A Hermite Interpolated LUT for RF Power Amplifiers

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ABSTRACT

Digital predistortion is one of the most widely used techniques to linearize a power amplifier (PA) to reduce the error vector magnitude (EVM) distortion and spectral regrowth. By far, the lookup table (LUT) predistorters are most frequently used scheme to mitigate the effects of non-linear power amplifier. In this paper, a new algorithm of joint-polynominal LUT predistorter which attains the best linearization performance is proposed. The algorithm employs the hermite interpolation LUT, which has a higher accuracy of interpolation. Simulation results show that the proposed method provides a better rejection of EVM distortion and an improvement of 30-40% of adjacent channel leakage ratio (ACLR) for the wideband code division multiple access at a minimal memory usage.

Keywords: Predistortion, linearization, lookup table, power amplifier, non-linear distortion

INTRODUCTION

One of the most important aspects of wideband digital communication system is the use of complex modulation scheme to increase spectral efficiency. These modulation schemes possess non-constant envelopes and high peak to average power ratios (PAPR). Transmission of these complex modulation schemes through a power amplifier results in spectral regrowth and low Peak to Average (PA) power efficiency.

Several baseband linearisation techniques have been proposed to resolve the conflict between the linearity and efficiency of PA (Soloveya 2015), and the complex-gain lookup table (LUT) (Teikari et al., 2004), (Feng et al., 2013) based digital predistorter is one of the most commonly used techniques due to its low complexity and fast convergence for adaptation.

It has been suggested that a linear interpolation approximation (LUT) improves the accuracy of modelling the inverse PA characteristics (Feng et al., 2013) compared with non-interpolated LUT. However, as the inverse function of the Lin-LUT PA characteristics is not a smooth curve, this would consequently lead to error vector magnitude (EVM) distortion and adjacent channel interference. In this work, a hermite interpolated complex-gain LUT (HMT-LUT) is derived to improve the accuracy of modelling the inverse PA characteristic. This in turn results in better attenuation of EVM distortion and adjacent channel interference hence requiring less LUT entries to be inhabited. The HMT-LUT has been validated to improve the predistorter performance in terms of power spectral density (PSD), adjacent channel leakage ratio (ACLR) and error vector magnitude at a minimal memory usage. The improvement of HMT-LUT is theoretically derived and evaluated through simulations.
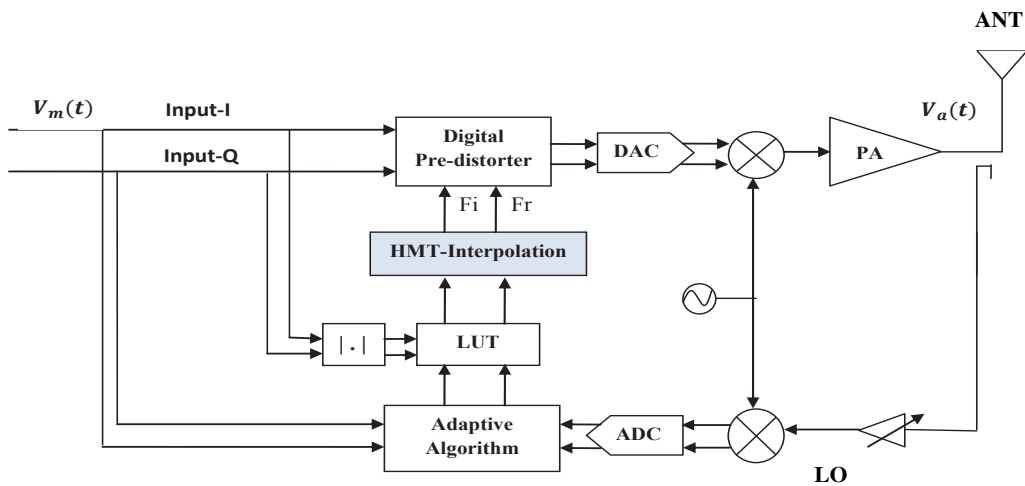

