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***Abstract* — In this paper, two multi-basis weighted memory polynomial models are proposed for radio frequency power amplifiers' behavioral modelling. In these models, the conventional memory polynomial function of the generalized and hybrid memory polynomial models is replaced by a weighted version of it. Experimental validation was performed on a power amplifier prototype exhibiting strong memory effects, and driven by a 20 MHz LTE signal with 1001 configuration. Proposed weighted generalized memory polynomial and hybrid memory polynomial models show superior performance when compared to their memory polynomial based conventional counterparts. Indeed, an NMSE improvement of 2 dB to 3 dB is obtained for the same complexity, and a reduction of almost 50% in the number of coefficients are achieved for the same performance.**

***Index Terms* — Behavioral modelling, distortions, generalized memory polynomial , hybrid memory polynomial, LTE, memory effects, memory polynomial, nonlinearity, power amplifier, weighted memory polynomial.**

I. Introduction

Nowadays, wireless communication standards necessitate the deployment of spectral efficient broadcasting systems (i.e. OFDM-based) to maximize the use of the highly over-crowded radio frequency (RF) spectrum. Moreover, wideband signals (with bandwidths of 20MHz and wider) are deployed to meet users' requirements of high speed communication. This inevitably induces the undesirable static nonlinear and dynamic behaviors of wireless transmitters and especially power amplifiers (PAs). The static nonlinear behavior as well as the dynamic behavior (i.e. memory effects) cause the generation of out-of-band distortions that negatively affect the transmission quality in neighboring wireless channels. As a result, regulatory agencies put stringent requirements on wireless communication service providers to meet predefined spectrum emission masks. A direct solution to the static nonlinear problem is to back-off the PA so that it works in its linear region. However, this affects the size and cost of power amplification systems. Thus, it is desired to have highly power-efficient PAs that work near their saturation region while ensuring satisfactory output signal fidelity (i.e. linearity).

Digital predistortion (DPD) linearization approach was shown to achieve the highest power efficiency among all other linearization techniques for base station applications. DPD technique simply predistorts the input signal with the inverse PA's function so that the output signal is linear. An essential first step for digital predistortion models quick-validation is to analyze the performance of the models in PA behavioral modeling context.

A wide range of behavioral models has been proposed in the literature [1]-[7][8]. Volterra series model is known to be the most comprehensive model; however, it is only used in the case of mildly nonlinear PAs with fading memory effects since the number of coefficients dramatically increase as the nonlinearity order or memory depth increase [6]. Accordingly, several pruning techniques have been used to reduce the number of coefficients in Volterra based models without affecting their performance [2]-[4]. The memory polynomial (MP) model, on the other hand achieves a good tradeoff between complexity and performance by including only the diagonal terms of Volterra series [6]. The performance of the MP model is further improved by including some leading and lagging cross-terms such as in the generalized memory polynomial (GMP) [7] and the hybrid memory polynomial envelope polynomial (HMEM) models [8]. GMP and HMEM models are attractive because of the ease of their identification procedure. In fact, these models are linear with respect to their coefficients and can be identified using linear system identification techniques such as the least square method. However, the number of coefficients of multi-basis function MP models (such as the GMP and HMEM) becomes large as the bandwidth of the transmitted signal increases. In both GMP and HMEM models, the most cumbersome sub-model which has the largest size is the memory polynomial function. This motivates the development of low complexity MP-based behavioral models.

A novel weighted MP-based model (WMP) was recently proposed in [10]. In this model, a power-dependent weight function is introduced to give more significant impact to the strongly-dynamic mildly-nonlinear distortions at low power levels and mildly-dynamic strongly-nonlinear distortions at high power levels. The model was shown to reduce the number of coefficients by approximately 50% while achieving the same normalized mean square error (NMSE) performance when compared to the conventional MP model. In this work, the weighted memory polynomial model is extended to the case of multi-basis function behavioral models. Two multi-basis weighted memory polynomial models are proposed: namely the weighted generalized memory polynomial (W-GMP) model, and the weighted hybrid memory polynomial envelope memory polynomial (W-HMEM) model. These models are obtained by replacing in the GMP and HMEM behavioral models, the MP function by the WMP function. The proposed models are validated experimentally on a high-efficiency PA driven by a 20 MHz LTE signal of 1001 configuration. The models are then benchmarked against conventional GMP and HMEM models.

