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Adaptive Filter for a Memory HPA Distortion in OFDM Signals

Mohamed I. Shujaa and Laith Falah Mohammed Hassan
Electrical Engineering Technical College, Middle Technical University, Baghdad, Iraq

Abstract: The Orthogonal Frequency Division Multiplexing (OFDM) technique is one of the recognized technologies in the wireless communications because of its resistance to frequency selective fading channel. The major element affecting nonlinearity is the High-Power Amplifier (HPA) when operated almost to a saturation point. The memory HPA makes the OFDM signal to suffer from degradation in its performance. In this study, the proposed Adaptive Filter Predistorter (AFP) and Simplicial Canonical Piecewise Linear (SCPWL) digital predistorters are used to eliminate the side effects of the HPA. Signal to Noise Ratio (SNR) vs. Bit Error Rate (BER) is taken as a normative of system performance. The results of the simulation present the strong performance of the proposed method for eliminating the nonlinearity and the memory effects of the HPA over SCPWL predistorter. The AFP has been provided a low BER under all situations. The SCPWL has been produced a very high BER under a memory HPA and better BER under a memoryless HPA. The Input Back Off (IBO) and Output Back Off (OBO) have been computed under memory HPA in three cases: without predistorter with SCPWL and with proposed. The IBO has been equal to (0.3982), (0.2992) and (0.2074) and the OBO has been equal to (0.1814), (0.1229) and (0.1252), respectively.

Key words: Non-linear system identification, nonlinear amplifier, predistortion, HPA, OFDM, IBO

INTRODUCTION

In modern communications systems, OFDM is a promising solution that supports the increase of data transmission to meet the need and demand coverage of the various services offered by these systems (John *et al*., 2012). These services include the Internet, digital television, online games and self-driving 257 (b), Cimini *et al*. (1998). One of the challenges faced by researchers is to mitigate the Peak to Average Power Ratio (PAPR) of the signal to increase the data transfer Bo *et al*. (2005). This effect distorts the signal causing expanding in its spectrum width when it passes through the nonlinear channel such as a HPA Rani and Rasheed (2014). The spreading of the bandwidth makes the system inefficient to use the spectrum 257 (c). Usually, the PA model is represented by two behaviors Amplitude-to-Amplitude Modulation (AM/AM) and Amplitude-to-Phase Modulation (AM/PM) curves.

Several studies suggest different methods to reduce the nonlinearity and the memory outcomes of different HPA Models: Kim and Braun (2003), proposed a combination of the equalizer and adaptive mapping predistorter in M-QAM OFDM signal based on the LMS algorithm that eliminates nonlinear properties in memory HPA. Montoro *et al* (2007) introduced an Adaptive Digital Predistortion DPD based on Nonlinear Auto-Regressive Moving Average predictive (NARMA) based on known Look Up Tables LUTs. The contents of the table are changed by developing an algorithm that initiates a multi-frame LDPE for predictive-NARMA DPD using the Field Programmable Gate Array (FPGA). Werner *et al*. (2008), proposed a Power Amplifier Nonlinear Cancellation (PANC) algorithm to reduce the harmful effects of the Solid-State Power Amplifier (SSPA) on the signal. The Wiener-Hammerstein is applied as a representation of the HPA nonlinear and memory effects. Yang *et al*. (2008), used a neural network to propose a predistorter based on Radial Basis Function (RBF) to minimize the impairments of a memory HPA.

Zhe *et al*. (2008), provided a simplified Volterra model for a predistorter to get a minimum of square error of a broadband RF signal due to the HPA. Garcia-Hernandez *et al*. (2012) introduced a DPD without having to turn the input matrix using dynamic derivation reduction-based Volterra series. Cheong *et al*. (2012), provided a novel complex-valued Simplicial Canonical Piecewise Linear (SCPWL) function. SCPWL Model is expressing the amplitude and phase in a single function. This model solved the complexity of direct path learning Hammerstein predistorter algorithm by providing more number of breakpoints and the noise value is compensated at the feedback of indirect path. Min and Xiuping (2014), proposed a non-linear equalizer based on the Volterra series to red use the nonlinearity of the wireless channel. Beidas (2016) proposed a novel adaptive

