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A novel Technique for Linearizing Digital Pre-distortion in Power Amplifiers for OFDM Applications

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ABSTRACT

In this paper, a novel technique is proposed for linearizing digital pre-distortion in power amplifiers for OFDM systems. For this purpose, a hybrid technique comprising search table method and polynomial method is employed such that as few as hardware are utilize in implementation in order to not only decreases computational complexity but also leads to a fast response capability. Furthermore, least mean square (LMS), as a competitive method, was employed in the proposed technique. Coefficients of look-up table are estimated by LMS method as a forward program with the least error amount in order to estimate modulator output of OFDM. In addition, designing of several RF power amplifiers and their linearization unit in ADS software results in elimination of non-linear distortions of these amplifiers by linearizing unit, and yet various realistic involved phenomena in base-band pre-distortion system design, including memory effect, antenna mismatch, and etc., are studied. Measures such as ACPR were adopted for the purpose of linearization measurement and comparison. High The peak-to-average power ratio (PAPR) is one of the biggest problems in OFDM systems that by combining these techniques, we improve it. The obtained results of the proposed technique are presented both by look-up table and frequency spectrum of output signal. The results also indicate appropriate performance of the proposed technique. Simulations were carried out on ADS software, while final signal output was extracted by MATLAB.

Keyword:
Digital Pre-distortion, Power amplifier, Linearization, OFDM, Look-up table method, Polynomial method

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INTRODUCTION

In recent years, many attentions have been paid on high spectrum performance by many digital radio system designers. In order to increase data speed per frequency band, systems with multi-level modulations, including M-QAM, OFDM, and etc., have been extended. OFDM method is a very proper technique in high rate sending and optimum band utilization, enabling it to be robust against multi-path distortions. It is, thus, utilized in many broadcasting stations[1]. However, the main problem of this method is the peak-to-average power ratio signal to mean power signal, which results along with non-linear characteristics of power amplifier in output distortion. Furthermore, due to wideness of signal band of OFDM, non-linear characteristics of power amplifier AM/AM/ and AM/PM are made frequency dependent (memory) [2]. So far, various techniques have been proposed to overcome this problem. As such, design improvement methods, the peak to average power ratio decrease methods, and linearization methods applied on amplifier. Linearization methods are: power storage method, feedback method with modulation and push, Polar and Cartesian loop [3], linear amplification with non-linear component (LINC) method [4], forward method, pre-distortion method. Pre-distortion method is the simplest linearization method in terms of concept. In this method, a distortion characteristic is constructed. This is precisely the supplement of distortion characteristics of RF power amplifier which are cascaded in a way that the overall input-output distortion is negligible [5]. Pre-distortion methods consist of analog and digital pre-distortion. Digital pre-distortion (DPD) are: (1) look-up table and (2) a polynomial function expressed by polar coordinates (amplitude and phase) or Cartesian coordinates [6]. So far, various applications of these methods and/or a combination of them are presented, which will be mentioned in the following.

In paper[7], is presented a combined approach to digital predistortion (DPD) and crest factor reduction (CFR). The new CFR is structured similar to DPD and is implemented by introducing a steady-state offset into the DPD coefficients. The DPD and CFR coefficients are estimated using separate adaptive processes but applied to the transmission path in a common module. In [8], a Slow Envelope Dependent digital pre-distortion (SED-DPD) was proposed capable of compensating non-linear distortion and memory effects. In [9]-[10], the performances of three different polynomial formats for PA pre-distortion are first discussed and pick out the most effective polynomial formats for PA pre-distortion and the computer simulation purposes to evaluate is presented methods. In paper [11], is presented a new wideband digital feedback pre-distortion (WDFBPD) technique by combining the inverse memory structure with the DFBPD structure. This technique not only maintains the advantages of the DFBPD technique, but also suppresses the memory effects. In [12], a 2-D modified memory polynomial method was proposed in order to compensate non-linear distortion in simultaneous dual-band transmitters. In [13], a novel pre-distortion model using orthogonal proposal was proposed which is composed of a ZERNIKE polynomial. ZERNIKE polynomial is a sequence of polynomials perpendicular to unit disc. In [14], a new and precise model with less complexity was that this model utilizes a parallel combination of look up table (LUT) and a memory polynomial MP-EMP, called PLUME. In [15], a 2-D MSP model was presented for digital pre-distortion. This model indicates comparative performance using conventional polynomial models such as general memory polynomial (GMP) by significantly less parameters. In paper[16], is presented a new mathematical description of the relationship between injected and output third-order inter-modulation (IM3), to predict the injection signals required for pre-distortion correction of a power amplifier (PA), without manual optimisation. Also, a new concept of interactions and an iteration algorithm are also presented in order to improve this technique. There are three new methods presented In this paper. In [17], two algorithms were analyzed. In addition, a combined algorithm comprising pre-distortion algorithm of look-up table and memory polynomial was introduced. In [18], a new model named TNTB was proposed. This model comprises of three models of PTNTB, RTNTB, and FTNTB. These proposed models obtain a more general model of non-linear distortion and memory effects compared to the previously presented models.

