One-step model extraction method for joint polynomial/interpolating lookup-table two-box nonlinear model of power amplifier

Chen Changwei\(^a\), Qin Kaiyu\(^b\), and Tang Bo\(^c\)

School of Aeronautics and Astronautics, University of Electronic Science and Technology of China, Chengdu, Sichuan, P. R. China
\(a\) ccw94@uestc.edu.cn
\(b\) kyqin@uestc.edu.cn
\(c\) tangbocd@126.com

Abstract: In this paper, a one-step model extraction method is proposed for parameter identification of two-box nonlinear model of power amplifiers. In order to simplify the extraction complexity, the Wiener and Hammerstein-based serial structure is replaced by a parallel structure. The dynamic nonlinear filter curve and the static piecewise function formed by linear interpolating LUT entry are jointly curve-fitted to identify the parameters of the two-box model in one step. Compared with the traditional two-box model extraction method, the resultant data shows a comparable linearization performance of the proposed model in suppressing the adjacent channel error power with simplified procedures.

Keywords: two-box model, digital predistortion (DPD), linear interpolating lookup-table (LILUT)

Classification: Microwave and millimeter-wave devices, circuits, and modules

References


1 Introduction

The modern wireless communication signal has developed towards higher order and more complex modulation. Due to the inherent non-linearity of a power amplifier, such broadband signals with a high peak to average power ratio will lead to in-band distortion and out-of-band spectrum leakage when passing through the power amplifier. Digital pre-distortion is an effective method to compensate for the memory non-linearity characteristics of the power amplifier. The Volterra model, or any of its simplified versions, such as a memory polynomial model, is widely used as a general model of characterization of memory non-linearity [1, 2]. However it often results in an over-sized model mainly due to the same non-linear orders in all memory branches. The Wiener and Hammerstein-based models consist of a linear filter and a static polynomial which assume that the memory effect is linear. However, the non-linear memory effect of the power amplifier is non-negligible for a broadband signal, and ignoring the memory non-linearity will result in a decrease in model precision. The piecewise function constructs a continuous nonlinear function using a series of low-order function sets. It is also a commonly used in power amplifier nonlinear modelling, such as Interpolated LUT [3], cubic spline [4] and canonical piecewise linear (CSCPWL) [5] function. The piecewise function can overcome the instability problem of the high condition number in the high-order polynomial parameter extraction process. The LUT can achieve the same identification quality as the polynomials model [6].

A joint polynomial/LUT two-box model [7] separates dynamic weak non-linearity from static strong non-linearity, effectively simplifying model complexity. The dynamic weak non-linearity is implemented by a low-order memory polynomial, while the static strong non-linearity is implemented by a LUT. In the traditional identification method of the two-box model, first, the dynamic non-linear filter box is identified based on the least square method. The input and output
vectors of the static non-linear module are de-embedded and derived. The corresponding static polynomial coefficients are obtained by polynomial fitting, and then the function value of the uniform distribution amplitude is calculated and is stored in the LUT. The separation of dynamic and static characteristics of the two-box model simplifies the complexity of the model extraction, but requires two steps to complete the model extraction, and the LUT without interpolation needs to take up much storage space.

In this paper, a one-step model extraction method is proposed based on the joint polynomial/LILUT two-box model parallel structure. In order to simplify the extraction complexity, the Wiener and Hammerstein-based serial structure is replaced by a Parallel structure of a LILUT and a memory nonlinear filter. The joint training sequence of a dynamic non-linear filter and a LILUT is derived, so that the memory nonlinear filter curve and the piecewise function formed by the LUT entry with linear interpolation are curve-fitted to identify the parameters of the two-box model in one step. With this method, the polynomial coefficients are derived and the LUT entries are directly adapted at the same time. In order to verify the effectiveness of the one-step extraction method, a test platform is built with a Gallium Nitride (GaN) power amplifier at a peak power of 10 W. The amplifier is biased in the AB class, working at a center frequency of 1.96 GHz. The resultant adjacent Channel Power Ratio (ACPR) data shows that the performance of the two-box model with the one-step extraction method is equivalent to that of the well-established MP model and the traditional two-box model extraction, and the identification procedures are simplified.

2 Joint MP/LILUT two-box nonlinear model

The non-linear two-box model is a behavior model consisted of a memoryless non-linear function and a low-order memory nonlinear filter. In this paper, the parallel nonlinear two-box (PNTB) structure is used to characterize the power amplifier, the LUT with linear interpolation and the memory polynomial function are placed in parallel, and their outputs are added to form a pre-distortion signal, as shown in Fig. 1.