Corresponding Author: Mohamed I. Shujaa, Electrical Engineering Technical College, Middle Technical University, Baghdad, Iraq

digital signal predistorter that drives the memory HPA distortion toward zero. The interference in frequency bands due to the growth of the spectrum and band distortion are main effects of the system. The proposed method will discard these effects efficiently with keeping the HPA performance. Volterra model is used to eliminate memory HPA effects which the proposed scheme is applying offline stochastic gradient method to make it adaptive through the training of the phase. This discards the nonlinearity that its characteristics are unknown a priori. Iqdour and Jabrane (2016), proposed a novel digital predistorter that progresses a high improvement in Bit Error Rate (BER) performance of HPA. The method of researchers is based on Fuzzy Wavelet Neural Networks (FWNN) to eliminate HPA impacts for WiMAX (Worldwide Interoperability for Microwave Access). The Traveling Wave Tube Amplifiers (TWTA) is considered as a model of HPA in memory and memoryless. Peng *et al.* (2018), proposed a digital harmonic canceling predistorter which integrated with digital predistorters to enhance HPA behavior. Harmonic distortions are converted to a baseband complex signals and they are modeled by memory polynomial. The coefficients of predistorter are based on direct learning structure. They are computed by nonlinear filtered-x affine projection algorithm (NFX-APA). Al-Ja'afari *et al.* (2018), used the genetic algorithm to find the optimum parameters to the SCPWL predistorter to compensate the nonlinearity of the Saleh model with memoryless HPA. This method provided a good compensating to the distortion and reducing to OBO and IBO of the memoryless HPA.

This study introduces a method for compensating each of nonlinearity and memory effects of SSPA amplifier based on adaptive equalizer technique. Moreover, The LMS algorithm was used to update FIR filter parameters and compare the results of this design with another design using SCPWL. The result indicates that the design was better to improve the amplifier than the SCPWL.

OFDM: The increasing request for the rise in data rate is as a result of the explosive growth of new multimedia-based wireless strategies. These wireless applications have triggered an increased interest toward enhancements which support fast transmission rates with the lowest probability of BER as well as portability. The wireless applications also encourage proficiently utilization of the available system resources Bingham, 1990). OFDM is among the best techniques that have led to appropriate application of the spectrum. It also provides an essential platform for making decisions for future-oriented fast information rate systems (Cimini, 1985). The OFDM based system is applied in a variety of broadband communications including IEEE802.16, WiMAX and IEEE802.11 257 (a) (Hamid, 2013). The central reason for adopting the OFDM system is that it is strong and offers great resistance to frequency 0hannel fading (Al-Dweik *et al.*, 2013; Li *et al.*, 1998). However, one of the major setbacks of the OFDM system is that it has a high PAPR. This emanates from the nonlinear element produced by the HPA at the transmitter side (Li *et al.*, 1998); Razavi *et al.* (2012). The mathematical model for the OFDM signal encompassing the N subcarriers is presented as follows (Jiang and Wu, 2008; Liang*et al.*, 2018):

$$f(n) = \frac{1}{N}\sum_{k=0}^{N-1} ak^{ke^{\frac{j2\pi kn}{N}}}, n = 0, 1, 2, ..., N-1 \tag{1}$$

Where:

ak = A complex input data
N = The number of subcarriers
n = Discrete sample in the time domain

MATERIALS AND METHODS

Power amplifier model

SSPA model: A HPA is regarded as among the essential parts of wireless communication systems. However, it is a highcost component regarding user terminals Wang *et al.* (2012). The nonlinearity of a HPA can be determined by two forms of models, that is, a memoryless model and memory Models 257 (d). The SSPA is a form of memoryless HPA model. It is also known as a Rapp Model Li *et al.* (1998). It is worth to note that the Rapp Model presents only the AM/AM conversion but neglects the AM/PM effect.

Rapp model: The general description of the Rapp Model Jimenez *et al.* (2011) has given in Eq. 2:

$$V_{out} = \frac{V_{in}}{\left(1+\left(\frac{|V_{in}|}{V_{sat}}\right)^{2p}\right)^{\frac{1}{2p}}} \tag{2}$$

where, input is represented by V_{in} and output represented by V_{out}, V_{sat} is the output at given saturation point ($V_{sat} = A\sqrt{2}$) and p is controlled through the smoothness of the transition from the linear region to the saturation region of a characteristic curve.

