

# Augmented Hammerstein Predistorter for Linearization of Broad-Band Wireless Transmitters

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**Abstract**—In this paper, an augmented lookup-table-based Hammerstein predistorter is proposed for the first time in order to further improve the pre-correction capability of the traditional Hammerstein predistorter in the context of broad-band high-power wireless transmitters. The predistorter scheme consists of two separate modules, and its parameters are determined in two steps, which are: 1) static predistorter identification and then 2) dynamic part identification. The performance assessment of the newly proposed predistorter is carried out on a wireless transmitter prototype, which includes an *L*-band push–pull GaAs field-effect transistor 45-dBm peak-envelope power amplifier. Moreover, one- and three-carrier Third-Generation Partnership Projects frequency-division duplex wide-band code-division multiple-access signals are used as test signals to verify the robustness of this novel predistorter under different bandwidth signals. The linearized transmitter prototype output spectrum demonstrates noticeable superiority of the proposed augmented predistorter in suppressing the spectrum regrowth caused by the memory effects in comparison to the traditional Hammerstein predistorter.

**Index Terms**—Augmented Hammerstein predistorter, broad-band wireless transmitters, Hammerstein predistorter, lookup table (LUT), memory effects.

## I. INTRODUCTION

HIGH-EFFICIENCY wide-band transmitter design for modern high-speed wireless communication systems, such as worldwide interoperability for microwave access (WiMAX), third-generation (3G) and beyond systems, etc., is a complex task since it involves numerous inconsistent requirements. In such contexts, simultaneously accomplishing high linearity and high-power efficiency is particularly a great challenge. In fact, to efficiently utilize the precious limited spectrum resources, several complicated modulation schemes have been widely used in the modern wide-band wireless communication systems. These modulated signals lead to a nonconstant envelope with large peak-to-average power ratios (PAPRs), which can be as high as 12 dB in some cases. Consequently, the power amplifier (PA) in the transmitter has to be designed either to operate near its saturated area, so as to provide higher system power efficiency, or at large backoff from its nonlinear region, in order to meet the required linearity. Accordingly, the PA ends up with either high efficiency, but bad linearity, or

vice versa. Therefore, to satisfy the linearity requirement while operating the PA at its nonlinear area, one has to correct for the different sources of distortion all along the entire transmitter chain. For this reason, different linearization techniques, such as feedback [1], feed-forward [2], and predistortion [3], [4] have been proposed to improve the linearity of the transmitter.

Among the various linearization techniques, digital baseband predistortion is one of the most promising and cost-effective linearization techniques due to its digital implementation that offers significant accuracy and flexibility. Considering its simplicity and relative ease of implementation, the lookup table (LUT) is by far the most widely used means for the construction of the inverse of the amplitude-modulation /amplitude-modulation (AM/AM) and amplitude-modulation /phase-modulation (AM/PM) characteristic curves of the transmitter or PA [5]–[8]. However, this type of predistorter is only valid for memoryless nonlinear cases such as the traditional narrow-band wireless communication systems.

In the wide-band transmitter/PA context, the memory effects exhibited by the transmitter/PA significantly limit the ability of the memoryless predistorter to suppress the spectrum regrowth [9]. These memory effects can generally be categorized as electrothermal memory effects and electrical memory effects. The electrothermal memory effects are mainly caused by the thermal capacitance and resistance that form a low-pass thermal filter. The electrical memory effects can be mainly attributed to the nonconstant frequency response of the transmitter around the carrier frequency, the impedance variation of bias circuits at baseband, and the harmonic loading in the PA power stage [10], [11]. In the context of a broad-band wireless transmitter, the electrical memory effects are the dominant sources of the spectrum regrowth since the thermal filter time constant is too large compared to the inverse of the signal bandwidth [12]. Therefore, the memory effects in the remainder of this paper are limited to the electrical memory effects.

Different predistorter architectures, which are intended to compensate for the nonlinearity, as well as the memory effects, have been reported in the literature. For example, a memory polynomial model was proposed in [13] and utilized in [14]–[16] to address these effects. However, a memory polynomial-based predistorter suffers from numerical instability when higher order polynomial terms are included because a matrix inversion is needed for the determination of the polynomial coefficients [17]. Alternatively, Raich *et al.* [17] employed orthogonal polynomials to alleviate the numerical instability problem associated with the traditional polynomials.

Two-box-based predistorters, which are called either a Hammerstein predistorter or a Wiener predistorter, depending on the cascading order of the nonlinear block and linear block,

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are another type of common predistorter architecture in the literature. For example, a Hammerstein predistorter, which is a cascade of a memoryless nonlinear block followed by a linear filter, was utilized to compensate for the nonlinearity, as well as the memory effects of a PA [18], [19]. Recently, Wang and Ilow [20] demonstrated the compensation performance using a Wiener predistorter to linearize the high power amplifier (HPA) with memory effects in an orthogonal frequency-division multiplexing (OFDM) transmitter while considering the HPA as a Hammerstein nonlinear system. In these two examples, the memoryless nonlinearity is represented by a complex high-order memoryless polynomial. In addition, the identification of the coefficients of the memoryless nonlinear block and the taps of the linear filter are concurrently resolved by means of complicated algorithms that are applied either in a time domain [18], [19] or frequency domain [20]. Moreover, Sano and Sun [21] proposed a new three-box efficient Wiener–Hammerstein predistortion scheme for pre-compensating the nonlinear distortion of an HPA. The identification algorithm of this scheme is implemented in a frequency domain.

In this paper, a LUT-based Hammerstein predistorter is initially developed to compensate for the nonlinearity and the memory effects that occur in a broad-band wireless transmitter. To further improve the compensation performance of the predistorter, an augmented Hammerstein predistorter is then proposed.

The remainder of this paper is organized as follows. Section II elucidates the details of the LUT-based Hammerstein predistorter and its corresponding identification procedure. In Section III, a new augmented Hammerstein predistorter is proposed in order to improve the correction performance for the nonlinearity and the memory effects in the context of the broad-band wireless transmitter. Section IV describes the test bed used in the experimental validation of different predistorters involved in this paper. In Section V, the validation results of the Hammerstein predistorter and augmented Hammerstein predistorter with different configurations under one- and three-carrier third-generation partnership projects frequency-division-duplex (3GPP-FDD) wide-band code-division multiple-access (WCDMA) signals are illustrated and discussed using an *L*-band 45-dBm GaAs field-effect transistor (FET) push-pull PA-based transmitter. Section VI presents the conclusion.