In this paper, a method by combining of look-up table and polynomial methods will be proposed in which look-up table coefficients is estimated by LMS by a forward program with the least error rate. This not only leads to increased convergence of algorithm, but also results in less hardware usage in implementation, making it less computationally complex and fast response capability. Furthermore, OFDM signals were used for linearization purposes. Operating frequency is close to 950MHz and OFDM 64-QAM signal is used for data rate increase. In the following, description of polynomial method, look-up table method, proposed algorithm, and simulation results will be addressed. Conclusion and references are the final parts.

1. Overview on Digital Pre-distortion(DPD) Models

1.1. Adaptive Digital Pre-distortion for linearity Power Amplifier (PF)

Linearity of pre-distortion as shown in Fig. 1, can be utilized in linearity more than one broad bandwidth. This can be obtained through signal pre-distortion before amplification by reverse characteristics of pre-distortion imposed on power amplifier. Thus, power amplifier (PA) output is a linearization function of a pre-distorter input (eq.1.):

$$y(t)=f(x(t)) \qquad (1)$$

$$y(t) = f[g(\omega(t))] = k.\omega(t)$$

Adaptive pre-distortion characteristic is to minimize mean error square between PA output and a small version of base band signal using LMS algorithm(Fig.2). This system's simulation indicates that this system is capable of reducing 40 dB in ACPR, reducing 3rd and 5th inter-modulation distortion (IMD). [19], [20].

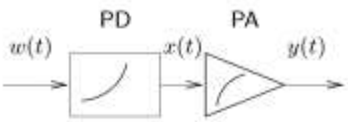

Fig.1. Base Diagram for Pre-distortion System

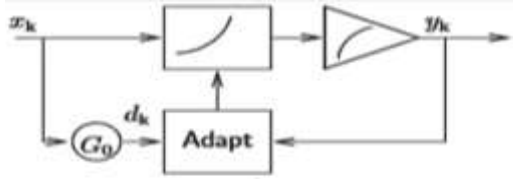

Fig.2 . Block Diagram for Pre-distortion System by adaptive LMS method

1.2. Digital Pre-distortion Technique of high-voltage Power Amplifier using Look-up Table

Fig.3 shows DPD block diagram comprising a DAC, an ADC and one FPGA in which DPD is programmed and delay and memory coordination block diagrams of LUT are constructed. At the instant $t=t_0$, FPGA sends an ideal sine signal U(t). The output of this non-linear system is constant time extendable by Tailor expansion of U(t) in which A_1, A_2 , and A_3 are first, second, and third gain of non-linear amplifier[21]. (eq.2.):

