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Memory models for behavioral modeling and digital predistortion of envelope tracking power amplifiers

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ABSTRACT

New advanced Envelope Tracking (ET) techniques can provide RF (Radio Frequency) transmitters with high-efficiency Power Amplifiers (PAs). On the other hand, system complexity substantially increases, requiring more advanced PA models for the representation and compensation of ET PA distortion effects. In this context, this paper proposes some solutions for behavioral modeling and digital predistortion of ET PAs. The adopted modeling strategy consists in including the modulated supply voltage as an additional independent model variable to define more accurate behavioral models capable of an increased accuracy when applied to model and compensate ET PAs. The new model variable is included in a polynomial model with memory whose nonlinear structure is derived from a binomial power series, whence the name of Memory Binomial Model (MBM). Another modeling approach is subsequently proposed, where the Cann model for static PA AM/AM nonlinearities is extended to model both AM/AM and AM/PM dynamic distortion occurring in ET PAs. The Extended Cann model includes an MBM structure for modeling dynamic AM/PM distortion effects. Both modeling approaches are tested on measured data-sets acquired using an ET measurement set-up including a commercial PA from RFMD and an envelope modulator designed using a commercial IC from Texas Instruments. The measured results showed that the proposed models could obtain a better modeling and predistortion performance when applied to ET PAs, with respect to the Memory Polynomial Model, here considered as a reference to represent the state-of-the-art of PA modeling and digital predistortion.

1. Introduction

Mobile communications have evolved through generations of advanced technologies to deliver higher data rates, better quality of service, increased capacity and higher number of simultaneous subscribers. 3rd Generation (3G) of mobile communications introduced the new access technology Wideband Code Division Multiple Access (WCDMA) to deliver internet mobile to mobile subscribers. In order to satisfy users' demand for faster and more reliable data connections, 4th Generation (4G) mobile communications have undertaken an even more substantial evolution deploying Carrier Aggregation (CA), multi-antenna techniques, and complex modulation formats such as SCFDMA (Single Carrier Frequency Division Multiple Access) and OFDMA (Orthogonal Frequency Division Multiple Access) [1]. The combination of such advanced technologies in 4G Long Term Evolution-Advanced (LTE-Advanced) can provide users with peak data-rates in the range of 3 Gbps (downlink) and 1.5 Gbps (uplink), which is the peak performance obtainable when aggregating five carriers with a channel bandwidth of 20 MHz using a category-8 User Equipment (UE) capable of multi-antenna techniques up to 8×8 MIMO (Multiple-Input Multiple-Output) [2]. Such high data rates are enabled by complex modulation schemes capable of high spectral efficiency at the expenses of an increased PAPR (Peak-to-Average Power Ratio), even greater than 10 dB for the OFDM signal used in the downlink access scheme [3]. The choice of SCFDMA as an access scheme for the uplink physical layer can mitigate the signal PAPR [3], but it still makes it very challenging for the RF (Radio Frequency) transmitter designer to keep simultaneous high values in the linearity and PAE (Power Added Efficiency) of the RF PA (Power Amplifier). The problem of obtaining the highest possible PAE, while keeping the linearity within the standard specifications,

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has a considerable importance, as the RF PA is the most power hungry component in the RF transmitter [4]. In order to solve this problem, high-efficiency PA architectures have been proposed in the form of Doherty and Chireix PA topologies, Envelope Elimination, Restoration (EER) and Envelope Tracking (ET) techniques. In handset applications, the PA needs to cover different mobile communication channels and the channel output power is maintained below 1 W [5]. These specifications favor ET as the best high-efficiency architecture to be chosen for UE (User Equipment) transmitters design. Differently from Doherty and Chireix topologies, ET completely avoids the problem of designing matching networks or power splitter and combiners over a wide frequency range covering all the wanted RF channels. On the other hand the insertion of an envelope modulator in the system architecture increases the system complexity, introduces a number of additional design challenges [6] and causes a number of additional distortion effects specific of the modulated voltage regime [7–10]. New advanced and increasingly complex ET systems therefore require more advanced and accurate PA models for emulating and compensating ET-specific distortion effects. State-of-the art PA models such as Volterra models, Wiener models, Hammerstein models and Artificial Neural Networks (ANN) can achieve high accuracy for stand-alone PAs, but they do not have an intrinsic predisposition to model distortion effects that are peculiar of three-terminal transmitters. Looking more specifically at the state-of-the-art of behavioral models for modeling and linearization of ET PAs, the same models used for stand-alone PAs are mostly deployed [11]. In [12] a new behavioral model for linearizing ET PAs is presented, but its application is related to the deployment of an envelope slew-rate reduction technique concurrently applied. The aim of this paper is to present behavioral models capable of higher accuracy when modeling and linearizing ET PAs inserted in any transmitter topology deploying the ET technique. The performance improvement obtainable using the presented models is shown through the comparison with the most used state-of-the-art behavioral model for stand-alone PAs, the Memory Polynomial Model (MPM) [13]. The rest of the paper is organized as follows: in Section 2 the proposed PA models are described, in Section 3 some solution for linearization of ET PAs are discussed, Section 4 describes measured results from an ET measurement set-up including a commercial GaAs PA for handsets, modeling and predistortion results are commented in Sections 5 and 6 and finally conclusions are outlined in Section 7.