Figure 1. The block diagram of the proposed adaptive DPD system

SYSTEM MODEL ARCHITECTURE

The power amplifier PA has non-linear characteristics both in dynamic and static situations. The static part consists of AM-AM and AM-PM conversion functions. The dynamic part consists of memory effects whereby the output signal is dependent not only on the current input signal but also the input signal at a preceding state. In this brief, the PA is considered as memory-less (Saleh, 1981) whereby V_m (and $V_a(t)$ represents the signal at the input and output of the PA respectively as shown in Figure 1. The input signal, $V_m(t)$ as in Figure 1 is predistorted using the LUT values with hermite interpolation by the predistortion block that operates on the modulated digital baseband signal prior to digital to analog conversion (DAC) and frequency up conversion. Assuming the input signal, $V_m(t)$ is a modulated complex baseband signal which is given as

$$V_m = I + jQ \tag{1}$$

The input signal is fed to the cascade of the baseband digital predistorter (DPD) and power amplifier (PA). The DPD distorts the modulated signal by applying a memoryless non-linearity to produce the predistorted signal $V_d(t)$ as

$$V_d = V_m \cdot f(|V_m|)$$ (2)

where the amplitude modulation and complex-gain of predistorter is represented by V_m and $f(.)$, which explains the AM/AM and AM/PM responses of the PA. From here, the output signal of the PA is expressed as

$$V_a = V_d \cdot g(|V_d|) = V_m \cdot f(|V_m|) \cdot g(|V_m| \cdot f(|V_m|))$$ (3)

where V_d and $g|V_d|$ are in a complex form representing the amplitude of the predistorted signal and the complex gain of the amplifier respectively. In the analysis, the amplifier is normalised so the saturation occurs at unit amplitude of its input so the amplitude range of both $|V_m|$ and $|V_d|$ lies within [0, 1]. The cascading of PA and DPD eliminates the non-idealities of AM-AM and AM-PM producing a complex linear gain K, where:-

$$K = f(|V_m|) \cdot g(|V_m| \cdot f(|V_m|))$$ (4)

In terms of mathematical convenience, the complex linear gain is normalised to one. From here, the output signal can be written as:

$$V_a = K \cdot V_m$$ (5)

The input signal to the DPD is predistorted by means of LUT values and each entry of the LUT is assumed to be optimised at the midpoint of its range. The RLS algorithm (Woo et al., 2007; Varahram et al., 2013) updates the LUT with

$$f_{i+1}^n = f_i^n + \lambda \cdot E_i$$ (6)

where λ is the gain vector, f_{i+1}^n and f_i^n are the nth LUT values at time i and $i+1$ respectively and E_i is the error vector at time i defined as the difference between input and output as given by

$$E_i = V_m(t) - V_a(t)$$ (7)

HERMITE INTERPOLATED COMPLEX-GAIN LUT METHOD

In a LUT based digital predistorter, each LUT entry is specified at only one single point of the inverse PA characteristics. To have a higher accuracy of estimation on modelling the inverse PA non-linear characteristic, one common method is to increase the number of LUT entries which consequently reduces the quantisation error as shown in (Chung et al., 2007). However, larger LUT entries tend to slower the convergence time and increase the computational complexity. In

order to overcome this drawback, a linear interpolated LUT (Lin-LUT) is proposed in (I. Teikari et al., 2004), (Feng et al. 2013). The Lin-LUT technique employs linear interpolation between the adjacent LUT entries for both predistortion and LUT updates which has been shown to improve performance. An inverse PA characteristic of Lin-LUT technique is shown in Figure 2. The Lin-LUT is proven to be the model that inverses more accurately the characteristics of the PA compared with non-interpolated LUT (Faulkner et al. 1994). However, as the inverse function of Lin-LUT is not a smooth curve as in Figure 2, this would consequently lead to EVM distortion and adjacent channel interference.
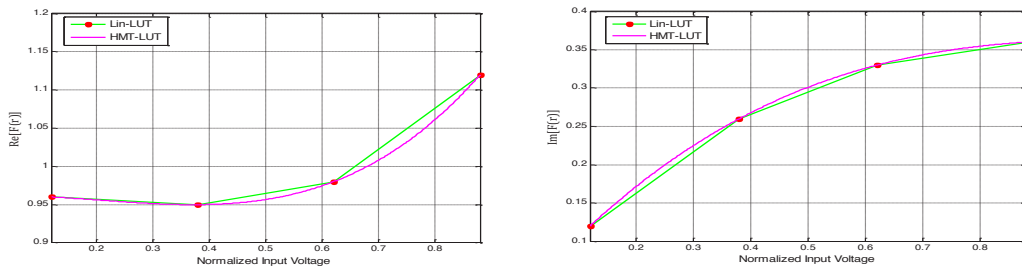

