A Data-Based Nested LUT Model for RF Power Amplifiers Exhibiting Memory Effects

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***Abstract*—In this letter, a new model is proposed for radio frequency power amplifiers exhibiting memory effects. The model is based on nested look-up tables that compute the estimated amplifier output signal, based on the current input sample and the preceding ones. The model is validated experimentally, using input and output waveforms of a high-power LDMOS based amplifier driven by a multicarrier WCDMA signal. It is shown that the performance of the proposed model is comparable to that of the conventional memory polynomial model. However, the nested look-up table based model significantly reduces the complexity of the identification of the model's parameters, as well as the computational complexity in calculating the estimated output signal.**

***Index Terms*—Distortion, look-up table (LUT), memory effects, nonlinearity, power amplifier (PA), 3G.**

I. INTRODUCTION

RADIO frequency (RF) power amplifiers (PAs) are among the most critical subsystems in modern wireless transmitters. Indeed, the PA's cost and performance greatly affect those of the overall transmitter. This is even more important in wireless communication systems that set stringent requirements on the linearity of the transmitter's RF front end, and especially of the RF power amplifier. Thus, the modeling of power amplifiers has been subject to numerous researches over the past years. In addition, the modeling of the PA is an important issue, not only for predicting the amplifier's output signal and its spectrum regrowth, but also for deriving the corresponding predistortion function for linearization purposes.

Due to the trend of using wideband signals and multicarrier power amplifiers, it is becoming essential to take into account the memory effects when modeling PAs. Several models have been proposed in the open literature to model RF power amplifiers and transmitters that exhibit memory effects. Among these models, one can distinguish Volterra series [1], memory polynomials [2], neural networks [3], [4], and two-box Wiener and Hammerstein models [5], [6]. These models either call for identification procedures that cannot be performed online or require high computational complexity for identifying the models' parameters.

In [7], an augmented Wiener model and its parameters identification procedure were proposed. In comparison with the previously mentioned modeling approaches, the procedure reported in [7] reduces the required computational complexity by extracting the static nonlinear function of the PA, using an averaging technique and then identifying the memory effects linear filter.

In this letter, a nested look-up table (LUT) based model for PAs with memory effects is proposed to further alleviate the computational complexity associated with the identification and implementation of PA models. This model fulfills the need for an accurate real-time model with low computational complexity in both the identification step and the output estimation step. The proposed model extends the use of LUT based models that have previously been limited to memoryless PAs.

The proposed model is presented in Section II; and, the accuracy of the new model in predicting the PA's output signal is assessed experimentally in Section III. The conclusions are presented in Section IV.

II. PROPOSED NESTED LUT BASED MODEL

For a nonlinear power amplifier with memory effects, the baseband output waveform $(y(n))$ is given as a function of the baseband input waveform $(x(n))$ according to

$$y(n) = f\left[x(n), x(n-1), \cdots, x(n-K)\right] \tag{1}$$

where f is the amplifier's nonlinear complex transfer function to be identified, and K is the memory depth.

In this work, a nested LUT architecture is used to model the PA's nonlinear complex transfer function. Fig. 1 illustrates a nested LUT based model having a second-order memory depth, where α_2, α_1 and α_0 correspond, respectively, to the index value at each level of the LUT's tree. First, the value α_2 of the indexing variable $I(n-2)$, corresponding to the sample $x(n-2)$, is used to select a two-level LUT's tree. Similarly, the value α_1 of the indexing variable $I(n-1)$, corresponding to the sample $x(n-1)$, is used to select one basic LUT cell among the basic LUT cells forming the lower level of the two-level LUT's tree, previously identified by $I(n-2)$. Finally, the value α_0 of the indexing variable $I(n)$, corresponding to the actual sample $x(n)$, will be used to select the appropriate complex gain of the PA's