## II. LUT-BASED HAMMERSTEIN PREDISTORTER AND IDENTIFICATION

### A. LUT-Based Hammerstein Predistorter

A Hammerstein predistorter, as illustrated in Fig. 1, is utilized to build a predistortion function for a broad-band wireless transmitter. Accordingly, the predistorter is decomposed into a nonlinear static memoryless subsystem and a linear dynamic one. The static memoryless subsystem is intended to pre-compensate for the static nonlinearity of the transmitter, while the linear dynamic filter is focused on suppressing the spectrum regrowth caused by the memory effects. The memoryless predistortion can be implemented using the traditional LUT. This LUT is constructed based on the AM/AM and AM/PM characteristics of the transmitter that are extracted directly from the

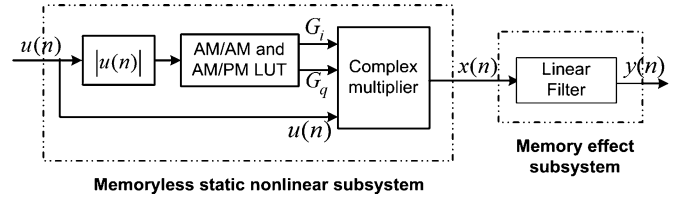


Fig. 1. Hammerstein predistorter diagram.

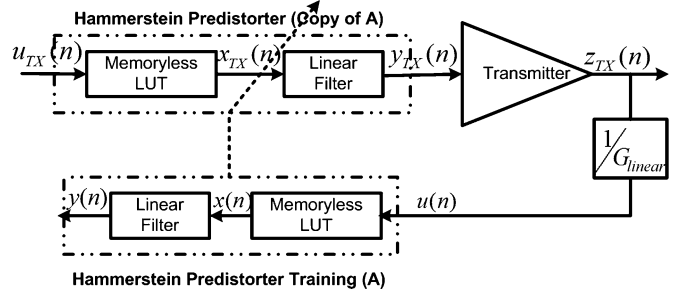


Fig. 2. Offline training scheme for Hammerstein predistorter identification.

baseband measurement data by means of a moving average procedure, as explained in [22]. Consequently, the complex dynamic predistortion problem is simplified to a relatively easy linear dynamic problem. In this way, resolving the Hammerstein predistortion becomes more convenient than the traditional solutions [18]–[20], where all of the linear and nonlinear parameters of the Hammerstein model are resolved concurrently by means of elaborate algorithms.

The identification of the static memoryless predistorter on the basis of raw measured baseband data  $u(n)$  and  $y(n)$  permits the extraction of the nonmeasurable variable  $x(n)$ , shown in Fig. 1, which is required in the identification of the linear filter subsystem. For this reason, the input signal  $u(n)$  of the predistorter is applied to the memoryless predistorter subsystem so as to get the dynamic linear filter input signal  $x(n)$ .

The input and output signals of the two blocks in Fig. 1 can be related as follows:

$$x(n) = [G_i(|u(n)|) + jG_q(|u(n)|)]u(n) = G(|u(n)|)u(n) \quad (1)$$

$$y(n) = f(x(n)) \quad (2)$$

where  $G(|u(n)|) = G_i(|u(n)|) + jG_q(|u(n)|)$  refers to the memoryless complex gain of the predistorter that depends only on the instantaneous magnitude of  $u(n)$ ;  $f(x)$  is a linear transfer function of the linear filter.

### B. Hammerstein Predistorter Identification

Hammerstein parameter identification is performed using an offline training scheme, as shown in Fig. 2. To identify the parameters of the predistorter, the output  $z_{TX}(n)$  of the transmitter is normalized by the designated linear gain  $G_{\text{linear}}$  of the transmitter and taken as the input training sequence  $u(n)$  of the predistorter, i.e.,

$$u(n) = \frac{z_{TX}(n)}{G_{\text{linear}}} \quad (3)$$

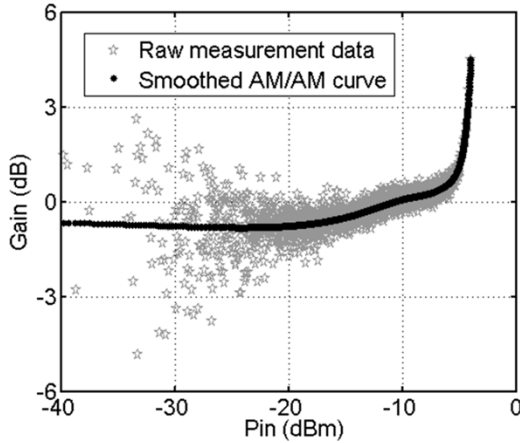


Fig. 3. Predistorter AM/AM curve smoothed with DEWMA versus the raw measurement AM/AM data.

The input  $y_{TX}(n)$  of the transmitter is used as the output training sequence  $y(n)$  of the predistorter, i.e.,

$$y(n) = y_{TX}(n). \quad (4)$$

The dynamic exponential weighted moving average (DEWMA) method [22] is then applied to the predistorter training sequences  $u(n)$  and  $y(n)$  in order to remove the dispersion of the dynamic AM/AM and AM/PM characteristics. As reported in [22], the weight factor  $\alpha$  should not be constant, as is used in the traditional EWMA, during the averaging process, in order to handle the variable dispersion along the whole input power  $P_{in}$  range. Therefore, we can define

$$\alpha = \alpha(|u(n)|) = \frac{\alpha_0}{\left( \beta + (1 - \beta) \frac{|u(n)|_{\max} - |u(n)|}{|u(n)|_{\max} - |u(n)|_{\min}} \right)^k} \quad (5)$$

where  $|u(n)|_{\min}$  is the minimum amplitude of the input,  $|u(n)|_{\max}$  is the maximum amplitude of the input,  $\alpha_0$  is a constant weight factor with value between 0–1,  $\beta$  is an adjustment factor with a value that is larger than 1, and  $k$  is a positive integer for changing the variation speed of the weight factor with the input.

