# 2-D Vector Quantized Behavioral Model for Wireless Transmitters' Nonlinearity and Memory Effects Modeling

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***Abstract* — This paper presents a two-dimensional look-up table model suitable for nonlinearity modeling in wireless transmitters exhibiting memory effects. The model is directly derived from the raw measured input and output waveforms of the device under test without additional intermediate signal processing. The model is validated on a 3G LDMOS based power amplifier driven by multi-carrier WCDMA signal. In the proposed model, the major limitation of table based models that is related to the length of the waveform used for the identification is alleviated by the use of an interpolation algorithm.**

***Index Terms* — 3G, distortion, look-up table, memory effects, nonlinearity, power amplifier.**

## I. Introduction

Modern wireless communication systems set stringent requirements on the efficiency and linearity of the RF front-end. The linearity performance is a requirement set by the spectrum emission mask while the efficiency is mainly a cost driven target. In fact, high efficiency will primarily translate into lower deployment and running costs for base stations and longer battery life for mobile terminals. In order to be able to predict the system level performance of the RF font-end from the early design stages, it is essential to develop accurate behavioral models. These models are also critical for nonlinearity compensation especially when digital predistortion techniques are considered.

Memoryless nonlinear behavioral models; such as Saleh, one-dimensional look-up tables (LUT), and memoryless polynomials; are unable to accurately model RF front-ends operated within emerging wireless communication systems. Indeed, such RF front-ends employ multi-carrier RF power amplifiers (PAs) handling wideband envelop varying signals. The envelop variations of these signals emulates the nonlinearity mainly generated by the power amplifier. In addition, the wide bandwidth of these signals is at the origin of the PA's memory effects. Thus, it is important to develop nonlinear behavioral models that take into account these memory effects. Numerous models suitable for nonlinear RF transmitters/power amplifiers exhibiting memory effects have been proposed over the last few years [1]-[7]. Such models are based on the Volterra series (Volterra series, pruned Volterra series, memory polynomials, etc…) [1]-[4] or two box models (Wiener, Hammerstein, augmented Hammerstein, etc…) [5]-[7]. However, the identification of these models either requires specific test set-ups only available in laboratory environment or involves high computational complexity.

In this paper, a 2-D LUT model is proposed for nonlinear RF transmitters/power amplifiers exhibiting memory effects. This model significantly reduces the computational complexity involved in state of the art models without compromising the accuracy in the prediction of the system output. Moreover, to alleviate the significantly long input waveform sequences required for the model initialization, an interpolation technique is used. In section II, the model is introduced and the experimental setup described along with the procedure used for the model identification. In section III, the performance of the model both in time and frequency domains is evaluated before and after applying the interpolation algorithm. The conclusions are presented in section IV.

## II. 2-D LUT Model

In conventional 1-D look-up-tables used for memoryless transmitters/PAs modeling, the complex gain of the device under test (DUT) is only a function of the actual input sample magnitude. In order to extend the LUT model for transmitters/PAs exhibiting memory effects, in this work, a new dimension is added to the LUT to take into account the dependency of the device behavior on the preceding samples. This 2-D LUT models the transfer function of the device under test as a complex gain that is a function of the magnitude of the actual and $M$ previous samples (where $M$ is the memory order of the DUT being modeled) as expressed in (1):

$$y(n) = G\left[\left|x(n)\right|, \left|x(n-1)\right|, \cdots, \left|x(n-M)\right|\right] \cdot x(n) \qquad (1)$$

The block diagram of the proposed 2-D LUT model is presented in Figure 1. In this 2-D LUT, the first axis (*x-axis*) index is a function of the actual input sample whereas the second axis (*y-axis*) index is a compound function of the preceding $M$ samples. The indexing according to both axes can be function of either the magnitude or the squared magnitude of the input signal with uniform or non-uniform optimal spacing as it is the case in memoryless LUT models [8]. In this work, the 2-D LUT is indexed using equally spaced magnitudes of the input signal. First, for each sample, the indexing variable (magnitude) is calculated and quantized over $N$ values. For a given sample, the values of the indexing variables corresponding to the preceding $M$ samples are used to calculate a compound index that will identify a line in the 2-D LUT model. Then, the quantized value corresponding to the actual sample is used for indexing along the second axis. This will identify a column in the 2-D LUT model. The combination of the two indexes will identify the cell of the LUT that contains the complex gain value of the transfer function.

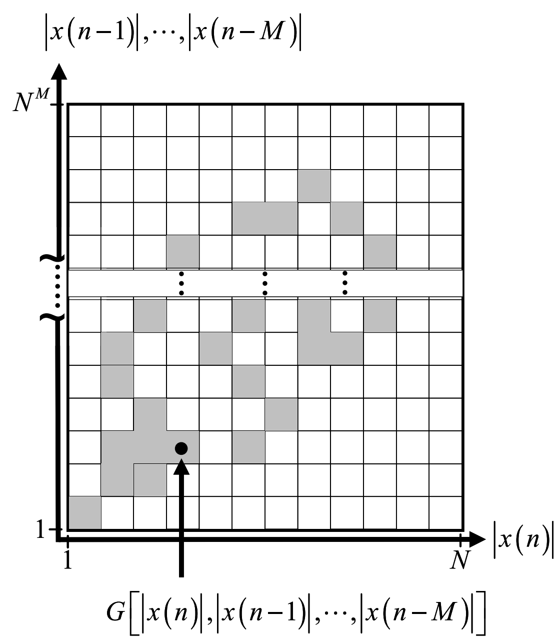


Fig. 1. Block diagram of the 2-D LUT model.

