An Adaptive Volterra Predistorter for the Linearization of RF High Power Amplifiers

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Abstract **— An efficient digital baseband predistortion linearizer is presented to compensate for nonlinear distortions induced by RF high power amplifiers in wireless communication systems. The proposed approach utilizes an indirect learning architecture with a fast Recursive Least Squares (RLS) filtering algorithm, implemented using V-vector algebra, to update the coefficients of a Volterra-based predistorter. There is no requirement for an initial identification of the nonlinear characteristics of HPA as in linearizers based on conventional pth-order inverse methods. Simulation results show that that good performance and low computational complexity are achieved in the linearization of both narrow and wide bandwidth system.**

I. INTRODUCTION

With the rapid growth of high volume multimedia data traffic in wireless communication systems, high power amplifier (HPA) linearization has become very important, since the nonlinearities, induced by the HPA cause amplitude and phase distortion, intersymbol interference, adjacent channel interference and other effects, which reduce spectral efficiency. To compensate for these nonlinear distortions, many linearization techniques have been proposed, such as feedback, feed-forward and predistortion. Most of these methods are analog and some of them are limited to narrow-band signals. Digital predistortion can be operated in both narrow and wide band systems, and is very flexible to implement. Furthermore, as digital signal processors (DSPs) become faster, the real-time correction of distortion effects of HPA through the application of digital predistortion is becoming an increasingly viable solution. The most commonly used technique to date is adaptive digital mapping predistortion [5]. However this kind of table look-up technique requires a massive amount of RAM to store a sufficiently accurate mapping, and is not practical for wideband systems, especially in multi-carrier CDMA, with a wide range of input signal amplitude levels. In addition, it does not take account of memory effects, which are quite critical in broadband systems.

A truncated Volterra series model (which allows for memory) has been used by a number of researchers to describe the relationship between the input and the output of a nonlinear system over many years. Based on this approach, the pth-order inverse [6] and fixed-point [7] approaches have been proposed to overcome system nonlinearity. Some of these techniques can achieve good performance. However, high computational complexity makes methods of this kind impractical for real-time implementation. In this paper, a new digital predistortion linearizer based on a fast Volterra filtering algorithm is proposed. This design scheme utilizes an indirect learning architecture to update the coefficients of a Volterra-based predistorter with memory. No prior modelling of the HPA response is required, since the method generates the inverse directly from the actual HPA response. Unlike the approach in [2], we utilize V-vector algebra [3] to implement a fast nonlinear RLS Volterra filtering algorithm, which reduces the computational complexity.

The remainder of the paper is organized as follows. Section 2 introduces the adaptive indirect learning predistorter structure, while the fast adaptive Volterra RLS filtering algorithm, based on V-vector algebra, is derived in Section 3. Section 4 gives the simulation system model and results. Conclusions are presented in Section 5.

II. ADAPTIVE PREDISTORTER STRUCTURE

One way to compensate for the nonlinear effects of a HPA, involves inserting a predistortion linearizer into the signal path prior to the amplifier. A simple implementation of adaptive baseband digital predistortion is shown in Fig. 1. The original baseband signals are multiplied with the coefficients of the predistorter to generate the desired predistorted signals. The predistorted signals are passed through the digital-to-analog converter (D/A), and then up-converted and passed to the PA. In order to update the coefficients of the predistorter, a small fraction of the transmit signal is fed back, transferred to baseband via a down-converter and A/D converted. Several variations of this system have been proposed over the last decade. In general, the main differences are in the implementation of the predistortion architecture or adaptive algorithm. In this paper, we utilize two identical Volterra models to construct the predistorter and the adaptive estimator, which are shown in Fig. 2. Both the predistorter and the estimator are implemented using transversal FIR filters. The estimator utilizes a fast RLS algorithm based on V-vector to estimate the non-linear parameters of the HPA, and update the coefficients. Then the updated coefficients are copied to the predistorter. At the beginning of system operation, the coefficients of the predistorter are set to 1. While the error signal e_n approaches zero, the overall output of the system approaches the system input, the desired output of the overall system, since the inputs to the identical networks are equal. When convergence is reached, the adaptive network can be removed. This algorithm generates the inverse response of the system directly from the actual HPA response, and therefore does not require an initial identification of the non-linear characteristics of HPA, or the construction of a specific non-linear model as required by conventional pth-order Volterra inverse methods [1].