This paper is organized as follows. In, Section II, the proposed multi-basis weighted memory polynomial models are introduced. The experimental setup and results are reported in Section III. Finally, conclusions are drawn in Section IV.

II. Multi-Basis Weighted Memory Polynomial Models

A. Weighted Memory Polynomial

The WMP model was proposed in [10]. This model assigns a power-dependent weight function to the static and dynamic terms of MP model. The WMP model is motivated by the fact that dynamic nonlinear behavior of a PA has two different trends. At low input power levels, PAs are observed to have mild static nonlinear behavior with strong memory effects, while at high input power levels, static nonlinear behavior is dominant with mild memory effects. This motivates the use of static and dynamic weighting functions that are applied on the static and dynamic terms of MP model, respectively. This is to include the varying intensity of static and dynamic distortions as a function of the input power level. The model's output signal (y_{WMP}) is expressed as a function of its input (x) as:

$$
\begin{aligned}
y_{WMP}(n) &= \sum_{i=0}^{N_S} \alpha_i \mathrm{w_S}\left(\left|x(n)\right|\right) x(n) \left|x(n)\right|^i \\
&+ \sum_{i=0}^{N_D} \sum_{j=1}^{M} \beta_{ij} \mathrm{w_D}\left(\left|x(n-j)\right|\right) x(n-j) \left|x(n-j)\right|^i
\end{aligned}
\tag{1}
$$

where N_S and α_i are the nonlinearity order and the coefficients of the static part of the model. N_D, M and β_{ij} are the nonlinearity order, the memory depth, and the coefficients of the dynamic part of the model. $\mathrm{w_S}\left(\left|x(n)\right|\right)$ and $\mathrm{w_D}\left(\left|x(n)\right|\right)$ represent the weighting functions applied on the static and dynamic terms of the model, respectively. The static and dynamic weighting functions adopted in this work are hyperbolic tangent functions similar to the functions used in [10]. The WMP model was proven to significantly improve the NMSE performance of the conventional MP model. Moreover, it was shown that it can achieve the same NMSE performance of MP model while requiring much lower number of coefficients.

B. Proposed Weighted Generalized Memory Polynomial

The GMP model was proposed in [6][7]. In this model, leading and lagging cross-terms are added to the conventional memory polynomial model for the sake of performance improvement. GMP model is mathematically expressed as:

$$
\begin{aligned}
y_{GMP}(n) &= \sum_{k=0}^{K_a-1} \sum_{l=0}^{L_a-1} a_{kl}\, x(n-l)\, |x(n-l)|^k \\
&+ \sum_{k=1}^{K_b-1} \sum_{l=0}^{L_b-1} \sum_{m=1}^{M_b} b_{klm}\, x(n-l)\, |x(n-l-m)|^k \\
&+ \sum_{k=1}^{K_c-1} \sum_{l=0}^{L_c-1} \sum_{m=1}^{M_c} c_{klm}\, x(n-l)\, |x(n-l+m)|^k
\end{aligned}
\tag{2}
$$

where x and y_{GMP} are the model's input and output waveforms, respectively. K_a and L_a are the nonlinearity order and the memory depth of the MP sub-model, respectively; (K_b, L_b) and (K_c, L_c) are the nonlinearity order and the memory depth of the lagging and leading cross-terms, respectively. M_b and M_c are the maximum orders of the lagging and leading cross-terms used in the GMP model. a_{kl}, b_{klm} and c_{klm} are the coefficients of the GMP model.