Memory effect model: The second effect that should be considered is the memory effect. The effect makes the modulated signal to suffer from Inter-Symbol-Interference (ISI). The linear filters of the memory effect have been achieved from the equation presented below in Eq. 3 (Beidas, 2016):

$$A(z)=\frac{1+0.1z^{-2}}{1+0.1z^{-1}} \text{ and } B(z)=\frac{1+0.1z^{-2}}{1+0.1z^{-1}} \quad (3)$$

Adaptive algorithm

Least mean square: The LMS algorithm is among the most popular Adaptive Filter (AF) algorithms. It was invented by Widrow and Hoff (1960), Widrow and Steams (1988). The LMS algorithm used in most common applications such as channel equalizer and echo cancelation, ..., etc. The basic functionality of this algorithm is to update the parameters of the filter automatically depending on the gradient vector estimation to reduce the Mean Square Error (MSE) ($E[|e^2(n)|]$) between the desired signal ($d(n)$) and the filter output ($y(n)$). The mathematical representation of the LMS algorithm summarized as (Bismor, 2012). The output of filter:

$$y(n)=\sum_{i=0}^{k-1} f(i)\omega^*(i)=W^H(n)F(n) \quad (4)$$

where, $f(n) = [f(i)f(i-1)f(i-2), ..., f(i-M-1)]$ is input vector of the FIR filter and $W(n) = [\omega(i)\omega(i-1)\omega(i-2), ..., \omega(i-M-1)]$ is the weight coefficients of the filter. Error estimation between desired signal and output signal:

$$e(n)=d(n)-y(n) \quad (5)$$

The update of the AF weight is given by:

$$W(n+1) = W(n)+\mu f(n)e^*(n) \quad (6)$$

Where:

μ = The step size parameter
k = The order of the filter

The LMS algorithm introduces inefficient behavior when it encounters a large incoming signal. Therefore, the rate of convergence will decrease and not reach the optimal solution correctly. This problem is known as a Gradient Noise Amplification (GNA) (Krishna and Yadav, 2016).

Normalized least mean square: The NLMS algorithm is a derivative of the LMS algorithm. The primary reason for adopting this algorithm is that a sudden change of the power signal over time will change the value of step size accordingly, so that, the rate of error convergence is improved. Hence, the GNA issue has been solved through the use of the NLMS algorithm by making the step size parameter's value normalized to match the input signal. The equation for updating weight coefficients is given below in Eq. 7 Ciochina *et al* (2016):

$$W(n+1) = W(n)+\frac{\beta}{C+|F(n)|^2}E^*(n)f(n) \quad (7)$$

where, c is a small constant positive value.

Dp techniques: In this study as supported by Al-Ja'afari *et al.* (2018); Seo *et al.* (2010), the SCPWL model and a proposed design with the corresponding mathematical representations will bedemonstrated to attenuate the adverse outcomes of the HPA.

Scpwl Model: In the digital predistorter structure, the SCPWL model is taken into consideration of this study AlJa'afari *et al.* (2018) and Seo *et al.* (2010). The SCPWL model is represented by primary structure of nonlinear filter realization *Seo et al.* (2010). The general expression of SCPWL function has given by as follows in Eq. (8) Cheong *et al.* (2012):

SCPWL:

$$M(n)=W_0+\sum_{i=1}^{\sigma-1}\lambda_i W_i \quad (8)$$

Where:

$$\lambda_i = \begin{cases} \frac{1}{2}(f(n)-\beta_i+|f(n)-\beta_i|)f(n)\leq\beta_i \\ \frac{1}{2}(\beta_\sigma-\beta_i+|\beta_\sigma-\beta_i|)f(n)>\beta_\sigma \end{cases} \quad (9)$$

The σ is introduced in SCPWL model Julian *et al.* (1999) that known as predefined partition points to divide the input space to (σ-1) linear affine regions, i is the i-th basis function and Wi are the coefficients of the SCPWL function $W_T = [W_0+W_1+, ..., +W_{N-1}]$. βi is the i-th predetermined partition point. The parameters βi divide the domain into equal partitions.

