Digital predistortion technique based on non-uniform MP model and interpolated LUT for linearising PAs with memory effects

Xiaowen Feng, Bruno Feuvrie, Anne-Sophie Descamps and Yide Wang

A new digital predistortion technique based on a direct learning architecture is proposed for linearising power amplifiers (PAs) with nonlinear memory effects. It is based on the non-uniform memory polynomial (MP) model and with a quadratically interpolated LUT.

There are mainly two innovations. First, compared with the conventional MP model, the nonlinearity order of each memory branch; secondly, compared with the linearly interpolated LUT, the quadratically interpolated LUT has higher accuracy, which is adopted to realise a part of the mathematical computations in the predistortion. The proposed solution is validated on a real PA ZFL-2500. It reduces the number of the model’s coefficients and achieves a spectrum regrowth suppression of about 15 dB with a table size of only 8.

Introduction: In wireless communication systems, the power amplifier (PA) plays an important role. It directly affects data quality and power efficiency of the whole transmission chain. It suffers from its inherent nonlinearity and memory effects (caused by the electrical or electro-thermal effects), which result in distortions of its output signal. To improve communication quality, and at the same time maintain high power efficiency, it is necessary to compensate for these undesirable effects. This is achieved by linearisation techniques.

Digital predistortion (DPD) is the most efficient and promising technique for linearising PAs, especially polynomial DPD. An adaptive closed-loop DPD based on polynomial nonlinear compensation is proposed in [1]. A memory polynomial (MP) DPD based on a direct learning architecture is proposed in [2]. The MP model is widely used and can closely mimic the nonlinear behaviour of a PA with memory effects. In [4], a MP DPD based on an indirect learning architecture is presented and the MP model’s advantages are specified. The above-mentioned MP model is the conventional MP model. The nonlinearity order of each memory branch is unexacted. In [5, 6], a non-uniform MP model is introduced, where the nonlinearity order of each memory branch may be unequal. It achieves a reduction of the number of the model’s coefficients while maintaining high modelling accuracy compared with the conventional MP model. In this Letter, the non-uniform MP model is used for the predistortion. A Hammerstein model based DPD with a root-finding solution is proposed in [7]. In this DPD, the root-finding procedure is very time-consuming. In [8], MP-LUT DPD is proposed, where a non-interpolated LUT is used based on the conventional MP model. It reduces the consuming of time but requires a sufficiently large size of LUT.

In our previous work [9], the linearly interpolated LUT is adopted in the DPD based on the conventional MP model. In this Letter, the DPD is based on the non-uniform MP model. To the best of our knowledge, this interesting model has never been used for the linearisation of the PA. In addition, the quadratically interpolated LUT is adopted instead of the linearly interpolated LUT in the DPD.

Proposed solution: The non-uniform MP model is described as follows:

\[
\begin{align*}
\gamma(nT) &= \sum_{p=0}^{P} c_p[nT]^p + G_0(nT) \\
\sigma(nT) &= \sum_{q=0}^{Q} c_q[nT]^q
\end{align*}
\]

where \(c_p\) are the model’s coefficients, \(P\) the memory depth and \(G_0\) the nonlinear order of the \(p\)th memory branch; \(\gamma(nT)\) denotes the output of the PD-PA system, \(\sigma(nT)\) the predicted signal (the output of the predistorter), \(u(nT)\) the input of the PD-PA system and \(G_0\) is the desired linear gain. In the conventional MP model, the nonlinearity order \(Q\) of each memory branch is equal. It results in an overestimation of the nonlinearity and oversizing of the model. In the non-uniform MP model, selecting the nonlinearity order of each memory branch flexibly can not only avoid the overestimation problem, but also decrease the number of the model’s coefficients.

As in [8], the output \(\sigma(nT)\) in (1) can be decomposed into two parts: the static part \(\sigma(nT)\) depending only on the current input sample \(p = 0\); and the dynamic part \(d(nT)\) which depends on the previous input samples \((p \text{ from } 1 \text{ to } P)\)

\[
\begin{align*}
\gamma(nT) &= \sigma(nT) + d(nT) = G_0u(nT) \\
\sigma(nT) &= \sum_{q=0}^{Q} c_q[nT]^q \\
d(nT) &= \sum_{p=1}^{P} \sum_{q=0}^{Q} c_{pq}[nT]^q[nT]^{q-1} - G_0u(nT)
\end{align*}
\]

From (2), \(d(nT)\) can be rewritten as

\[
d(nT) = e^{-j\omega_0} \sum_{q=0}^{Q} c_{pq}[nT]^{q+1} = G_0u(nT) - d(nT)
\]

where \(\omega_0\) is the phase of the predistorted signal \(\gamma(nT)\) and \(\sigma(nT)\) denotes its amplitude. By definition, \(d(nT)\) depends only on the previous samples, the right-hand side of (3) and coefficients \(c_{pq}\) are known at instant \(nT\). \(\gamma(nT)\) can be calculated by considering only the absolute value

\[
\sum_{q=0}^{Q} |c_{pq}|[nT]^{q+1} = |G_0u(nT) - d(nT)|
\]

Equation (4) is a high-order nonlinear equation, the predistorted signal \(\gamma(nT)\) can be found by a root-finding procedure [7]. In this Letter, the root-finding procedure is replaced by using a quadratically interpolated LUT. The structure of the LUT is described as follows. According to the range of input signal \(u(nT)\), the range of \(\gamma(nT)\) can be estimated. The estimated range of \(\gamma(nT)\) is decomposed into \(K\) intervals (the length of each interval is equal to \(\Delta x\)), denoted by \(P_k\). The LUT is shown in Table 1 (\(k\) from 0 to \(K\)). In this Table

\[
\begin{align*}
P(k) &= k \Delta x \\
E(k) &= \sum_{q=0}^{Q} c_{pq}(k\Delta x)^{q+1}
\end{align*}
\]