The proposed weighted generalized memory polynomial (W-GMP) model replaces the conventional MP function in the GMP model by its weighted version. Thus, W-GMP is expressed as:

$$
\begin{aligned}
& y_{WGMP}(n) = y_{WMP}(n) \\
& + \sum_{k=1}^{K_b-1} \sum_{l=0}^{L_b-1} \sum_{m=1}^{M_b} b_{klm} x(n-l) \, | x(n-l-m) |^k \\
& + \sum_{k=1}^{K_c-1} \sum_{l=0}^{L_c-1} \sum_{m=1}^{M_c} c_{klm} x(n-l) \, | x(n-l+m) |^k
\end{aligned} \quad (3)
$$

where x and y_{WGMP} are the model's input and output signals, respectively. The model parameters are the same as those defined in (1) for the weighted time-aligned memory polynomial sub-model, and in (3) for the leading and lagging cross-terms sub-models.

C. Proposed Weighted Hybrid Memory Polynomial

The HMEM model, introduced in [6][8], is composed of the parallel combination of a conventional MP function and an envelope memory polynomial (EMP) function [10]. This model can be viewed as a special case of the GMP model where only lagging cross-terms are included. It was motivated by the fact that MP model performs well in frequency regions that correspond to ON carriers while EMP model performs well in the regions that correspond to OFF carriers. Thus, the HMEM model was devised in order to combine the benefits of both.

The signal (y_{HMEM}) at the output of the HMEM model is related to its input signal (x) through:

$$
\begin{aligned}
y_{HMEM}(n) = & \sum_{k=0}^{K_{MP}-1} \sum_{l=0}^{L_{MP}-1} a_{kl} x(n-l) \, | x(n-l) |^k \\
& + \sum_{k=1}^{K_{EMP}-1} \sum_{l=0}^{L_{EMP}-1} b_{kl} x(n) \, | x(n-l) |^k
\end{aligned} \quad (4)
$$

where K_{MP} and L_{MP} are the nonlinearity order and the memory depth of the MP sub-model, respectively; and K_{EMP} and L_{EMP} are the nonlinearity order and the memory depth for the EMP sub-model, respectively. Similar to the W-GMP model, the W-HMEM model is expressed as:

$$
y_{WHMEM}(n) = y_{WMP}(n) + \sum_{k=1}^{K_{EMP}-1} \sum_{l=0}^{L_{EMP}-1} b_{kl} x(n) \, | x(n-l) |^k \quad (5)
$$

where x and y_{WHMEM} are the model's input and output signals, respectively. The model parameters are the same as those defined in (1) for the weighted time-aligned memory polynomial sub-model, and in (4) for the envelope memory polynomial sub-model.

III. EXPERIMENTAL SETUP

The measurement setup used to validate the proposed models consists of the device under test (DUT), a vector signal analyzer (VSA), an arbitrary waveform generator (AWG) and a personal computer. An LTE signal is generated using Keysight's advanced design system (ADS) software and is downloaded into the AWG. The AWG output signal is fed to the DUT. Input and output baseband waveforms are then used to derive the DUT's behavioral model. The DUT used is a high-efficiency power amplifier with a small-signal gain of 62 dB. The test signal is a 20 MHz LTE signal sampled at 92.16 MHz and centered around a carrier frequency of 2140 MHz. The LTE signal has a peak to average power ratio (PAPR) of 10.5 dB at 0.01% CCDF. The measured AM/AM and AM/PM characteristics of the DUT are reported in Fig. 1. These curves show significant dispersion especially for the low input power values as well as a highly nonlinear static behavior for high input power levels.