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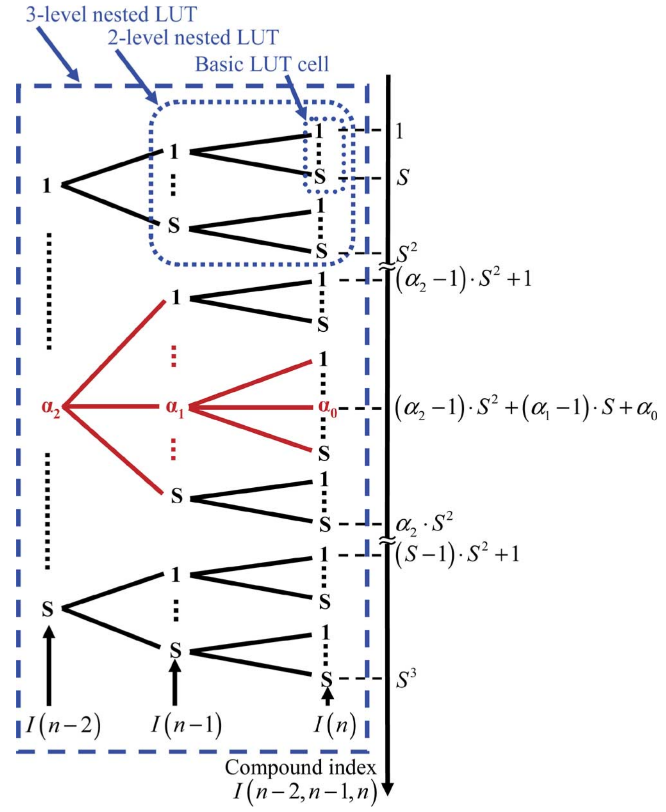

Fig. 1. Nested LUT architecture.

model from the basic LUT cell defined by the combination of the two previous indexes, $I(n-2)$ and $I(n-1)$.

The basic LUT cell is equivalent to a memoryless LUT based model. Accordingly, $K+1$-level nested LUTs are required to model a PA whose memory depth is K. Assuming that the indexing variable $I(n)$ is quantized over S values, the i-level nested LUT will consist of S^{i-1} basic LUT cells, each of which contains S elements. Thus, the overall size of the i-level nested LUTs will be S^i elements.

As shown in Fig. 1, the elements of the LUT's tree are equivalent to multiple nested LUTs indexed using a compound index $I(n-2,n-1,n)$. In the more general case of a PA having a memory depth K, the compound index is

$$I(n-K,\cdots,n)=1+\sum_{i=0}^{K}\left((I(n-i)-1)\cdot S^i\right). \quad (2)$$

The proposed model is, by far, more computationally efficient than all the previously reported models for PAs exhibiting memory effects. The advantage of the proposed model extends over the initialization step and the output estimation or modeling step. In fact, the identification procedure of the proposed model is straightforward. During the initialization step, the input and output baseband waveforms are used to fill the LUT elements with the corresponding complex gain value. This gain value will be applied to the input signal to estimate the PA's output waveform during the modeling step.

Fig. 2 describes the operation of the proposed model during the initialization and modeling steps. Accordingly, the initialization step of the model does not require any identification process. In addition to the instantaneous complex gain estimation, only an index calculation is performed, which implies $K+1$ additions and $K+1$ multiplications per LUT element. This is a major advantage when compared to the identification procedures required by the reported models. For example, the identification of the widely spread memory polynomial model ($K+1$ branches with an N order polynomial in each branch) requires the calculation and the inversion of a Vandermonde matrix, which is $((N+1)\times(K+1))\times L$, where L is the length of the data frame used for identifying the polynomial model.

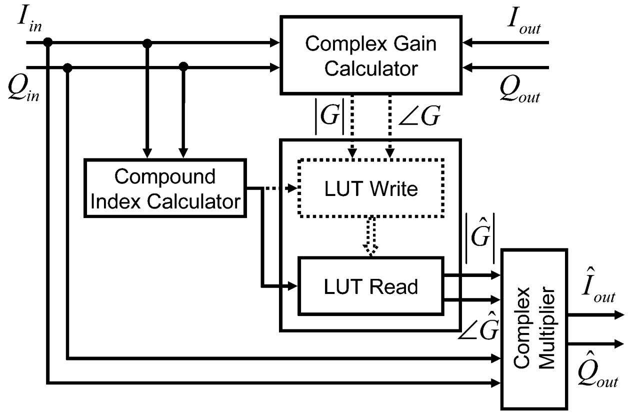

Fig. 2. Block diagram of the proposed model.

The augmented Wiener model reported in [7] is among the models that require the least computationally extensive identification procedures. However, this still involves the extraction of the static nonlinearity, using a dynamic exponentially weighted moving average technique and then the identification of the linear filter. Compared to these models' identification approaches, the computational efficiency improvement of the proposed model is significant.