Figure 2. Inverse PA characteristics of Lin-LUT and HMT-LUT

Theoretically, the inverse PA characteristics can be more accurately modelled with high order polynomials. However, the computational complexity introduced by these high-order polynomials does not validate high accuracy. In this paper, a hermite interpolated complex-gain LUT (HMT-LUT) is proposed. Compared with other high order polynomials, HMT-LUT has a lower computational complexity. Additionally, it has a higher accuracy of interpolation compared with Lin-LUT. By employing the Hermite-Interpolation between the adjacent LUT indices (the n-1th, nth and n+1th) which are closest to the input voltage $|V_m|$, the HMT-LUT, entry can be calculated as follows:

$$f(|V_m|) = (H^{n-1}(|V_m|)f_i^{n-1} + H^n(|V_m|)f_i^n + H^{n+1}(|V_m|)f_i^{n+1}) - (H^{n-1'}(|V_m|)f_i^{n-1'} + H^{n'}(|V_m|)f_i^{n'} + H^{n+1'}(|V_m|)f_i^{n+1'}) \tag{8}$$

where f_i^{n-1}, f_i^n and f_i^{n+1} are the n-1th, nth and n+1th LUT values at time i, $f_i^{n-1'}$, $f_i^{n'}$ and $f_i^{n+1'}$ are the first order LUT values of f_i^{n-1}, f_i^n and f_i^{n+1}, and $H^{n-1}(.)$, $H^n(.)$, $H^{n+1}(.)$, $H^{n-1'}(.)$, $H^{n'}(.)$ and $H^{n+1'}(.)$ are the hermite weighing functions that can be approximated as

$$H^{n-1} = \left(1 - 2(V_m - x_{n-1})L^{n-1'}(|V_m|)\right)(L^{n-1}(|V_m|))^2 \tag{9}$$

$$H^n = \left(1 - 2(V_m - x_n)L^{n'}(|V_m|)\right)(L^n(|V_m|))^2 \tag{10}$$

$$H^{n+1} = \left(1 - 2(V_m - x_{n+1})L^{n+1'}(|V_m|)\right)(L^{n+1}(|V_m|))^2 \tag{11}$$

$$H^{n-1'} = (V_m - x_{n-1}) \cdot (L^{n-1}(|V_m|))^2 \tag{12}$$

$$H^{n'} = (V_m - x_n) \cdot (L^n(|V_m|))^2 \tag{13}$$

$$H^{n+1'} = (V_m - x_{n+1}) \cdot (L^{n+1}(|V_m|))^2 \tag{14}$$

where $L^{n-1}(.)$, $L^n(.)$ and $L^{n+1}(.)$ are the lagrange weighing functions that can be approximated as

$$L^{n-1}(|V_m|) = \frac{(|V_m| - x_n)(|V_m| - x_{n+1})}{(x_{n-1} - x_n)(x_{n-1} - x_{n+1})} \tag{15}$$

$$L^n(|V_m|) = \frac{(|V_m| - x_{n-1})(|V_m| - x_{n+1})}{(x_n - x_{n-1})(x_n - x_{n+1})} \tag{16}$$

$$L^{n+1}(|V_m|) = \frac{(|V_m| - x_{n-1})(|V_m| - x_n)}{(x_{n+1} - x_{n-1})(x_{n+1} - x_n)} \tag{17}$$

where $L^{n-1'}$, $L^{n1'}$ and $L^{n+1'}$ are the first order lagrange weighing functions and x_{n-1}, x_n and x_{n+1} are corresponding voltage of n-1th, nth and n+1th LUT indices respectively. If the LUT is uniformly spaced, the equations can be simplified as

$$L^{n-1}(|V_m|) = \frac{(|V_m| - x_n)(|V_m| - x_{n+1})}{2T_r^2} \tag{18}$$

$$L^n(|V_m|) = \frac{(|V_m| - x_{n-1})(|V_m| - x_{n+1})}{2T_r^2} \tag{19}$$

$$L^{n+1}(|V_m|) = \frac{(|V_m| - x_{n-1})(|V_m| - x_n)}{2T_r^2} \tag{20}$$

where T_r is the resolution of LUT indices? An inverse PA characteristic of HMT-LUT technique is shown in Figure 2. It can be clearly seen that the usage of hermite interpolation leads to a smooth curve between LUT as it requires more referenced information compared with linear interpolation. Besides, the first order LUT values of HMT-LUT are continuous across the boundary between the adjacent LUT indices (the n-1th, nth and n+1th) which increases the accuracy of estimating the inverse PA characteristics. With the selection of T_r as the order of 2, the divisions can be employed with logic shifters. This in turn results in better rejection of EVM distortion and adjacent channel interference while maintaining similar computational complexity with Lin-LUT.

