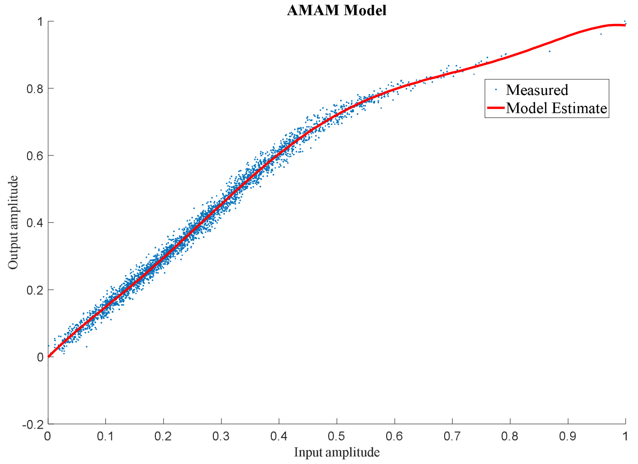

Fig. 4. AM/AM model characterizing the output signal of the PA in AM-AM distortion curve

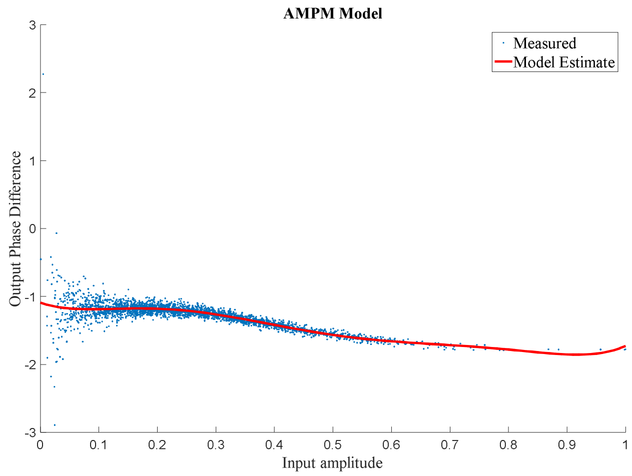

Fig. 5. AM/AM model characterizing the output signal of the PA in AM-PM distortion curve

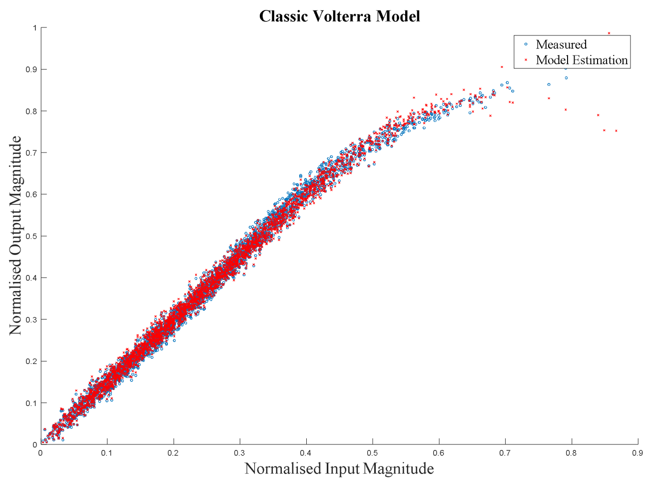

Fig. 6. Classic Volterra Model characterizing the output signal of the PA in AM-AM distortion curve

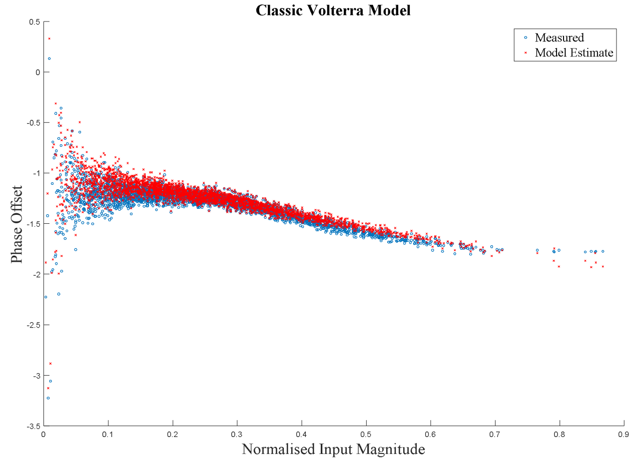

Fig. 7. Classic Volterra Model characterizing the output signal of the PA in AM-PM distortion curve

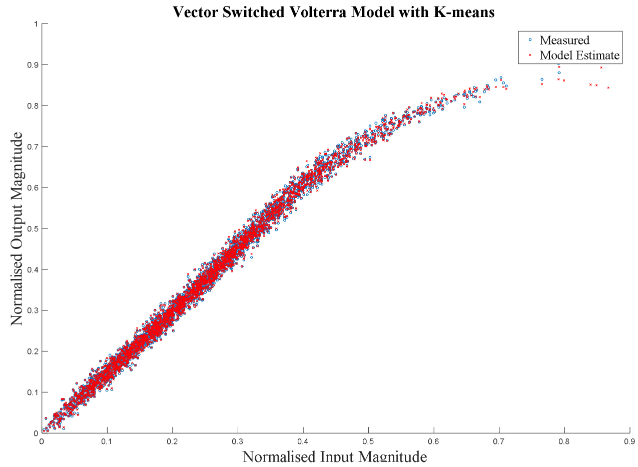

Fig. 8. Vector Switched Volterra Model (VSV) characterizing the output of the PA in AM-AM distortion curve.