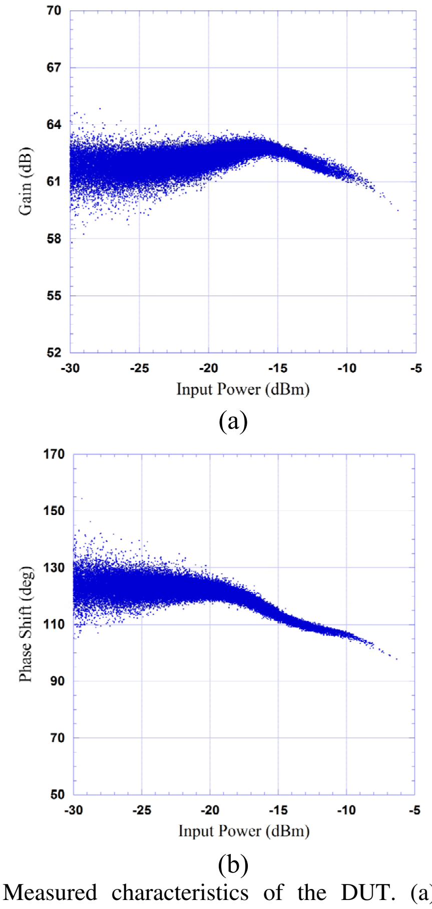

Fig. 1. Measured characteristics of the DUT. (a) AM/AM characteristic, (b) AM/PM characteristic.

The performances of the proposed W-GMP and W-HMEM models were benchmarked against the conventional GMP and HMEM models, respectively. In order to ensure fair comparison between memory polynomial based models and their weighted counterparts, N_S and N_D are chosen to have the same values in both cases. Dimensions of the models were determined using the general sweep method presented in [7]. For each model, the minimum NMSE was evaluated as a function of the total number of coefficients. The results are depicted in figures 2 and 3 for the GMP and the HMEM based models, respectively. Fig. 2 demonstrates the superiority of the proposed W-GMP model over the conventional GMP in terms of NMSE performance as it leads to an improvement of 2 to 3 dB for the same number of coefficients. Moreover, at equal NMSE performance, the proposed W-GMP model requires significantly less coefficients than the conventional GMP model. Similarly, Fig. 3 shows the consistent improvement in NMSE performance for the proposed W-HMEM model when compared to the conventional HMEM model. Moreover, the proposed W-HMEM model achieves an NMSE of approximately 36.2 dB with only 50 coefficients, while the conventional HMEM model is unable to reach this performance even with 80 coefficients.

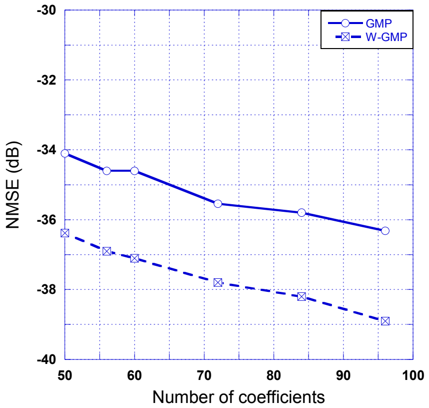

Fig. 2. NMSE performance of the GMP and the proposed W-GMP models.

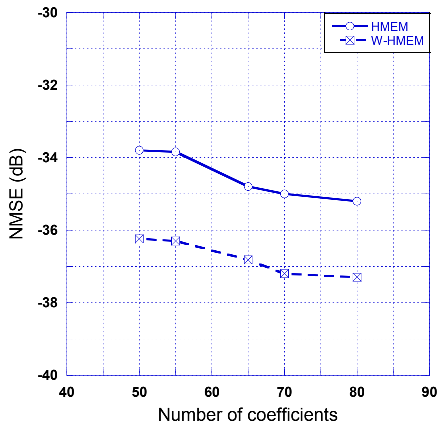

Fig. 3. NMSE performance of the HMEM and the proposed W-HMEM models.

VII. Conclusion

Two multi-basis weighted memory polynomial models were proposed for modelling RF power amplifiers with strong memory effects. A 20 MHz LTE signal with 1001 configuration was used to drive a high-efficiency PA for the sake of performance validation. Proposed models were benchmarked against their conventional MP based counterparts. Results show the superiority of proposed models as they lead to an improvement of 2 dB to 3dB in NMSE performance at equal number of coefficients, and a reduction of almost 50% in the total number of coefficients at equal performance.

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