In the joint polynomial/LILUT parallel two-box model, the pre-distorter output $z(n)$ may be divided into static high-order nonlinear and dynamic memory weak nonlinear filters [9]. The two parts are shown as follows.

$$z(n) = s(n) + d(n)$$  \hspace{1cm} (1)

---

**Fig. 1.** Block diagrams of the parallel two-box models.
Where $d(n)$ represents a dynamic non-linear function, represented by a memory polynomial as follows:

$$d(n) = \sum_{k=0}^{K_1} \sum_{m=1}^{M} a_{km} x(n-m) |x(n-m)|^k$$  \hspace{0.5cm} (2)

Where $x(n)$ and $d(n)$ are input and output of the memory polynomial function, respectively. $M$ and $K_1$ are the memory depth and the non-linear order, respectively.

$s(n)$ represents a static high-order nonlinear function which depends on the current input signal and is described by the LILUT. For the non-interpolated LUT, the quantization error is large when the LUT size is small. In order to obtain a good linearity performance, it is necessary to significantly increase the size of the LUT. Therefore, the interpolation technology is necessary and is widely used in the LUT. The static nonlinear box is represented by a piecewise linear function $s(x)$ in real interval $[0, (N - 1)\delta]$. The function value is defined by a straight line between adjacent LUT entries to reduce the size of the LUT. Assuming that there are two adjacent discrete points $(a_i, b_i)$ and $(a_{i+1}, b_{i+1})$, the corresponding linear interpolation function is

$$s(x) = b_k + (b_{k+1} - b_k) \frac{x - k\delta}{\delta}$$

$$k\delta \leq x \leq (k + 1)\delta$$  \hspace{0.5cm} (3)

Where $(x, s(x))$ is an interpolated point, $\delta$ is the LUT interval, $x$ is an input value, $b_k$ and $b_{k+1}$ are values stored in the LUT table.

The interpolation formula can be regarded as a weighted average of the adjacent LUT entry values on $s(x)$, and the weight is inversely related to the distance from $x$ to the adjacent endpoints. The weight is $\frac{x - k\delta}{\delta}$ and $\frac{x - (k+1)\delta}{\delta}$, and the weight sum is 1. The function $s(x)$ may be recorded as follows:

$$s(x) = \left(1 - \frac{x - k\delta}{\delta}\right)b_{k-1} + \left(1 + \frac{x - (k + 1)\delta}{\delta}\right)b_k$$

$$k\delta \leq x \leq (k + 1)\delta$$  \hspace{0.5cm} (4)

Since the $s(x)$ function value is determined by the adjacent LUT entry values, the whole $s(x)$ piecewise function may be defined as follows [8]:

$$s(x) = \sum_{i=0}^{N-1} a_i \Lambda(|x| - i\delta)$$

$$0 \leq |x| \leq (N - 1)\delta$$  \hspace{0.5cm} (5)

$\Lambda(x)$ is a linear interpolation piecewise function defined as follows,

$$\Lambda(x) = \left(1 - \frac{|x|}{\delta}\right)w\left(\frac{|x|}{\delta}\right)$$  \hspace{0.5cm} (6)

Where,

$$w(x) = \begin{cases} 1, & 0 \leq x \leq 1 \\ 0, & otherwise \end{cases}$$  \hspace{0.5cm} (7)

Thus, the pre-distortion function may be represented as:
3 One-step parameter identification of a parallel two-box model

The least squares (LS) method [10] is used to perform adaption of the joint MP/LILUT parallel two-box model. The equation (3) may be rewritten in the form of a matrix as follows:

$$
\tilde{Z} = CA
$$

(9)

Where: \( \tilde{Z} \) is a vector of pre-distorted output signal, \( L \) is the length of the input samples used for identification.

$$
\tilde{Z} = [z(n)z(n - 1) \cdots z(n - L + 1)]^T
$$

(10)

\( C \) is a matrix of \( L \times (MK_1 + N) \), which is shown as follows:

$$
C(x) = \begin{bmatrix}
\tilde{U}(n) & x(n)\tilde{\Lambda}(x(n)) \\
\tilde{U}(n - 1) & x(n - 1)\tilde{\Lambda}(x(n - 1)) \\
\vdots & \vdots \\
\tilde{U}(n - L + 1) & x(n - L + 1)\tilde{\Lambda}(x(x - L + 1))
\end{bmatrix}
$$

(11)

Where,

$$
\tilde{\Lambda}(x) = \begin{bmatrix}
\Lambda(x) \\
\Lambda(x - \delta) \\
\vdots \\
\Lambda(x - (N - 1)\delta)
\end{bmatrix}^T
$$

(12)

$$
\tilde{U}(x) = \begin{bmatrix}
x(n - 1) \\
\vdots \\
x(n - M) \\
x(n - M)|x(n - M)| \\
\vdots \\
x(n - M)|x(n - M)|^K
\end{bmatrix}^T
$$