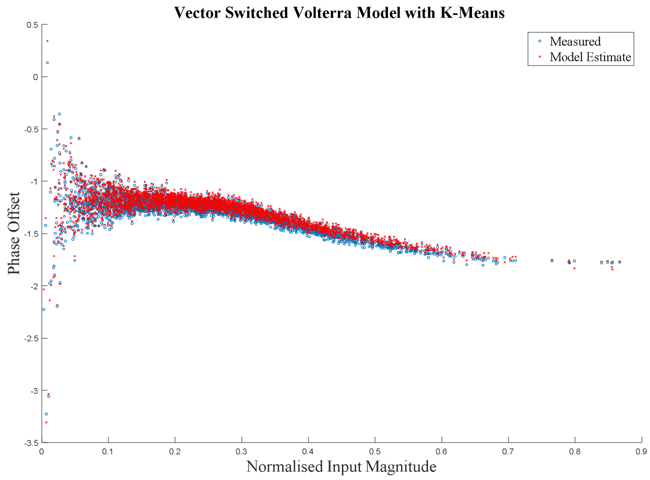

Fig. 9. Vector Switched Volterra Model with K-Means characterizing the output signal of the PA in AM-PM distortion curve

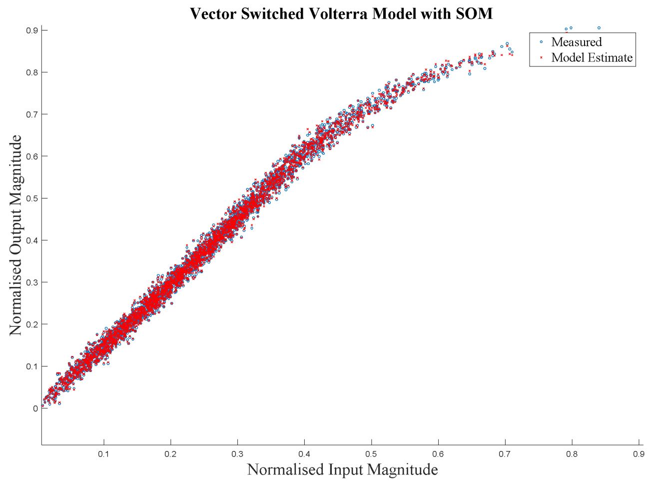

Fig. 10. Vector Switched Volterra Model with SOM characterizing the output signal of the PA in AM-AM distortion curve

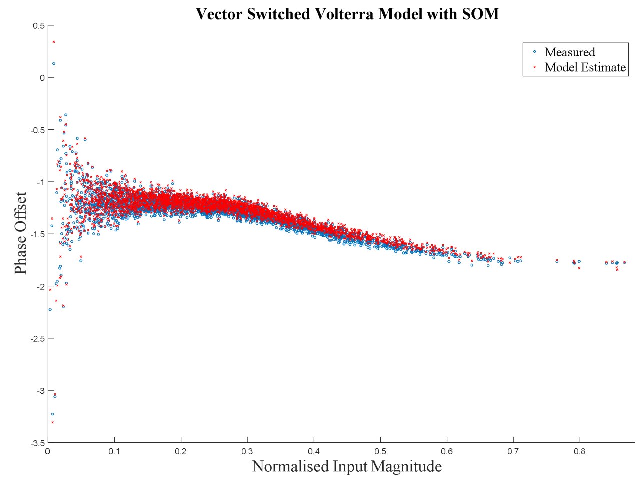

Fig. 11. Vector Switched Volterra Model (SOM) characterizing the output signal of the PA in AM-PM distortion curve

TABLE I. COMPARISON OF BEHAVIOURAL MODELS

Model Name	NMSE (dB)
AM/AM & AM/PM	-24
Volterra Series	-27
VSV with SOM	-29
VSV with k-means	-29

Table 1 summarizes the relative performance of the different behavioral modelling techniques used, by comparing their Normalized Mean Squared Error value (NMSE). NMSE is a well-accepted metric that provides an evaluation of the accuracy of the Behavioral model used. Lower the value obtained for NMSE indicates a better approximated model. It can be clearly deduced from analysis summarized by table 1 and from the figures 3 to 11 that the state-of the art Vector switched Volterra models with SOP and SOM offers the best approximation. In terms of computational effort AM/AM & AM/PM model require 12 coefficients, classical Volterra series require 35 coefficients and Vector switched Volterra series require 105 coefficients. For better accuracy of extra 5dB higher order model is required. In Doherty type applications where the power sweep has two clear regions of operation, models such as VSV offers better approximation.

V. CONCLUSIONS

In summary a tuned asymmetric Doherty PA was fabricated and tested using an LTE test signal, which was then characterized using four different behavioral modelling techniques. AM/AM & AM/PM, classic Volterra series and piecewise Volterra series. The piecewise Volterra series provides a more accurate representation of PA behavior compared to the two previous approaches. This level of precision and fast modelling proves their value in using behavioral models in testing a several advanced DPA structures in a more complex integrated structure such as a distributed array.

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