The extracted smoothed AM/AM and AM/PM curves are then used to construct the LUT of the predistorter. Figs. 3 and 4 show typical extracted AM/AM and AM/PM curves, which are based on the measurement data when the transmitter is driven with a three-carrier 3GPP-FDD WCDMA signal. This latter is synthesized according to 3GPP test-model-3 with a carrier separation of 5 MHz from each other [23].

The intermediate training data set  $x(n)$  is deduced via the application of the input training data  $u(n)$  to the previously constructed LUT. Based on the data set  $x(n)$  and  $y(n)$ , the AM/AM and AM/PM characteristics of the memory effect subsystem in Fig. 1 are traced and shown in Figs. 5 and 6. These two figures illustrate the removal of the strong static nonlinearity.

In this paper, a finite impulse response (FIR) filter is chosen instead of an infinite impulse response (IIR) filter to build the

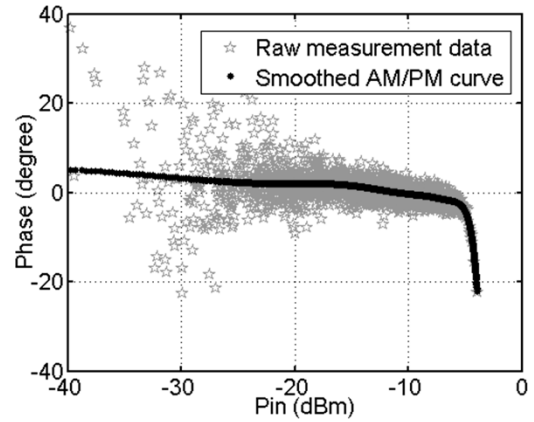


Fig. 4. Predistorter AM/PM curve smoothed with DEWMA versus the raw measurement AM/PM data.

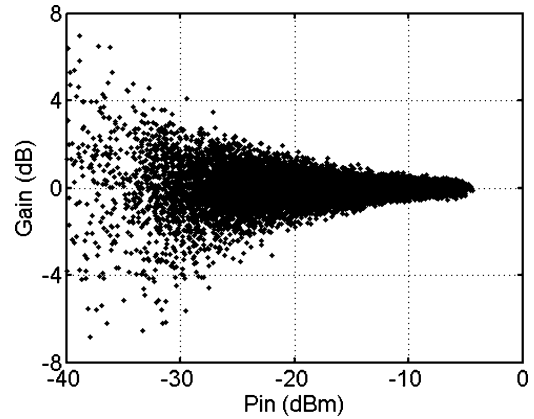


Fig. 5. Dynamic AM/AM characteristics of the linear filter extracted from the measurement data.

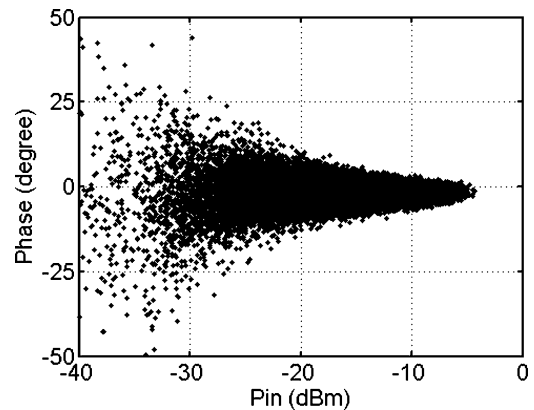


Fig. 6. Dynamic AM/PM characteristics of the linear filter extracted from the measurement data.

dynamic linear filter in order to avoid the potential instability of an IIR filter. Thus, (2) can be expressed as

$$y(n) = \sum_{i=0}^{M-1} a_i x(n-i) \quad (6)$$

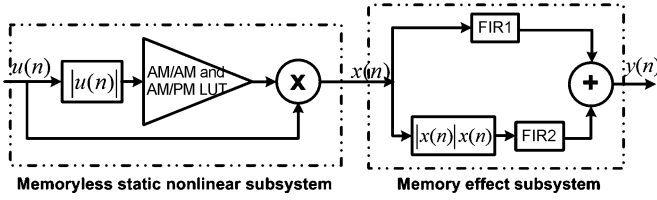


Fig. 7. Augmented Hammerstein predistorter diagram.

where  $M$  denotes the number of the FIR filter taps and  $a_i$  denotes the coefficients of the FIR filter taps. Equation (6) can then be rewritten in matrix format as follows:

$$\mathbf{Y} = \mathbf{A}\mathbf{W} \quad (7)$$

where

$$\mathbf{Y} = [y(M), y(M+1), \dots, y(N)]^T \quad (8)$$

$$\mathbf{W} = [a_0, a_1, \dots, a_{M-1}]^T \quad (9)$$

$$\mathbf{A} = [\mathbf{X}(M) \quad \mathbf{X}(M+1) \quad \dots \quad \mathbf{X}(N)]^T \quad (10)$$

$$\mathbf{X}(n) = [x(n) \quad x(n-1) \quad \dots \quad x(n-M+1)]^T, \quad n = M, M+1, \dots, N. \quad (11)$$

The FIR filter parameter identification can be performed using the recursive least squares (RLS) algorithm [24], where the deduced  $x(n)$  and the measured  $u(n)$  are taken as the input signal and desired signal, respectively.

Once the memoryless LUT and the linear filter parameters are identified, the offline training procedure is ended, and the Hammerstein predistorter parameters are updated accordingly. This offline training procedure is required to be repeated several times until  $y_{TX} - y$  is minimized. The training process is then suspended until the output spectrum of the transmitter fails to satisfy the predefined requirements again. In this way, the adaptive predistortion can be easily achieved with the feedback loop.

### III. AUGMENTED HAMMERSTEIN PREDISTORTER

As discussed in Section II, the memory effects are pre-compensated by means of a linear FIR filter in the traditional Hammerstein predistorter. This linear filter corrects for the electrical memory effects that can be attributed mainly to the nonconstant frequency response of the transmitter around the carrier frequency. Consequently, it fails to completely pre-compensate for the electrical memory effects due to the impedance variation of the bias circuits and harmonic loading of the power transistors. For that reason, an augmented Hammerstein predistorter, as shown in Fig. 7, is proposed to enhance the correction capability in the context of broad-band wireless transmitters.