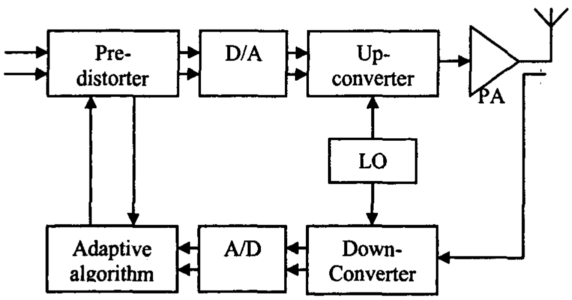

Fig. 1. A predistortion linearizer

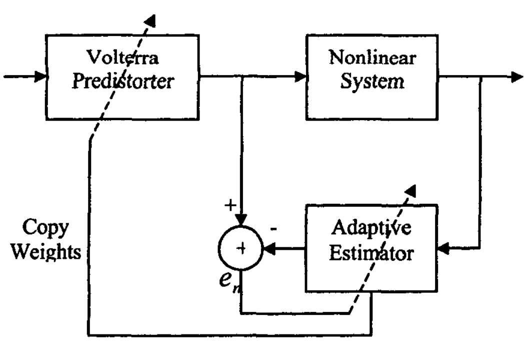

Fig. 2. The implementation of the adaptive algorithm

III. ADAPTIVE VOLTERRA FILTERING

The outputs of a Volterra filter are linear with respect to the filter coefficients, and so an RLS adaptive algorithm for Volterra systems can be implemented using the same general procedure as would be employed for conventional linear filters with the exception that the input vectors must be redefined appropriately. However, due to the loss of the time–shift property in the input data vector, direct application of linear adaptive algorithms to the Volterra case can significantly increase the computational complexity, which is critical issue for many real-time applications. In this paper, we use a fast adaptive Volterra filtering algorithm based on V-vector algebra, to replace the conventional RLS adaptive method. The V-vector is a novel nonrectangular structure matrix [3], shown in Fig.3, which can preserve the linear time-shift property for non-linear data vectors thereby avoiding the complex permutations that would otherwise be required. A complete algebra based on V-vectors and V-matrices can be developed, allowing direct adaptation of linear filter algorithms to higher-order Volterra filter design.

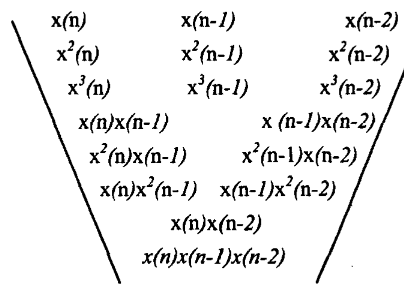

Fig.3 Input data V-vector of third-order, memory-length 3 Volterra filter

In the linear case, in order to pass from the input data vector at time n to that at time $n+1$, we have to discard the last element of the vector and add the new input at the beginning of the vector. This property does not apply to the input data vectors of Volterra filters, since they are formed from a different product of input samples. But, for the nonrectangular matrix in Fig.3, it is clear that the first left column of is formed by the elements which have been added going from X_{n-1} to X_n, while the last right column of X_n is formed by the elements which will be discarded in the transition from X_n to X_{n+1}. This is similar to linear case, and therefore permutations can be avoided. By the use of the V-vector formalism, a fast and numerically stable adaptive Volterra filtering algorithm was derived in [3]. The algorithm used in this paper is an extension of that work.

Corresponding to the input data V-vector in Fig. 3, we write the coefficients of the RLS filter (Volterra kernel) as shown in Fig. 4. Note that many kernels are discarded here by using various symmetries. Furthermore, the output of the filter may also be represented as a V-vector.

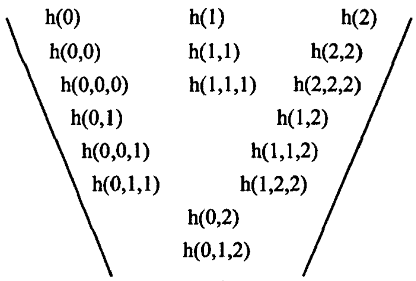

Fig.4. The coefficients V-vector of third-order, memory-length 3 Volterra filter

The adaptive filter output at time k is given by:

$$o_n(k) = w_n^T X_k \tag{1}$$

We update the weights by

$$w_n = w_{n-1} + c_n e_{n-1}(n) \tag{2}$$

where c_n is the Kalman Gain [4] and the estimation error $e_n(k)$ is given by

$$e_n(k) = d(k) - w_n^T X_k \tag{3}$$

where $d(k)$ is the desired output.

Using V-vector formalism, we obtain the extended input data V-vector $\overline{X}_n$ as,

$$\overline{X}_n = \begin{bmatrix} v_n & X_{n-1} \end{bmatrix} = \begin{bmatrix} X_n & r_{n-1} \end{bmatrix} \tag{4}$$

i.e. by adding v_n to X_{n-1} as the first left column, or by adding r_{n-1} to X_n as the last right column (the two definitions are equal), where v_n is the vector to be added and r_{n-1} is the vector to be discarded in the transition from X_{n-1} to X_n.

In order to update the gain V-vector c_n, the relevant update equations were obtained from the relationships of the forward prediction filter and the backward prediction filter [8],

$$A_n = A_{n-1} - c_{n-1} f_{n-1}^T(n) \tag{5}$$

$$B_n = B_{n-1} - c_n b_{n-1}^T(n) \tag{6}$$

where, A_n and B_n are the coefficient vectors of the forward predictor and the backward predictor respectively. And the prediction error vectors $f_n(k)$ and $b_n(k)$ are defined as

$$f_n(k) = v_k + A_n^T X_{k-1} \tag{7}$$

$$b_n(k) = r_{k-1} + B_n^T X_k \tag{8}$$

respectively.