$$o(t) = A_1 . u(t) + A_2 . u(t)^2 + A_3 . u(t)^3 + \ \ldots \qquad (2)$$

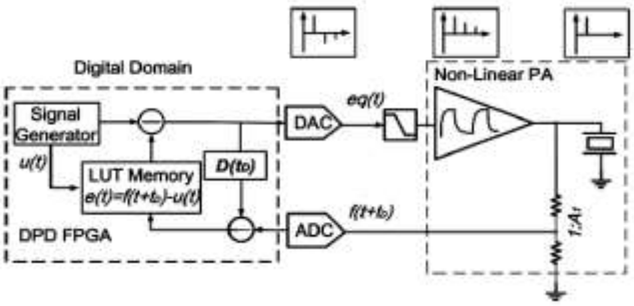

Fig.3. Block diagram of DPD System of Look-up Table

Digital pre-distortion based on look-up table method for ultrasonic transmitters, DPD scheme perform in the digital amplitude And Implementation of this method is divided into calibration and evaluation phases.Fig.4. In calibration step, using least mean square of error, system searches optimal error and stores the error in look up table memory. In evaluation phase, equalized input signal phase is added to the input. Then, the equalized input is converted to analog signal using DAC and transmitted to AB class for elimination of non-linear characteristic. In this algorithm, both signals work with constant amplitude.[6], [21].

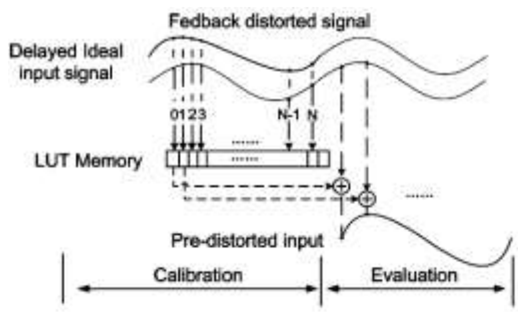

Fig.4. Pre-distortion System Effect on Harmonics and Calibration and Evaluation Phases in LUT Method

1.3. Digital Pre-distortion (DPD) System by Polynomial Method

Polynomial digital pre-distortion system is shown in Fig.5 and Fig.6 System input will be modulation signal quadrature amplitude modulation (QAM). At first, base-band signal will have bandwidth of 150 kHz. This signal is distorted to a modulated analog signal which was prior introduced and amplified into a digital signal via a polynomial pre-distorter. Base-band signal is converted into polar coordinates in order to distort independently into AM-AM and AM-PM. Power amplifier (PA) output is sampled using an analog-digital converter (ADC), and then it is utilized to update pre-distortion in relation to pre-distorter input. Least mean square (LMS) is used to adjust polynomial coefficients. Thus, error mean square of each cycle is computed and compared with previous cycle's mean square error (MSE) using LMS algorithm. [9-10],[21]

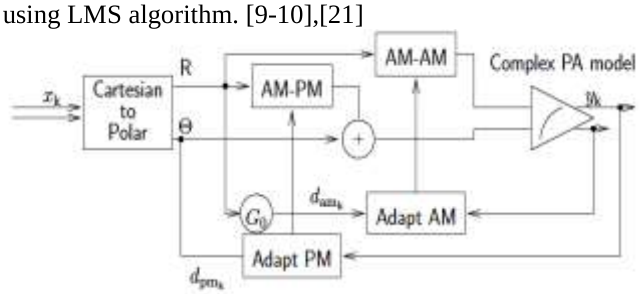

Fig.5. System diagram of polynomial method for simultaneous improvement of distortion amplitude and phase

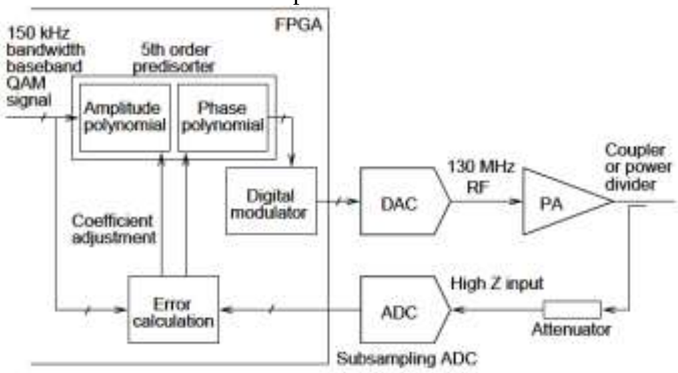

Fig.6. System diagram of polynomial method Pre-distortion and Implementation Procedure