This augmented Hammerstein predistorter is a cascade of a strong nonlinear static subsystem and a dynamic weak nonlinear subsystem. The strong nonlinear subsystem, which is based on averaged AM/AM and AM/PM characteristics of the predistorter, can be implemented using LUTs. However, the dynamic weak nonlinear subsystem is composed of a new dynamic FIR-based filter, which is responsible for annulling the spectrum regrowth produced by the dynamic distortion sources at the trans-

mitter output when the transmitter is driven with a modulated signal. For this new dynamic FIR-based filter, an extra parallel branch is added to the linear FIR filter. In this parallel branch, the input signal  $x(n)$  is multiplied by its magnitude  $|x(n)|$  in order to generate even-order distortions that will be applied to a second FIR filter. Accordingly, the new predistorter includes distortions sources that are close to those encountered in the real transmitter to be linearized. Thus, a superior performance to that obtained with a simple linear FIR filter is anticipated.

Assuming that the two FIR filters in the dynamic FIR-based filter have  $M_1$  and  $M_2$  taps, respectively, the input signal  $x(n)$  and the output signal  $y(n)$  of this predistorter, given in the Fig. 7, can be correlated as follows:

$$y(n) = \sum_{i=0}^{M_1-1} a_i x(n-i) + \sum_{i=0}^{M_2-1} b_i |x(n-i)| x(n-i) \quad (12)$$

where,  $M_1$  and  $M_2$  denote the memory depth of the predistorter.  $a_i$  and  $b_i$  represent the tap coefficients of the two FIR filters, FIR1 and FIR2, respectively.

The memoryless static nonlinear module in the augmented Hammerstein predistorter can also be expressed by (1). Based on the training sequence  $u(n)$  and  $x(n)$ , the moving average procedure proposed in [22] can be utilized to extract the AM/AM and AM/PM LUT to construct a memoryless predistorter. After removing the strong static nonlinearity using the obtained LUT, the identification of the coefficients  $a_i$  and  $b_i$  can be largely simplified. Let

$$v(n-i) = |x(n-i)| x(n-i). \quad (13)$$

Equation (12) can be rewritten as

$$y(n) = \sum_{i=0}^{M_1-1} a_i x(n-i) + \sum_{i=0}^{M_2-1} b_i v(n-i). \quad (14)$$

Consequently, (14) can be resolved with the RLS algorithm if (9) and (11) are modified as follows:

$$\begin{aligned} \mathbf{W} &= [a_0, a_1, \dots, a_{M_1-1}, b_0, b_1, \dots, b_{M_2-1}]^T \\ \mathbf{X}(n) &= [x(n), \quad x(n-1), \quad \dots, \quad x(n-M_1+1), \\ &\quad v(n), \quad v(n-1), \quad \dots, \quad v(n-M_2+1)]^T, \\ &\quad n = M, M+1, \dots, N; \quad M = \max(M_1, M_2) \end{aligned} \quad (15)$$

where  $M$  is the largest value of  $M_1$  and  $M_2$ . Since only the first- and second-order terms of the input signals are involved in this new predistorter scheme, the RLS algorithm exhibits good numerical stabilities.

FIR1 in Fig. 7, which is widely used in the Hammerstein structure, permits compensation for the frequency response of the transmitter around the carrier frequency. In this case, the linear filter FIR1 plays the role of a pre-equalizer. If the PA exhibits only the odd-order nonlinearities, this filter will be enough

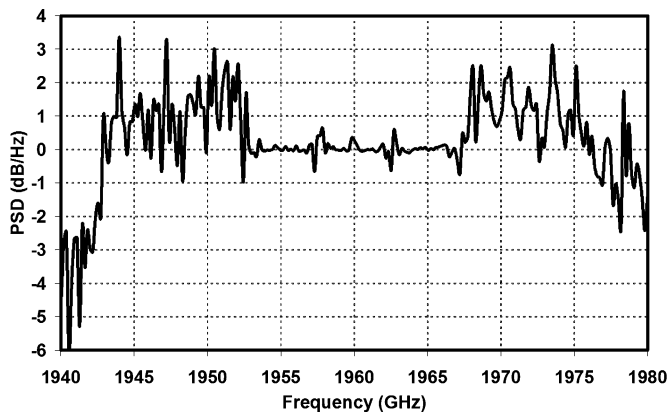


Fig. 8. Frequency response of the added FIR2 (ten-tap FIR filter) used in the augmented Hammerstein predistorter while applying a three-carrier 3GPP-FDD WCDMA signal.

to get rid of the memory effects. However, the PA is an actual nonlinear RF circuit that, in principle, generates even-order harmonics and intermodulation products in addition to the dominant odd-order intermodulation products and harmonics. In particular, the second harmonic and envelope components, when remixed afterwards with the in-band signal, will end up with passband distortions that will be added to those produced by the odd-order nonlinearities [10], [25]. In addition, since the signal excitation is wide-band, the frequency response of the matching circuits at the harmonics and the biasing circuits will cause additional memory effects. With the parallel filter branch in the predistorter, one can generate baseband even-order distortions, which compensate for those introduced by the passband PA even-order distortions when remixed with the in-band signal. The baseband distortions are then shaped using FIR2 to take into account the frequency response of biasing circuits and matching circuits around harmonics. The parallel branch is, therefore, contributing to the cancellation of the nonlinearity effects introduced by the nonideal biasing and matching circuits in a real PA.

To demonstrate the effectiveness of this new memory effect subsystem, the frequency response of the added filter (FIR2) in the augmented Hammerstein predistorter is plotted in Fig. 8, where a three-carrier 3GPP-FDD WCDMA signal is used. Hence, one can measure the contribution of the filter to the memory effect compensation. FIR2 admits a flat frequency response around the carrier frequency. Indeed, the biasing circuits and the harmonics load's impedances are almost constant for a small frequency shift from the carrier frequency. However, at the frequency points far from the carrier frequency, the filter has a more noticeable frequency response to compensate for the impedance variation of the bias circuits and harmonic loads.