PA:

$$M_A = \text{convolution}(A, M(n)) \quad (10)$$

$$M_n(n)=\frac{M_A(n)}{\left(1+\left(|\frac{M_A(n)}{V_{sat}}|\right)^{2p}\right)^{\frac{1}{2p}}} \quad (11)$$

$$zf=\frac{Z}{G} \quad (13)$$

$$z = \text{Convolution}(B, M(n)) \quad (12)$$

Weight update:

$$e=f(n)-zf(n) \quad (14)$$

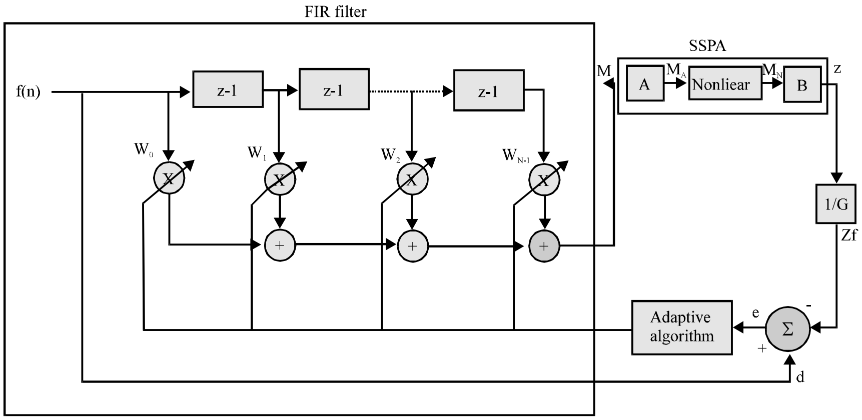

Fig. 1: The main structure of SCPWL Model

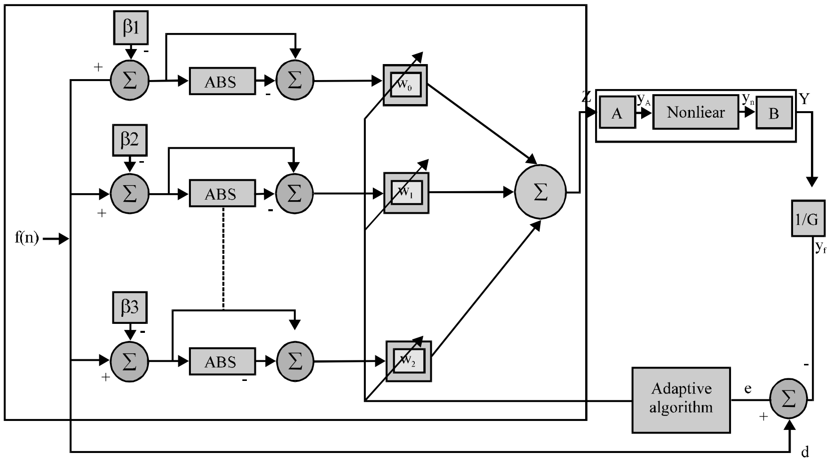

Fig. 2: The general model of AFP

$$W_i(n+1) = W(n) + \frac{\mu}{c+|\lambda_i(n)|^2} e(n)\lambda_i^*(n) \quad (15)$$

where, μ is the step size of the adaptive algorithm. The block diagram configuration of the SCPWL model is taken into consideration in this study is presented in Fig. 1.