2. Proposed Algorithm for Linearity of power Amplifier

RF power amplifiers linearization in order to eliminate negative effects of non-linear distortions resulting from these amplifiers is one of the modern electronic and communication engineering issues. In this paper, a novel hybrid method comprising polynomial method and Look-up table method is used in order to linearization pre-distortion in power amplifiers based on the proposed adaptive LMS algorithm. In this method, in order to estimate output modulator of OFDM system, coefficients related to look-up table are estimated by LMS method as a forward programming with the least rate error. In addition, OFDM signals are used for linearity purpose. Operating frequency is close to 950 MHz and OFDM 64-QAM signal is used for data rate increase. In summary, the hybrid look-up table and polynomial are given as: 1) Before data storage related to input signal distortion, data is improved by a polynomial algorithm in polynomial block, then it is stored for input signal distortion in LUT memory. 2) Signal phase is used as a memory key for data revision. 3) The attenuated signal by polynomial algorithm is used in the related block for generation of reversed distortion of unwanted harmonics. 4) It should be noted that, high memory is required in the absence of polynomial algorithm. In addition, application of this algorithm leads to reduced signal for updating look-up table. In fact, simultaneous application of look-up table and polynomial algorithm results in reduced time to reach optimum solution.

3. Simulations and Discussions

Various steps should be considered in design of a power amplifier. These steps are: DC simulation to find system operating point, small-signal simulation to achieve S-parameters values and estimate stability model in corresponding frequency and bias range, adaptive networks of input and output impedance using simulation test Load-pull to find the best solution. Finally, overall system should be optimized in order to have output power, gain, and efficiency.

3.1. Load-pull Simulation

The aim of Load-pull test is to find optimum load value maximizing output power and efficiency. Thus, various values are dedicated to load impedance in order to optimize this value. Then, adaptive output circuit for optimum impedance load is designed. Before implementation of simulation, several parameters are given as follows:

RF_{freq}=950MHz , V_{high}=28V , V_{low}=5V , Gain_Comp =1 dB, P=30dBm, Z_0=50Ω.

These values result in optimum load in 1dB compactness. Load-pull simulation results are shown in Fig.7 . Optimal load is Z_l=7.161+j2.480 Ω, resulting in optimum output power of 35.85dB and PAE=2.31%. Load-pull is one of the best methods for output power calculation.

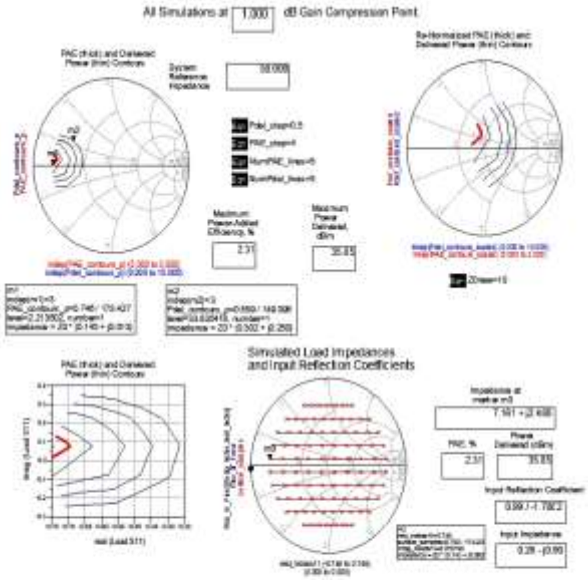

Fig.7. Load-pull Simulation Results

3.2. Designing Input and output matching network

One of the most important parts of the transmitter is power amplifier, thus power amplifier must have proper gain and generate less noise as possible. The power amplifier must also act as linear as possible. Linearity is determined with two parameters of third-order intercept point (IP3) and gain one dB compression point (P-1dB). In addition, wave of the power amplifier should not be reflected the power amplifier to the input or output of the power amplifier, and in order to receive and transfer maximum power, should be set impedance matching at the input and output of the power amplifier. Power consumption is considered an important parameter in designing the amplifier, so that the power amplifier should consume small power as possible. The most important point in all these parameters, they are in contrast with each other.Thus establishment and ensuring is that appropriate values all the above parameters, is time consuming and almost difficult to do. So among all the parameters checked, impedance matching is of the particular importance and must of power amplifier designing methods are based on their quantity and the optimization. Given the output load and reference impedance of 50Ω, the output reflection coefficient would be as(eq.3.):