#### IV. VALIDATION EXPERIMENTAL SETUP

The experimental setup used to evaluate the compensation performance of the conventional Hammerstein predistorter and the augmented Hammerstein predistorter is shown in Fig. 9. The broad-band wireless transmitter prototype includes an RF vector modulator, two digital-to-analog converters, and an RF PA at

the frequency band of 1930–1990 MHz. The RF PA is a cascade of three stages. The first stage contains a 40-dBm linear LDMOS PA MHL-19936 with 29-dB gain from Freescale Semiconductor, Austin, TX. The second stage is based on a Freescale Semiconductor MRF19045 LDMOS transistor. The final stage is comprised of a 45-dBm peak-envelope-power push-pull FET transistor (FLL600IQ-2) from Eudyna Devices USA Inc., San Jose, CA. The whole lineup of the RF PA has 53-dB gain and 45-dBm saturated power. Moreover, the RF vector modulator and two digital-to-analog converters are emulated with an electronic signal generator (ESG) (E4438C, Agilent Technologies, Palo Alto, CA). Therefore, the transmitter prototype is physically constructed with the ESG and PA.

The host digital signal processor (DSP) is implemented with a personal computer (PC), where the in-phase/quadrature (I/Q) signal is initially synthesized using the 3GPP library in Agilent's Advanced Design System (ADS). In this study, the I/Q test signals have one 3GPP-FDD WCDMA carrier and three neighboring 3GPP-FDD WCDMA carriers (carrier spacing 5 MHz for every two neighboring carriers), which are configured according to 3GPP test-model-3 with 32 code channels [23].

The baseband I/Q signal is firstly preprocessed by the predistortion function and then downloaded to the I/Q arbitrary waveform generator of the ESG via the general-purpose interface bus (GPIB) interface with the help of the dynamic link existing between the ADS and ESG. After that, the predistorted baseband signal is modulated to an RF carrier in the ESG and fed to the PA. In this way, the ADS in the host DSP, the ESG, and the PA work together to form a baseband linearized transmitter prototype. The baseband data at the output of the transmitter is captured by an RF receiver. As shown in Fig. 9, this receiver consists of an RF/IF down-converter, a high-speed analog-to-digital converter, a digital down-converter, and the host DSP. In this study, the receiver prototype is physically constructed by a high-performance spectrum analyzer (PSA) (E4446A, Agilent Technologies), a vector signal analyzer (VSA) (89611A, Agilent Technologies) and a PC.

The spectrum analyzer serves as a down-converter, which transforms the RF signal to a 70-MHz IF. The IF signal is then digitized by means of the high-speed digitizer module Agilent 1439C and digitally down-converted to baseband I and Q signals. The VSA software in the PC captures the baseband I and Q data via the high-speed IEEE1394 interface. It should be noted that the time delay between the input baseband data sequence and the equivalent output baseband data sequence should be accurately aligned. The baseband input and output data are first captured by the VSA (without delay compensation). The time delay between these two sequences is then estimated using a co-variance-based algorithm. To increase the accuracy of the delay estimation, a Lagrange interpolation is implemented to increase the sampling rate. Finally, this estimated delay time is used to set the delay calibration parameter in the VSA, and the baseband input and output data are captured again. Therefore, the captured input and output data are correctly aligned.

Furthermore, the measurement setup, shown in Fig. 9, has a modulation bandwidth of 39 MHz. The sampling rate used in the experiment is equal to 46.08 million samples per second (MSPS) and 92.16 MSPS for one- and three-carrier WCDMA

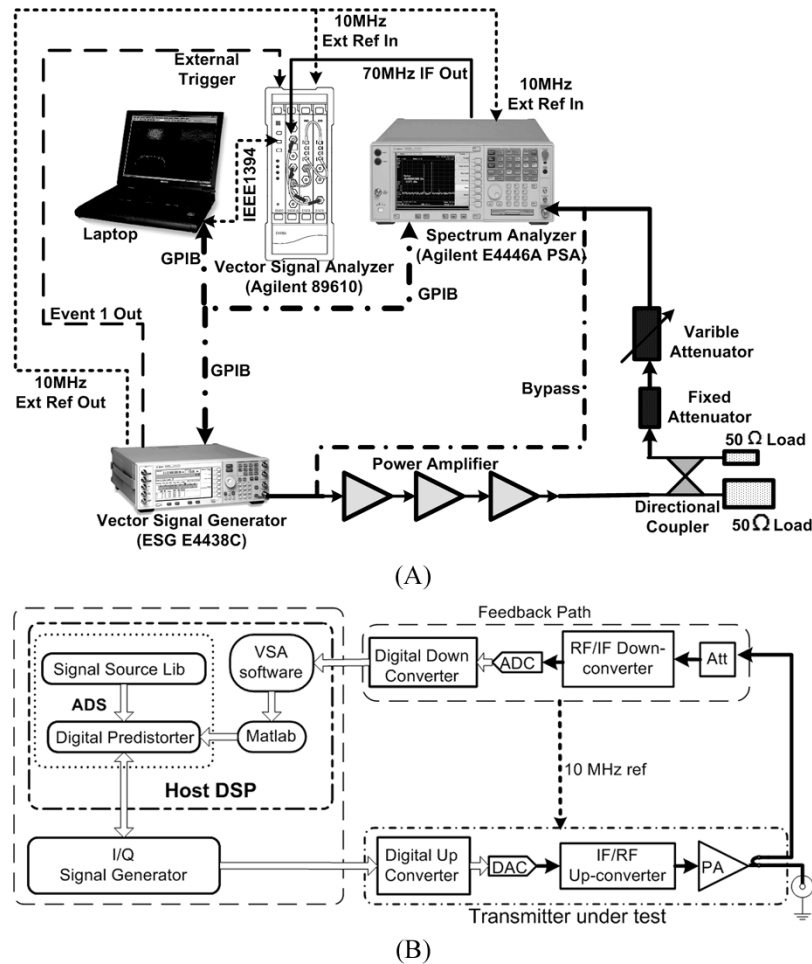


Fig. 9 Experimental setup for verifying digital predistorters. (A) Experimental set up diagram. (B) Functional diagram of the experimental setup.

signals, respectively. As shown in Fig. 9(A), both the VSA and spectrum analyzer are synchronized by a 10-MHz reference signal from the ESG.