SIMULATION RESULTS

The proposed algorithm has been evaluated using MATLAB, using Saleh Model's PA (Saleh, 1981), which possesses non-linear characteristics that can be expressed as

$$K(u) = \frac{\alpha_a u}{1 + \beta_a u^2} \tag{21}$$

$$\emptyset(u) = \frac{\alpha_p u^2}{1 + \beta_p u^2} \tag{22}$$

where $K(u)$ and $\phi(u)$ are the amplitude and phase corresponding to the non-linear characteristic of the PA. The parameters α_a= 2.2 , β_a = 0.23 , α_p = -4.033, and β_p = 9.104 are considered in initial simulation which relates to memoryless PA with a gain of 2.16 dB and phase deviation of -22.87°. The simulations are performed using a wideband code division multiple access (WCDMA) signal with a bandwidth of 5MHz. The simulated output spectrums of the linearly amplified input signal (WCDMA) along with the PA under different conditions in terms of power spectral density (PSD) are shown in Figure 3. Spectral regrowth is prominent due to the non-linear characteristics of PA (Cavers, 1999), which consequently increase, the adjacent channel leakage ratio (ACLR). The ACLR is defined as the ratio of the power in the adjacent channel to the transmitted power. The proposed method (HMT-LUT) performs better in terms of linearity compared with non-interpolated LUT and linear interpolated LUT (Lin-LUT), hence reducing the ACLR about 11.8 dBc for the LUT size of 8 entries.

This is expected as HMT-LUT provides an accurate approximation of inverse PA non-linear characteristics and better windowing samples between the LUT entries which requires less LUT to be inhabited.
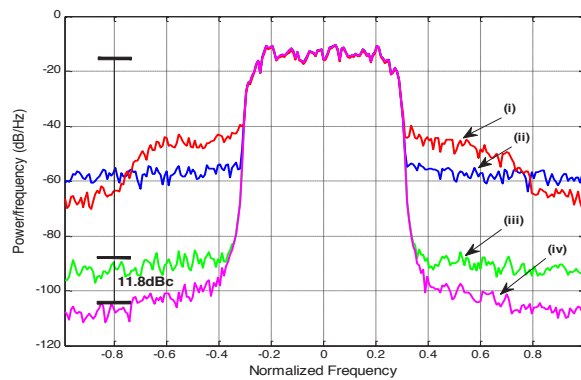

Figure 3. Simulated WCDMA signal spectrum before and after predistortion (i) Without DPD, (ii) DPD without interpolation (iii) DPD with linear interpolation and (iv) DPD with hermite interpolation

To have a similar comparison, the simulation is further assessed in terms of Error Vector Magnitude (EVM) with the same Saleh model PA non-linear characteristics. The EVM is defined as the ratio of power of the error vector to the root mean square (RMS) power of the reference. The result in Figure 4 shows that the HMT-LUT improves the EVM of WCDMA at least by 6 dB for the LUT size of 8 entries with 500 iterations. As the iteration increases, the EVM improves as shown in Figure 4 and summarised in Table I for non-interpolated LUT, linear interpolated LUT (Lin-LUT) and hermite interpolated complex-gain LUT (HMT-LUT) respectively. The proposed method significantly reduces the EVM distortion as the approximation errors introduced by HMT-LUT from modelling the inverse PA characteristics are lower compared with non-interpolated LUT and linear interpolated LUT. As a conclusion, a significant improvement of adjacent channel interference and EVM distortion is observed with the usage of HMT-LUT while maintaining similar computational complexity with linear interpolated LUT (Lin-LUT).
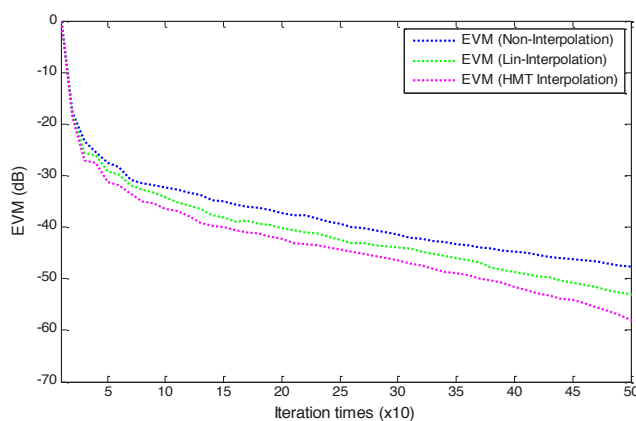

Figure 4. Error Vector Magnitude (EVM) before and after predistortion with different DPD LUT's

Table 1
Simulated EVM of WCDMA signal

Simulated Output Spectrums	8 entries EVM (dB)
Non-Interpolated LUT	-48.82
Linear Interpolated LUT	-52.64
Hermite Interpolated LUT	-58.57

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