Using (4)-(8), the extended Kalman Gain V-vector $\overline{c}_n$, as demonstrated in [3], can be written as follows,

$$\overline{c}_n = \begin{bmatrix} \alpha_n^{-1} f_n(n) & A_n \alpha_n^{-1} f_n(n) + c_{n-1} \end{bmatrix} \tag{9}$$

or

$$\overline{c}_n = \begin{bmatrix} c_n + B_n \beta_n^{-1} b_n(n) & \beta_n^{-1} b_n(n) \end{bmatrix} \tag{10}$$

Let μ_n and m_n indicate, respectively, the last right column and the remaining first columns of $\overline{c}_n$,

$$\begin{bmatrix} m_n & \mu_n \end{bmatrix} = \overline{c}_n \tag{11}$$

Then it is possible to obtain that

$$c_n = \left(1 - b_{n-1}^T(n)\mu_n\right)^{-1}\left[m_n - B_{n-1}\mu_n\right] \tag{12}$$

Finally, the coefficients of the estimate Volterra filter are copied into those of the Volterra predistorter.

IV. SIMULATION RESULTS

In this section we demonstrate the performance of the proposed predistorter via computer simulation. A third-order Volterra-based linearizer with memory-length 3 is implemented in Simulink software from Mathworks, Inc. In this paper, all operations are performed at baseband and up- and down-conversions are not included. A class AB power amplifier model is used as the basis of the simulation, the initial power and phase characteristics of which are extracted from vector-network-analyzer (VNA) measurements. These are then interpolated using splines to represent the nonlinear parameters of the HPA in Matlab.

To illustrate the linearizer's ability to suppress intermodulation distortion (IMD), the output spectra resulting from a two-tone test are shown in Fig.5. In the two-tone test, the amplitudes of the tones are equal and the frequency spacing is 25kHz. Note that the intermodulation product is −16dBc before linearization. When the predistorter is inserted in the signal path, the highest IMD level is reduced to −31dBc, an improvement of 15dB.

Both baseband IS-95 CDMA and W-CDMA signals are used to evaluate the capability for suppression of ACP (Adjacent Channel Power). For the IS-95 signal, the chip rate is 1.2288 Mcps, and, with a peak-to-average ratio of 10.2dB, the ACP improvement is about 10 dB at an average output level of 35dBm, as shown in Fig. 6.

For the W-CDMA signal, which has a chip rate of 3.84Mcps and a peak to average ratio of 11dB, the corresponding ACP improvement is about 9dB, as shown in Fig. 7.

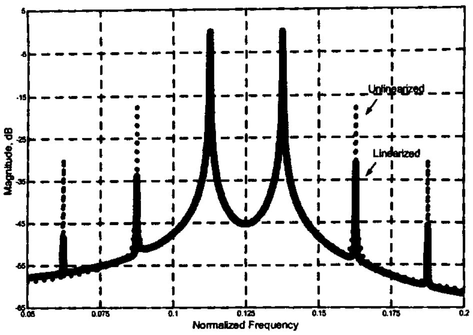

Fig.5. Two–tone test for IMD suppression

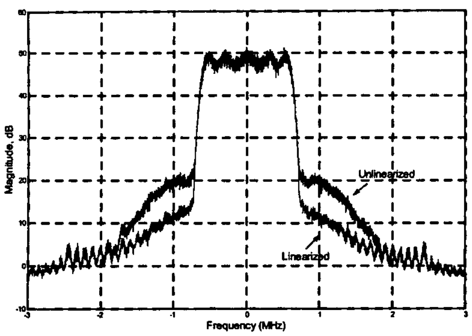

Fig. 6. IS-95 CDMA signal output spectrum with and without predistorter

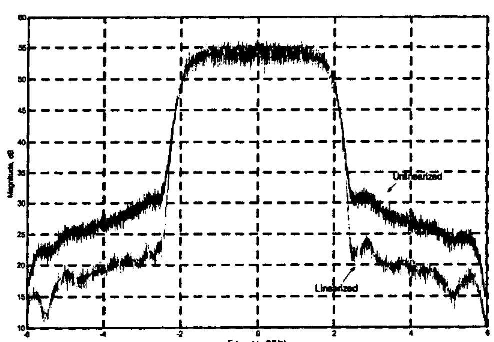

Fig. 7. W-CDMA signal output spectrum with and without predistorter

V. CONCLUSIONS

In this paper we have developed an efficient baseband predistortion digital linearizer to compensate for nonlinear distortions induced by RF high power amplifiers in wireless communication systems. The computer simulation results presented here show that the proposed Volterra-based predistorter can achieve very promising performance in both narrow and wide bandwidth systems.

ACKNOWLEDGEMENTS

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