The captured baseband data at the input and output of the prototype transmitter are processed in MATLAB in order to deduce the parameters of the predistorter. Finally, the obtained predistorter parameters are sent to the ADS to update the corresponding predistorter parameters. The performance of the different predistorters can be evaluated by comparing the output spectra of the transmitter obtained with the various predistorter schemes.

## V. VALIDATION RESULTS AND DISCUSSION

To validate the pre-compensation ability of the predistorter, the 1024-entry LUT and dynamic FIR filter are constructed using the offline training method introduced in Section IV. At first, the LUT is built using the DEWMA method in MATLAB. The RLS algorithm is then applied to determine the coefficients of the dynamic filter. The constructed predistorter is then implemented in ADS to synthesize the predistorted version of the test signal that will be fed to the wide-band transmitter. To test the generality of the predistorter, a frame of the 3GPP-FDD WCDMA signal, which is different from the frame used in the predistorter identification stage, is applied to the predistorter during the validation phase.

### A. Hammerstein Predistorter

To optimize the Hammerstein predistorter, the dynamic FIR filter is configured with a different numbers of taps so as to evaluate the variation of the residual spectrum regrowth. Fig. 10 illustrates the ability of the Hammerstein predistorters, with different FIR taps, to suppress the output spectrum regrowth of the transmitter, while applying the predistorted one-carrier 3GPP-FDD WCDMA signals. The spectrum of the Hammerstein predistorter with the 128-tap FIR filter shows the larger sidelobe suppression. In comparison to the spectrum of the transmitter obtained using a memoryless predistorter, one can conclude that, to some extent, all of the different Hammerstein predistorters are able to partially suppress the spectrum regrowth caused by the memory effects. Fig. 11 shows the adjacent channel power ratio (ACPR) at the output of the transmitter for different predistorters, which are assessed at several frequency offsets ( $-15$ ,  $-10$ ,  $-5$ ,  $5$ ,  $10$ , and  $15$  MHz) from the center frequency within the 3.84-MHz bandwidth. The improved ACPR value at the 5-MHz offset for the transmitter with the Hammerstein predistorter that has the 128-tap FIR filter is as high as 15 dB. The average output power of the transmitter linearized by the Hammerstein predistorter with the 128-tap FIR filter is approximately 36.6 dBm.

Furthermore, Fig. 10 clearly exemplifies that all of these Hammerstein predistorters cannot effectively suppress the

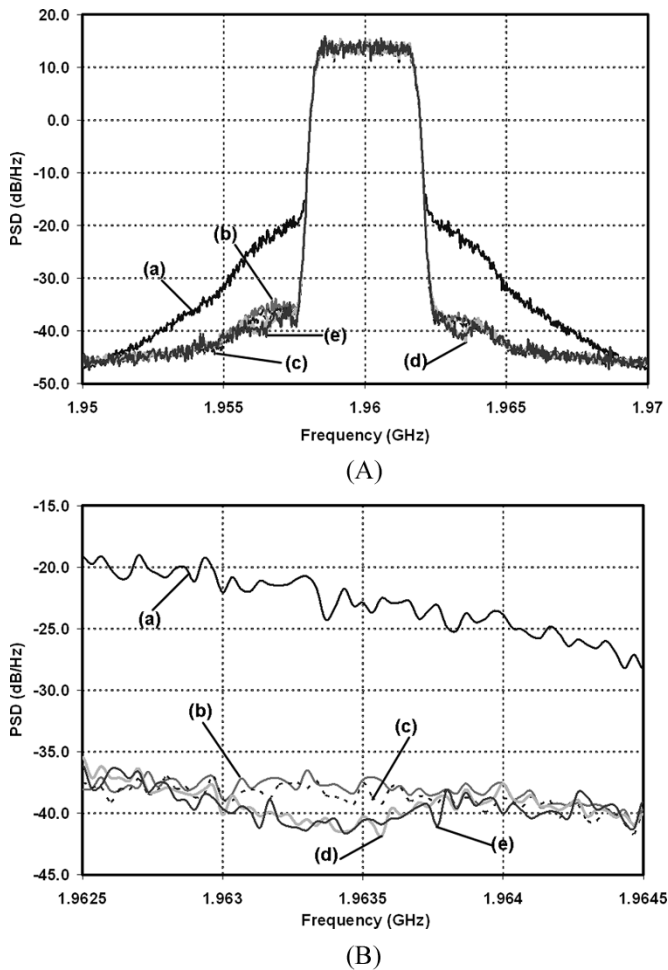


Fig. 10. Spectrum comparison of the transmitter with different Hammerstein predistorters. (a) Without predistorter. (b) With memoryless predistorter. (c) Hammerstein predistorter with a ten-tap FIR filter. (d) Hammerstein predistorter with a 64-tap FIR filter. (e) Hammerstein predistorter with a 128-tap FIR filter. (A) Full spectrum comparison. (B) Zoom-in spectrum comparison.

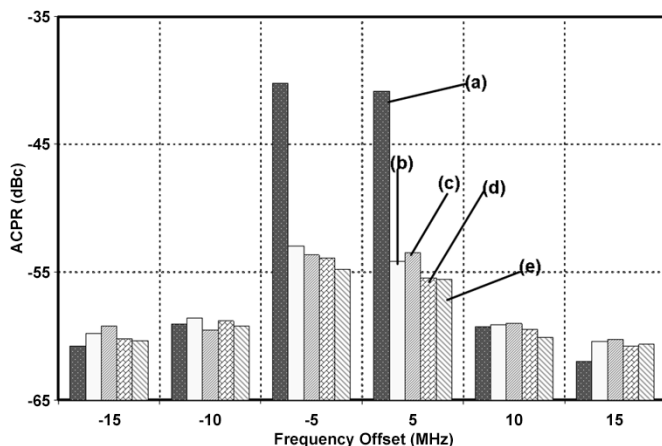


Fig. 11. ACPR comparison of the transmitter with different Hammerstein predistorters. (a) Without predistorter. (b) With memoryless predistorter. (c) Hammerstein predistorter with a ten-tap FIR filter. (d) Hammerstein predistorter with a 64-tap FIR filter. (e) Hammerstein predistorter with a 128-tap FIR filter.