At the modeling step, the estimation of each PA's output sample involves the compound index calculation, and one single complex multiplication. The calculation of the compound index requires $K+1$ additions and $K+1$ multiplications. Thus, it is clear that the calculation of the estimated output signal using the proposed model is less computationally demanding than all the previously reported PA/transmitter models that take into account memory effects.

Moreover, it is worth mentioning that the proposed model is data-based, and is independent from the nonlinearity shape and order, and also from the device technology of the power amplifier. In addition, it can be applied to model the entire transmitter, if the transmitter's input and output waveforms are used instead of those of the PA.

III. EXPERIMENTAL VALIDATION OF THE MODEL'S ACCURACY

The proposed PA model was validated on a 100-W peak power LDMOS amplifier operating in class AB. The device under test was driven by a two-carrier WCDMA signal. First, the complex time domain waveforms at the input and output of the PA were extracted, using the characterization technique proposed in [8]. The measured data were used to generate the nested LUT model described in the previous section. The LUTs were indexed by the envelope magnitude, which was quantified

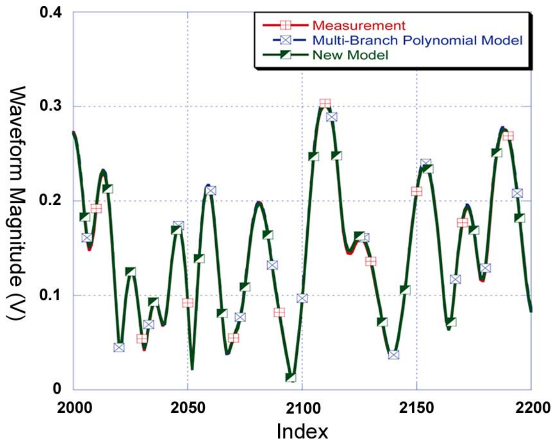

Fig. 3. Measured and estimated PA's output waveforms.

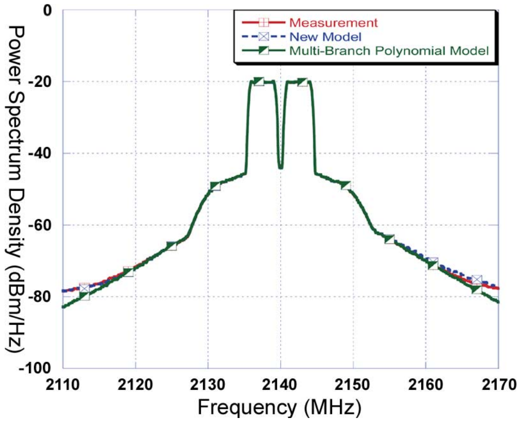

Fig. 4. Measured and estimated PA's output spectra.

into 128 levels. The memory depth was set to $K = 2$. Hence, the total LUT size was 2M words (128^3).

The measured input and output waveforms were also used to derive the memory polynomial model of the device under test, for which the same memory depth was used, resulting in a three-branch polynomial model. The polynomial orders were set to 12 per branch. Both models were constructed using 50% of the input waveform that was applied during the model validation step. The PA's output waveforms were first estimated using both identified models. The estimated output signals are plotted in Fig. 3, along with the measured waveform at the output of the PA.

As shown in Fig. 3, the accuracy of the proposed model in the prediction of the time domain waveforms was similar to that of the memory polynomial model. Similarly, the PA's output spectra were considered for additional model validation purposes. Fig. 4 presents the measured spectrum at the output of the PA and the estimated output spectra obtained by both models. According to this figure, both models resulted in the accurate estimation of the PA's output spectra. The slight discrepancies between the models' predictions and the measurements at 20 MHz away from the central frequency were due mainly to the limited bandwidth (40 MHz) of the vector signal analyzer used to capture the baseband waveforms data and to identify the models.

IV. CONCLUSION

In this letter, a new data-based nested LUT structure suitable for the modeling of power amplifiers exhibiting memory effects is presented. The model is constructed directly from the measured input and output waveforms. The experimental validation demonstrated the model's accuracy in estimating the output signal under multicarrier WCDMA excitation. The model performance is comparable to that of the well established memory polynomial model. The major advantage of the proposed model over the existing models is its low computational complexity in both the identification step and the output estimation step.

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