(13)

\( \tilde{A} \) is a column vector of the polynomial and the LUT entry. The column vector has a number of \( (MK_1 + N) \times 1 \), and is shown as follows:

$$
\tilde{A} = [a_{0,1}a_{0,2} \cdots a_{K_1,M}b_0,b_1 \cdots b_{N-1}]^T
$$

(14)

For the indirect learning method, the coefficient may be updated with the LS method as follows:

$$
\tilde{A} = ((C(\tilde{Y}))^HC(\tilde{Y}))^{-1}(C(\tilde{Y}))^H\tilde{Z}
$$

(15)

Where \( \tilde{Y} \) is a vector of the PA output signal, which is time aligned with the \( \tilde{X} \) signal vector, as shown in Fig. 1.
Experimental verification

The experiment setup is built to evaluate the proposed model performance, consisting of a ESG vector signal generator E4438C available from Agilent and a signal analyzer PXA N9030B. The measured PA is built by GaN HEMT (CGH40010 available from Cree) at a center frequency of 1.96 GHz. A dual-carrier WCDMA signal is used to drive the power amplifier. The PXA N9030B, VSA 89600 and MATLAB software are used to record signals and process signals. The baseband signal data is generated by the computer and downloaded to the ESG. The data is modulated by the signal source and then input to the PA. The output of the PA is fed by the coupler to the PXA signal analyzer. The behavioral model extraction is completed by MATLAB. 10,000 samples of the input signals are used in the identification step. The LS method is used to estimate the model. The number of complex multiplications calculated by the LS matrix is \( \frac{L}{C^2}Q^2 + \frac{L}{C^2}Q + Q^3 \) [10], where \( Q \) is the number of model parameters to be identified and \( L \) is the number of sampling points. In the one-step extraction method, the LS matrix has a large number of zero elements, greatly reducing the calculation amount, as shown in Table I for details.

In order to verify the availability of the proposed method, the calculation amount and the ACPR performance in the following three cases are compared:

1) MP DPD model: the memory depth \( M \) is 4, and the non-linearity order \( K \) is 7. The coefficient number \( Q = (M + 1)(K + 1) = 40 \).

2) The traditional MP/LUT two-box model extraction method, in which the static nonlinearity calculates LUT entries after being polynomial adaptive (the non-linearity order \( K_s \) of the LUT module is 7, the non-linear filter has a memory depth \( M \) of 4, and the non-linearity order \( K_d \) is 3. The coefficient number \( Q = (M + 1)(K_d + 1) + K_s + 1 = 28 \).

3) One-step extraction method of the MP/LILUT two-box model: the size of the LILUT \( N \) is 16, the non-linear filter has a memory depth \( M \) is 4, and the non-linearity order \( K_d \) is 3. The coefficient number \( Q = M(K_d + 1) + N = 32 \).

The output spectrum of the Device Under Test (DUT) after using three types of pre-distortion linearization method is as shown in Fig. 2. The detailed results of the ACPR of the original signal and the linearized signal are shown in Table I, which proves that the proposed adaptive method obtains an approximate performance. The ACPR less than \(-52\) dBc proves that the algorithm is feasible and the calculation amount is greatly reduced at the same time.

<table>
<thead>
<tr>
<th>case</th>
<th>the number of coefficient</th>
<th>complex multiplications</th>
<th>ACPR (dBc) +5 MHz/−5 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO DPD</td>
<td>–</td>
<td>–</td>
<td>−33.8/−31.5</td>
</tr>
<tr>
<td>MP</td>
<td>40</td>
<td>42,464,000</td>
<td>−51.2/−50.8</td>
</tr>
<tr>
<td>MP/LUT</td>
<td>28</td>
<td>8,928,512</td>
<td>−48.5/−47.7</td>
</tr>
<tr>
<td>MP/LILUT</td>
<td>32</td>
<td>6,692,768</td>
<td>−50.9/−51.7</td>
</tr>
</tbody>
</table>
5 Conclusion

The two-box model is widely used in modeling the power amplifier and the transmitter, and is high in modeling precision and low in computational complexity. However, the traditional two boxes model need to be solved separately, including embedding data to construct the training sequence of the second module. In order to simplify the parameter extraction step of the two-box model, this paper presents a joint curve fitting method for a nonlinear filter curve characterizing weak memory nonlinearity and a piecewise function characterizing static strong nonlinearity to identify the parameters of its model in one step. The proposed method has a linearization performance similar to that of conventional method but has simplified extraction steps.

Acknowledgments

This work was supported in part by the National Natural Science Foundation of China under Grant 61305092.