spectrum regrowth close to the main channel. The best ACPR value at the 5-MHz offset for the transmitter with the Hammerstein predistorters is approximately  $-55.5$  dBc. In comparison

to  $-54.2$  dBc of the ACPR obtained with the memoryless predistorter, there is no obvious improvement for further suppression of the spectrum regrowth using these traditional Hammerstein predistorters. Consequently, based on the results obtained, one can conclude that, in actual transmitter systems, the ability of the Hammerstein predistorter for reducing the transmitter spectrum regrowth caused by the memory effects is limited. This may be due to the fact that real broad-band transmitters cannot be accurately characterized by, and do not obey, a Wiener nonlinear model. This is in agreement with the simulation results and conclusion reached in [19], where a perturbed Wiener PA model was simulated and further linearized using a Hammerstein predistorter.

### B. Augmented Hammerstein Predistorter

The parameter identification of the augmented Hammerstein predistorter is firstly carried out in terms of the procedure explained in Section III. A 1024-entry LUT is constructed and two FIR filters with ten or 20 taps are identified. To illustrate the superior accuracy of this new predistorter scheme, the spectrum and ACPR results obtained while cascading the transmitter with a 128-tap Hammerstein predistorter or a memoryless predistorter are used as references in the validation process. In addition, the spectrum and ACPR of the transmitter without a predistorter are also added in the comparison of results to illustrate the performance improvements under the conditions of with and without predistortion. To verify the robustness of the proposed new Hammerstein predistorter, one- and three-carrier 3GPP-FDD WCDMA signals are chosen as the test signals.

The average output powers of the transmitter linearized by the augmented Hammerstein predistorter are approximately 36.6 and 36.4 dBm for the one-carrier 3GPP-FDD WCDMA signal and the three-carrier 3GPP-FDD WCDMA signal, respectively.

The spectrum and ACPR comparison results shown in Figs. 12–15 for one- and three-carrier 3GPP-FDD WCDMA signals indicate that the novel augmented Hammerstein predistorter can suppress the memory effects of the transmitter more effectively than the conventional Hammerstein predistorter. Although the memory effects are not strong for the one-carrier 3GPP-FDD WCDMA signal, as shown in Fig. 12, the augmented Hammerstein predistorter still provides obvious improvement for suppressing the spectrum regrowth caused by the memory effects.

When the transmitter is applied with the three-carrier 3GPP-FDD WCDMA signal, the transmitter exhibits strong memory effects, as illustrated in Fig. 14, curve (b). Fig. 14, curve (c) reveals that the traditional Hammerstein predistorter cannot efficiently stifle the spectrum regrowth attributed to the memory effects. Nevertheless, Fig. 14, curve (d) clearly demonstrates that the new augmented Hammerstein predistorter can successfully compensate for the memory effects.

Moreover, to clearly show the improvement with the augmented Hammerstein predistorter in suppressing the out-of-band emission, the spectrum differences between the Hammerstein predistorter with a 128-tap FIR filter and the augmented Hammerstein predistorter with two ten-tap FIR filters for the three-carrier 3GPP-FDD WCDMA signal are plotted in Fig. 16. This figure proves the spectrum regrowth that

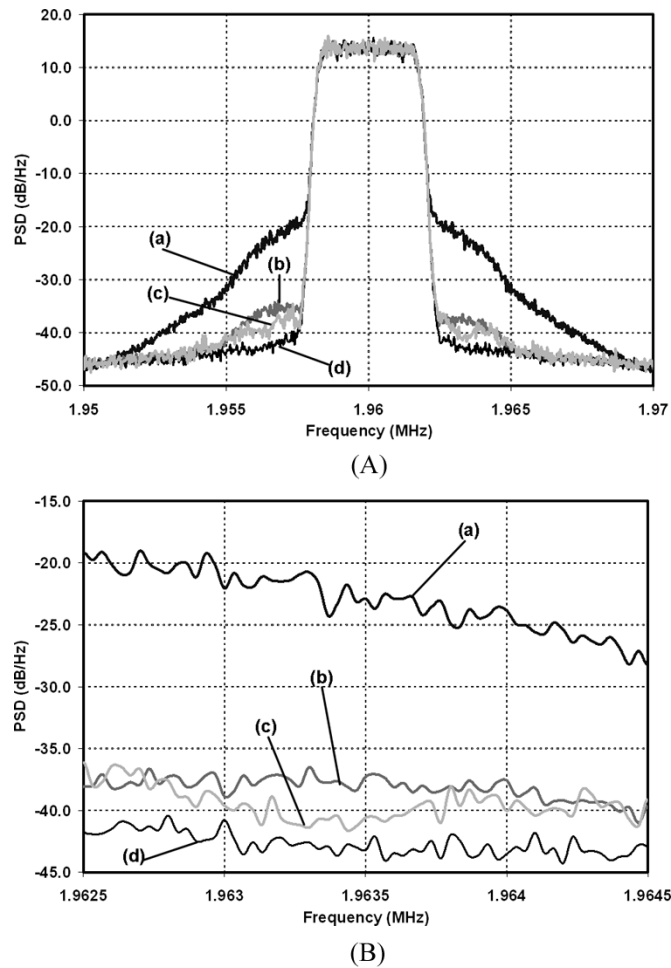


Fig. 12. Spectrum comparison of different predistorters for a one-carrier WCDMA signal. (a) Without predistorter. (b) Memoryless predistorter. (c) Hammerstein predistorter with a 128-tap FIR filter. (d) Augmented Hammerstein predistorter with two 20-tap FIR filters. (A) Full spectrum comparison. (B) Zoom-in spectrum comparison.