The compound index calculation is based on a bijective (one-to-one) function to guarantee a unique mapping of $M$-dimensional history vector. Accordingly, when the indexing variable is quantized over $N$ values, a 2-D LUT having $N$ columns and $N^M$ lines is needed for a device under test exhibiting $M^{th}$ order memory effects.

The identification of the 2-D LUT model requires the capture of the baseband complex waveforms at the input and output of the device under test. The experimental setup used for the model assessment is presented in Figure 2. The device under test considered is made of an arbitrary waveform generator (E4438C) and a power amplifiers lineup operating around 2.14 GHz. The output signal is attenuated, down-converted and demodulated using a vector signal analyzer (E4440A) in order to get the baseband complex waveform.

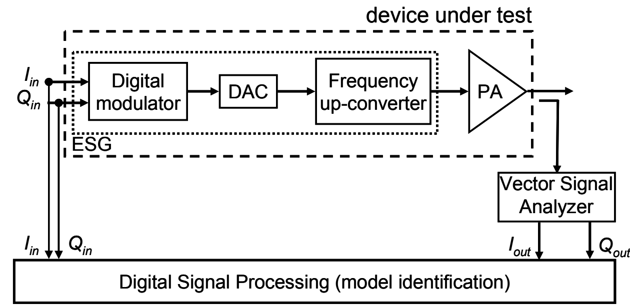


Fig. 2. Measurements setup used for experimental validation.

The major advantages of the proposed model are related to the simple identification procedure that it requires. This procedure is summarized in the flow chart shown in Figure 3. In fact, the model identification is straightforward and computationally efficient since it only involves data alignment (delay estimation and compensation), calculations of the indexing variables and of the complex gain values. However, usually a long waveform sequence is required to initialize the LUT as it is the case for all table based models. This is even more critical due to the size of the considered 2-D LUT. To circumvent this limitation, a considerably shorter waveform sequence is used. Once the 2-D LUT is initialized using this sequence, an interpolation algorithm is applied to fill the remaining elements of the LUT that have not been initialized.

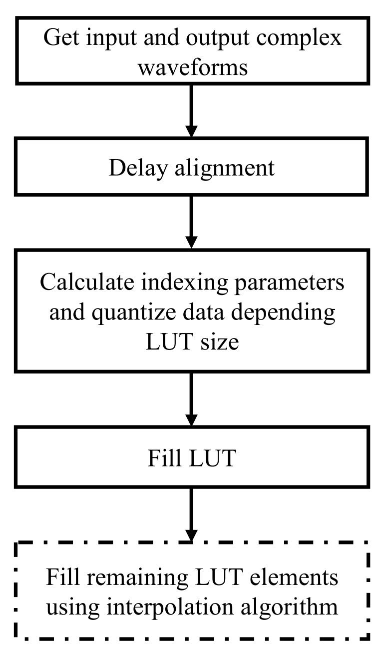


Fig. 3. Flow chart of the model identification process.

## III. Model Performance Validation

In order to assess the performance of the proposed model, the device under test presented in the previous section was emulated using a 2-carriers WCDMA signal having 10 MHz bandwidth and 10.4 dB peak-to-average power ratio. The waveform used consists in a 15 slots WCDMA signal. The total length of the time domain waveform was set to 10 msec, and its sampling rate to 92.16 MHz. The magnitude of the input signal was quantized over $2^7$ equally spaces values. The memory order of the device under test was set to 2. This resulted in a total LUT size of around $2 \cdot 10^6$ elements.

First, the LUT cells are all initialized to unity gain value. Then, the model is identified using the $K$-first slots of the input and output waveforms, where $K$ is swept from 1 to 15 in steps of 1. For each identification sequence, two 2-D LUT models were identified. For the first model, the LUT elements that are not up-dated by the identification sequence are kept equal to unity. In the second model, these LUT elements are up-dated using an interpolation algorithm. The performance of the proposed 2-D LUT model (with and without interpolation) are evaluated both in the time and frequency domains.