Adaptive Filter Predistorter (AFP): The AF is the superior method to discard the unwholesome impressions through reverse the undesired characteristics of the channel to the modern communication systems. The most prominent of these problems is the non-linear behavior of the HPA signal as well as the Inter-Symbol Interference (ISI) problem known as memory effect. The Adaptive Filter Equalizer (AFE) will be used as an AFP to mitigate these problems. Figure 2 illustrations the overall structure of the AFP Grover (2014). The mathematical model of APE is:

Equalization:

$$Z(n) = W^H(n)F(n) \quad (16)$$

Power amplifier:

$$y_A(n) = \text{convolution}(A, Z(n)) \quad (17)$$

Weight update:

$$y_n A, Z(n) = \frac{y_A(n)}{\left(1+\left(\frac{|y_A(n)|}{V_{sat}}\right)^{2p}\right)^{\frac{1}{2p}}} \quad (18)$$

$$y = \text{Convolution}(B, Z(n)) \quad (19)$$

$$yf = \frac{y(n)}{G} \quad (20)$$

$$e = f(n)\text{-}yf(n) \qquad (21)$$

$$W_e(k+1) = W_e(k) + \frac{\beta}{c+|Z(n)|^2} e(k)Z(n) \qquad (22)$$

RESULTS AND DISCUSSION

The results will report the efficiency of the proposed predistorter in the memory and memoryless SSPA using MATLAB simulations. There will be performed the OFDM system over the Additive White Gaussian Noise (AWGN) channels with 16-QAM and 64-QAM modulation schemes. The comparison between SCPWL and AFP is computed to measure the performance of AFP Model regard BER versus SNR (dB) am-AM and AM-PM curves. The size of the frame is equal to 5200. Therefore, the value of the predistorter weights returns to the initial primary value at the beginning of each frame to make the experiment more challenging.

From Fig. 3, the AFP and SCPWL are evaluated under memory and memoryless HPA with 16-QAM and 64-QAM modulations.

From Fig. 3, the AFP has provided BER of 16-QAM performance in the memory HPA more than memoryless HPA because the presence of Memory has a more significant impact and the cancellation of it led to reducing of a nonlinear effect better than Memoryless case. Also, the NLMS algorithm slightly overcomes the LMS algorithm and the improvement is increased as SNR is increased.

The SCPWL gives an unacceptable performance in the case of the HPA memory. It, also, gives worse performance than AFP in the case of memoryless HPA shows in Fig. 4.

The BER performance of memory HPA at 16-QAM is suffering when using SCPWL predistorter. This makes the SCPWL less important in such a circumstance. On the other hand, this method offers better performance in case of memory. In the memoryless HPA, the performance of the NLMS and LMS algorithms are the same. And in case of memory HPA, the BER performance of NLMS algorithm is better than LMS algorithm.

When the 64-QAM is applied, it is noted that the behavior remains similar to Fig. 3 and 4 with an increase in BER because of increasing the degree of modulation (Fig. 5 and 6).

The performance of the AFP has been observed in three curves as in Fig. 7. The first curve represents the effect of nonlinear characteristics with memory and the second is the compensated signal using AFP. However,