2. Behavioral models for envelope tracking power amplifiers

Due to the varying envelope regime, ET PAs are affected by very specific nonlinear effects and dynamic distortions which are not observed in stand-alone PAs biased with a fixed power supply. Inaccuracy in the synchronization of envelope and RF paths [8], effects of various envelope voltage levels [7,9] and envelope modulator non-idealities are all causes of distortion effects specifically occurring in ET transmitters. Moreover, an ET transmitter is not only more complex but also more flexible. An ET PA can be operated with a number of nuances in its operational mode according to the wanted trade-off between the overall optimization of transmitter efficiency and linearity. For example, an ET transmitter typically deploys a supply shaper which can be designed to improve system linearity, efficiency or a combination of them [14,15]. Each shaper can produce a different version of the envelope and operate the PA in different conditions that can affect its system level parameters. Another example of the versatile ET operation consists in the deployment of a bandwidth reduction technique [16,17] or a slew rate reduction technique [18,19]. Bandwidth reduction and slew rate reduction are usually achieved modifying the envelope

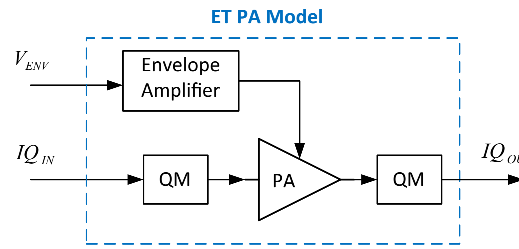

Fig. 1. Block diagram of an equivalent baseband behavioral model for ET PAs including the envelope voltage as independent variable. The PA equivalent baseband model has complex baseband I–Q input and output signal. Quadrature Modulators (QM) are used to represent ideal up-conversion and down-conversion.

waveform by means of digital filters or other dynamic systems that induce peculiar memory effects at the PA output. All of these peculiar ET distortion effects are induced by the application of the time-varying envelope voltage at the PA collector node. Therefore the introduction of the PA collector (or drain in case of Field Effect Transistors (FET)) voltage V_{CC} as an additional model variable is a promising way to improve the accuracy of PA models for ET PAs. The choice of a reference plane directly at the envelope port includes the envelope amplifier in the whole ET PA behavioral model and the additional model independent variable is hence the envelope signal V_{ENV} (Fig. 1).

Based on the inclusion of such a new independent model variable V_{ENV}, two memory models are here proposed for modeling and linearization of ET PAs. First, a 2D polynomial structure with memory is proposed, named Memory Binomial Model after its structure inspired by binomial power series [20]. Secondly a different approach is proposed, where the Cann model for RF PAs is extended including the new independent variable V_{ENV} and defining new functions for modeling of dynamic AM/AM and AM/PM distortion effects [21].

2.1. Memory Binomial Model architecture

The Memory Binomial Model (MBM) is defined on the basis of a dual-input structure including all the nonlinear terms defined in the binomial series:

$$y = \sum_{i=0}^{N} (a+b)^i \tag{1}$$

where y represents the output of the series expansion, a and b the input terms of the series and N the maximum order of the binomial products that are part of the series. Eq. 1 can be further expanded as:

$$y = \sum_{i=0}^{N} \sum_{k=0}^{i} \binom{i}{k} a^{i-k} b^k \tag{2}$$

In order to include the capabilities to model and compensate for PA memory effects, the proposed behavioral model is designed adding a FIR filter after each of the nonlinear terms of the binomial expansion. The complete model structure is represented by the block diagram in Fig. 2. Due to its structure defined by a binomial series with a cascaded bank of filters, the proposed model is called Memory Binomial Model (MBM). The MBM can be described as:

$$y[n] = \sum_{p=0}^{P} \sum_{b=0}^{p} \sum_{m=0}^{M} c[p,b,m]\, x[n-m]^{p-b}\, V_{ENV}[n-m]^b \tag{3}$$

where x and y are respectively the PA input and output baseband complex signals, V_{ENV} is the modulated voltage supply, $c[p,b,m]$ are the model coefficients, P is the maximum nonlinear order and