The estimated time domain waveforms are compared to the measured waveform at the output of the device under test. The mean squared error (MSE) between the actual DUT output waveform and the estimated waveform at the output of the model was calculated for the models derived with and without interpolation using different identification sequences. The calculated MSE is given by:

$$MSE(dB) = 10 \cdot \log_{10}\left(\frac{1}{K} \cdot \sum_{k=1}^{K} \left|y(k) - \hat{y}(k)\right|^2\right) \qquad (2)$$

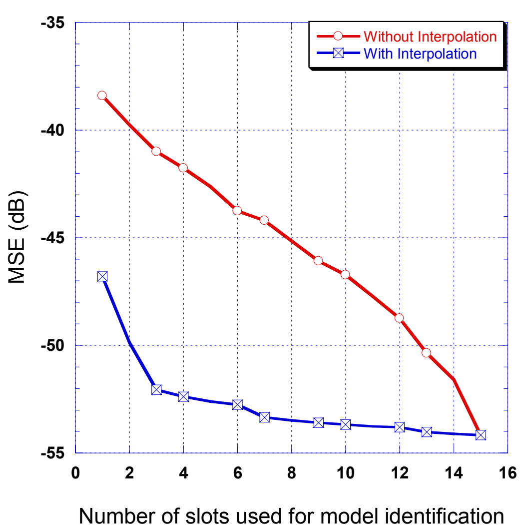



Fig. 4. Time domain mean-squared error.

Figure 4 presents the calculated MSE as a function of the number of slots used in the identification sequence for both 2-D LUT models. According to this figure, one can clearly conclude that the use of the interpolation technique can significantly improve the accuracy of the model even when short identification sequences are used. In fact, a 13 slots identification sequence is required for the model that does not include an interpolation algorithm to achieve a MSE better than 50 dB. This represents 87% of the data used for the accuracy assessment. However, when the interpolation algorithm is used, only a 2-slots identification sequence (13% of the data used for the accuracy assessment) is needed to reach an MSE better than 50 dB.

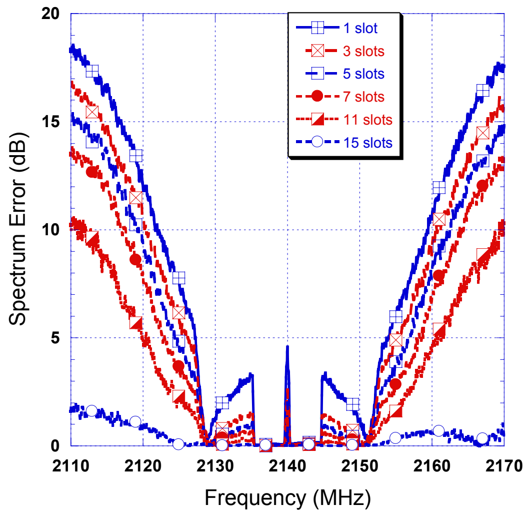
The accuracy of the proposed model was also evaluated in frequency domain. For this purpose, the spectrum error as defined in (3) was calculated as a function of the length of the identification sequence.

$$Error_{Spec}(dB)(f) = \left|PSD_{Meas}(f) - PSD_{Estim}(f)\right| \qquad (3)$$

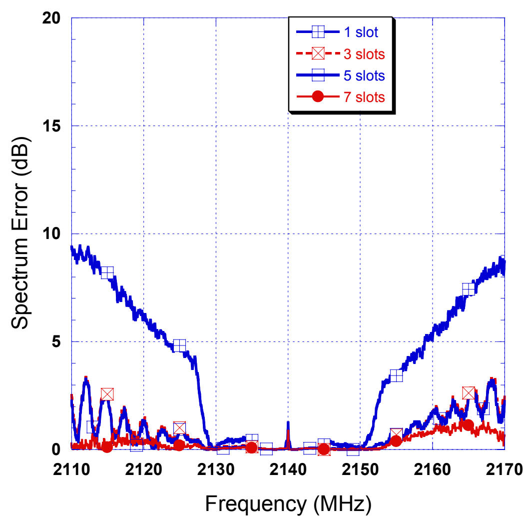
The results are summarized in Figure 5 (a) for the model that does not include the interpolation algorithm and Figure 5 (b) for the model that takes advantage of the interpolation algorithm. Figure 5 (a) shows that the spectrum error is significantly high even for identification sequences length of up to 11 slots when no interpolation algorithm is used. Conversely, Figure 5 (b) corroborates the results observed in time domain (MSE) according to which the use of the interpolation algorithm considerably improves the model's accuracy even when the length of the identification sequence does not exceed 5 to 7 slots. The slight discrepancy between the predicted and the measured spectra in the frequency ranges that are 20 MHz away from the carrier frequency are attributed to the limited accuracy of the receiver used in the DUT characterization step.

## IV. Conclusion

In this paper, a novel 2-D LUT model suitable for nonlinear RF transmitters/power amplifiers exhibiting memory effects was presented. This model is directly derived from the measured input and output complex waveforms and does not require any specific identification procedure. An interpolation algorithm was used to reduce the length of the identification sequence waveform. The model accuracy was evaluated on a 3G transmitter driven by multi-carrier WCDMA signals. The results showed good agreement between the measured waveform at the output of the device under test and the estimated waveform both in time and frequency domains. The use of the interpolation algorithm significantly reduced the length of the data sequence required for the model identification without compromising its performance.




(a)




(b)

Fig. 5. Frequency domain error. (a) without interpolation, (b) with interpolation.

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