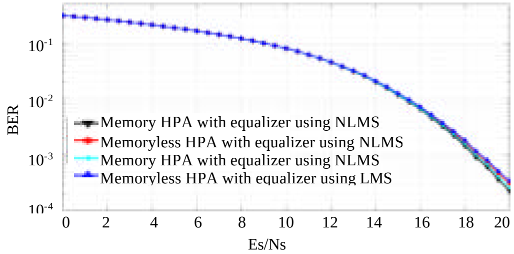

Fig. 3: The BER performance of the AFP

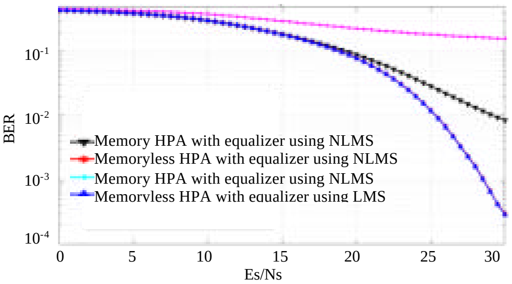

Fig. 4: The BER performance of SCPWL

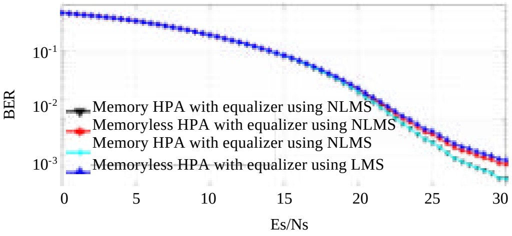

Fig. 5: The BER performance of AFP for 64-QAM

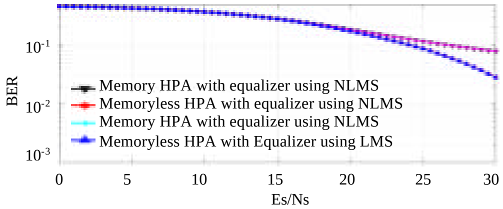

Fig. 6: The BER performance of SCPWL for 64-QAM

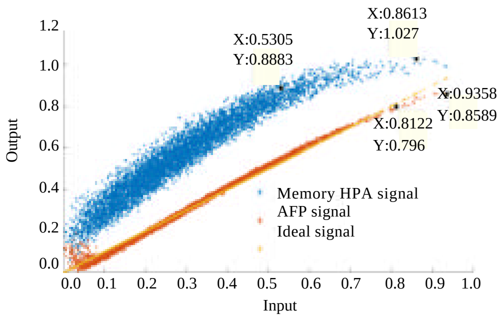

Fig. 7: Illustration fo the performance fo the AFP compared with the memory HPA

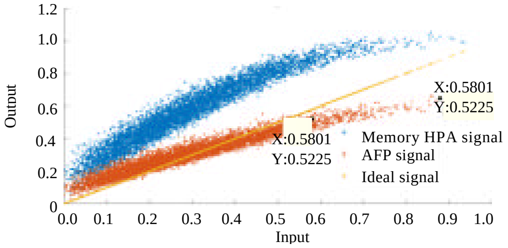

Fig. 8: Illustration the performance of the SCPWL compared with the memory HPA

Table 1: Simulation parameters

Parameter	Disruption
Modulation techniques	16 and 64-QAM
Normalized factor modulation	$0.34\times\sqrt{10}$ and $0.34\times\sqrt{42}$
# of samples/symbol	4 or 6
AWGN channel	Yes
SNR range	[0-30]
Bit rate	10MB/sec
FFT/IFFT	64
Adaptive predistorter of SCPWL Model (NLMS)	$\omega = \omega 0.001/\lambda^1{}_i{}^*\lambda_i+0.1\ \lambda_i e$
Adaptive predistorter of AFP Model (NLMS)	$\omega_e = \omega_e 0.001/Z^1{}_i{}^*Z_i+0.1\ Z_i e$
Frame time	100
Optimum predefined partition point	$\beta_i = [00.351\ 0.61]$
Filter A_0	[100.1]
Filter B_0	[1-0.1]
Filter A_1	[1-0.1]
Filter B_1	[1-0.2]
P	1.5
V_{sat} (A)	1
Weights length of predistortion	11
Frame size	5200

this curve is compared with the third curve as a reference to measure the enhancement of the system. The performance of the IBO and OBO for the first curve were 0.3982 and 0.1814 and for the second curve were 0.2074, 0.1252, respectively.

Also in Fig. 8, the memory SCPWL has observed in the same method as AFP shows in Fig. 7. The SCPWL produces a low performance than AFP as seen in the second curve. The IBO and OBO of this curve are 0.2992 and 0.1229, respectively (Table 1).

CONCLUSION

In conclusion, it is evident that a new method for a digital predistorter has been introduced depending on an adaptive filter equalizer to mitigate the undesired impact of an SSPA amplifier. In addition to this an adaptive SCPWL digital predistorter based the HPA behavior has also been introduced. Both techniques based on NLMS. The performance of HPA in OFDM system is assessed through the BER and SNR under AWGN channel using MATLAB. Two types of modulation schemes (16-QAM and 64-QAM) are used for measuring the performance under different conditions. The results demonstrate that the APE gives the best results than SCPWL in two cases (memory HPA, memoryless HPA). APE introduces the best result in a state of memory HPA effects than nonlinear HPA effects. Beside, the SCPWL provides a worst-case regarding the memory HPA effects. SCPWL gives a good result in the memoryless HPA effects than memory HPA effects but down than APE. Finally, it can be stated that the AFP has improved the performance of the memory HPA over memoryless HPA. So that, the SCPWL and AFP are considered as a memoryless and a memory predistorters respectively.

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