Table 1: Values of LUT for DPD

<table>
<thead>
<tr>
<th>INLUT</th>
<th>OUTLUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_k)</td>
<td>(E(k))</td>
</tr>
</tbody>
</table>

For the non-interpolated LUT, the quantification error is large when the LUT size is small. To achieve good linearisation performance, it requires a sufficiently large size of LUT [8]. Hence, an interpolation technique is necessary. Generally, the linear interpolation is widely used in the LUT [10]. The linearly interpolated LUT uses linear interpolation between adjacent LUT entries. It can reduce the table size of the LUT. However, the curve with linear interpolation is not smooth enough. Actually, the curve restored by the LUT should be smooth. There is still room for improving interpolation accuracy. The quadratic interpolation is another interpolation technique, where the interpolated point is calculated by the nearest three points. The principle of quadratic interpolation is described as follows. Suppose that there are three adjacent discrete points \((a_{-1}, b_{-1}), (a_0, b_0)\) and \((a_{+1}, b_{+1})\). The quadratic interpolation function is

\[
b' = f_{-1}(a')b_{-1} + f_{0}(a')b_0 + f_{+1}(a')b_{+1}
\]

where \((a', b')\) is the interpolated point, \(a'\) is known and \(b'\) needs to be calculated. \(f_{-1}(a')\), \(f_{0}(a')\) and \(f_{+1}(a')\) are the weighting functions [11]

\[
\begin{align*}
f_{-1}(a') &= (a' - a_{-1})(a' - a_{+1}) \\
f_{0}(a') &= (a' - a_{-1})(a' - a_{+1}) \\
f_{+1}(a') &= (a' - a_{-1})(a' - a_{+1})
\end{align*}
\]

Since there is more referenced information in quadratic interpolation than in linear interpolation, the curve with quadratic interpolation is smoother than that with linear interpolation. An example for the comparison of linear interpolation and quadratic interpolation is shown in Fig. 1. Therefore, the quadratically interpolated LUT is adopted in this Letter

\[
\gamma(nT) = QILUT(G_0u(nT) - d(nT))
\]

where QILUT is the quadratically interpolated LUT.
DPD algorithms: Before the predistortion, first the model’s coefficients $c_{qn}$ are obtained by the identification of the non-uniform MP model [5]. Secondly, the LUT is generated by (5). The predistortion algorithm is described as follows.

Algorithm 1 Non-uniform MP/quadratically interpolated LUT DPD

1 Initialise $n = 0$, $d(0) = 0$
2 Begin loop
\{  
3 Calculate $[G_d(nT)−d(nT)]$, denoted by $|s(nT)|$
4 Find three adjacent values $E(k−1)$, $E(k)$ and $E(k + 1)$ from Table 1, which are the three closest to $|s(nT)|$
5 Calculate the corresponding phase by
$$\angle x(nT) = \arg \left( \sum_{nT}^{nT} s(e^{i\angle x(nT)}) \right)$$
6 Calculate the corresponding phase by
$$\angle x(nT) = \arg \left( \sum_{nT}^{nT} s(e^{i\angle x(nT)}) \right)$$
7 Calculate $x(nT) = |s(nT)|e^{i\angle x(nT)}$
8 Calculate $n = n + 1$
9 Calculate
$$d(nT) = \sum_{p=1}^{P} \sum_{q=0}^{Q} c_{pq}[|s(n-pT)|x(n-pT)|^2]$$
10 } Goto loop

Experimental results: To validate the proposed DPD, it is tested on the actual PA ZFL-2500 driven by a 64QAM modulated signal with a 3.84 MHz bandwidth at a carrier frequency of 1.8 GHz. The experimental setup consists of a PA (ZFL 2500), a PC providing the baseband signal and realising the DPD, a vector signal generator (Rohde & Schwarz SMU 200 A) to generate the RF signal and a spectrum analyser (Agilent E4440A) to analyse the input and output signals of the PA. The sampling frequency is 80 MHz. The measured input sequence has 200 symbols (4000 samples). To make the PA work in its nonlinear region, the PA output power of 15 dBm is chosen (average output power at 1 dB compression point is around 17 dBm for ZFL 2500).

Fig. 2 Output spectrums when average output power is 15 dBm

A set of data of input and output of the PA ZFL2500 is acquired without DPD. It is used for the identification of the PA model. The normalised mean squared error (NMSE) between the real and modelling output of the PA is calculated. For the conventional MP model, it needs 15 coefficients (NMSE = -43.9 dB, $P = 2$ and $Q_0 = Q_2 = 4$). For the non-uniform MP model, it only needs 7 coefficients (NMSE = -43.9 dB, $P = 2$, $Q_0 = Q_2 = 1$, and $Q_2 = 0$). The non-uniform MP model reduces the number of the model’s coefficients by 53% without reducing the modelling accuracy. The power spectral density (PSD) of output signals with the proposed DPD and without DPD is presented in Fig. 2. It can be seen that the proposed DPD achieves a spectrum regrowth suppression of about 15 dB. The table size is only 8. In addition, the proposed DPD is compared with the DPD in [4]. It shows that the performance of the proposed DPD is better than that of [4].

Conclusion: A DPD solution based on the non-uniform MP model and quadratically interpolated LUT is proposed in this Letter. The DPD effect is validated on an actual PA ZFL-2500. To the best of our knowledge, it is the first time that the combination of the non-uniform MP model and the quadratically interpolated LUT is used for linearising a PA. The proposed solution reduces the number of the model’s coefficients and achieves a spectrum regrowth suppression of about 15 dB with a table size of only 8.

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