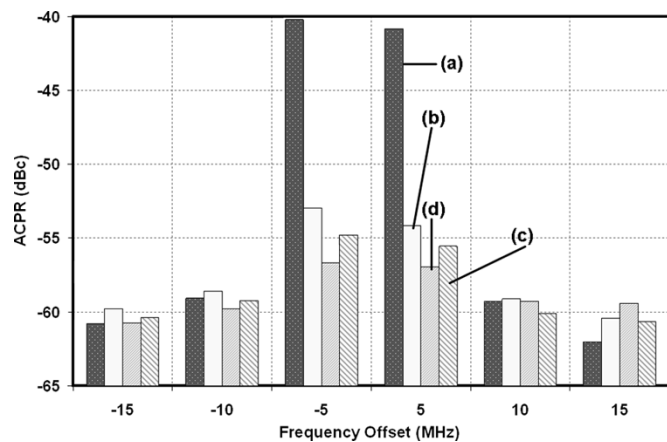


Fig. 13. ACPR comparison of different predistorters for one-carrier WCDMA signal. (a) Without predistorter. (b) Memoryless predistorter. (c) Hammerstein predistorter with a 128-tap FIR filter. (d) Augmented Hammerstein predistorter with two 20-tap FIR filters.

resulted from the nonlinearities, which are mainly attributed to the bias and harmonic loading of the PA, can be effectively cancelled by adding a weak nonlinear branch to the traditional linear FIR filter.

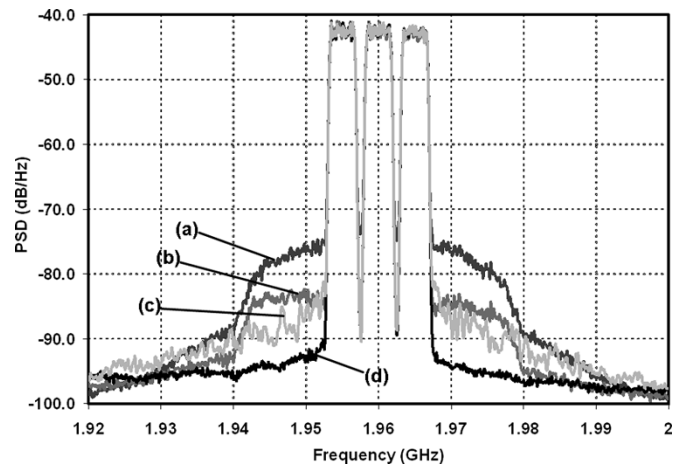


Fig. 14. Spectrum comparison of different predistorters for a three-carrier WCDMA signal. (a) Without predistorter. (b) Memoryless predistorter. (c) Hammerstein predistorter with a 128-tap FIR filter. (d) Augmented Hammerstein predistorter with two ten-tap FIR filters.

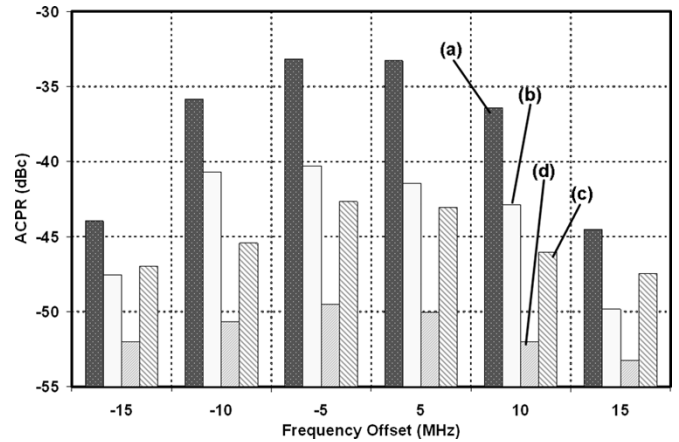


Fig. 15. ACPR comparison of different predistorters for a three-carrier WCDMA signal. (a) Without predistorter. (b) Memoryless predistorter. (c) Hammerstein predistorter with a 128-tap FIR filter. (d) Augmented Hammerstein predistorter with two ten-tap FIR filters.

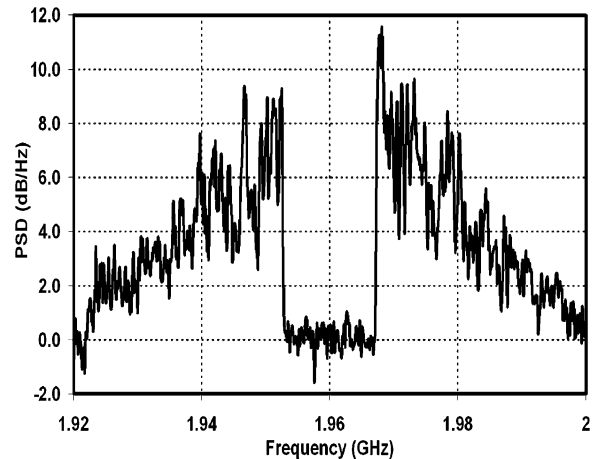


Fig. 16. Spectrum differences between the Hammerstein predistorter with a 128-tap FIR filter and the augmented Hammerstein predistorter with two ten-tap FIR filters for a three-carrier WCDMA signal.

## VI. CONCLUSION

In this paper, a LUT-based Hammerstein predistorter has been employed to suppress the spectrum regrowth caused by

nonlinearity and the memory effects in a wide-band wireless transmitter. The identification procedure of this predistorter has been discussed in detail. Considering the limitation of the traditional Hammerstein predistorter in pre-compensating for memory effects, an augmented LUT-based Hammerstein predistorter has been proposed. In this augmented Hammerstein predistorter, a weak nonlinear FIR-based dynamic filter has been utilized to compensate for the memory effects of the transmitter instead of the linear FIR filter used in the conventional Hammerstein predistorter. To the best of the authors' knowledge, this is the first time that an augmented Hammerstein predistorter is proposed and implemented to compensate for the dynamic nonlinearity existing in a broad-band wireless transmitter. Finally, the LUT-based Hammerstein predistorter and the new augmented LUT-based Hammerstein predistorter have been tested using a 45-dBm peak-envelope-power GaAs FET push-pull amplifier-based transmitter prototype driven by one- and three-carrier 3GPP-FDD WCDMA signals. Both the linearized output spectrum and ACPR comparison results have demonstrated that the proposed augmented LUT-based Hammerstein predistorter outperforms the conventional LUT-based Hammerstein predistorter in suppressing the spectrum regrowth caused by the memory effects of the broad-band wireless transmitter.

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