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{7.161 + j2.480 - 50}{7.161 + j2.480 + 50} = 0.75\langle 174. \quad (3)$$

The output reflection coefficient is stability zone. Load design perform using Smith chart by an open circuit's parallel stop and series stop and the following results obtained.Fig.8 .

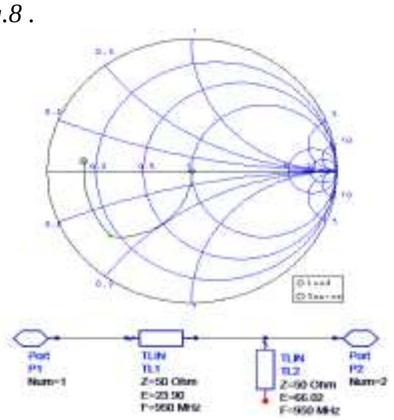

Fig.8 . The ouput matching circuit

For the The ouput matching circuit (eq.4.) :

$$\Gamma_{in} = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L} = 0.976\angle 178.564 \qquad (4)$$

Due to the choosing of matching circuit for the input it approaches to transistor instability region, Fig.9 would be as. The available values are as follows:

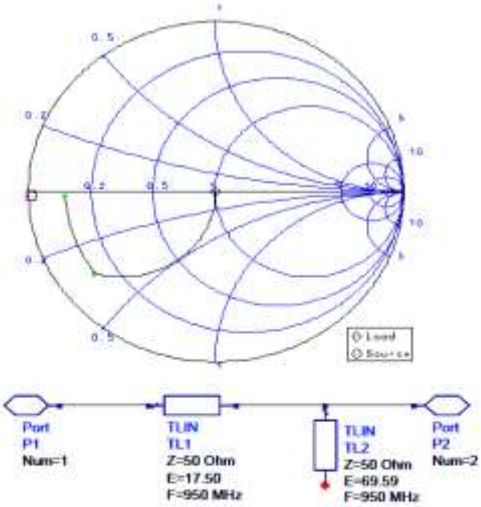

Fig.9 . The output matching circuit

Regarding the results of the matching network, although maximum power is transmitted, but gain of the circuit would be far from the desired value and reduces gain. Therefore, we optimize the circuit for better performance.

3.3. Designing of Final Circuit of Amplifier

The final designed circuit is shown in Fig.10 . In order to design amplifier, first to prevent memory effects a passive bias circuit, consisting of inductors and capacitors, is used which is selected by operating frequency 950 MHz.

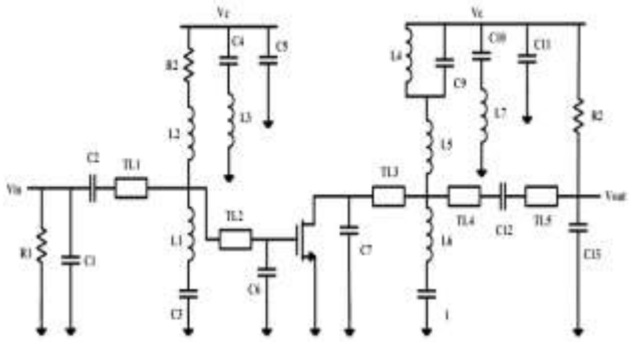

Fig.10. Schematic of Final Circuit Amplifier

Considering designed final circuit and harmonic test of circuit, the following results are obtained. Fig.11. High the peak to average power ratio (PAPR), is one of the main challenges in OFDM systems, affecting system performance. In most of the reported literature, this problem is considered as the most important problems in OFDM. In this paper, high PAPR problem is resolved by a combination of the proposed methods.

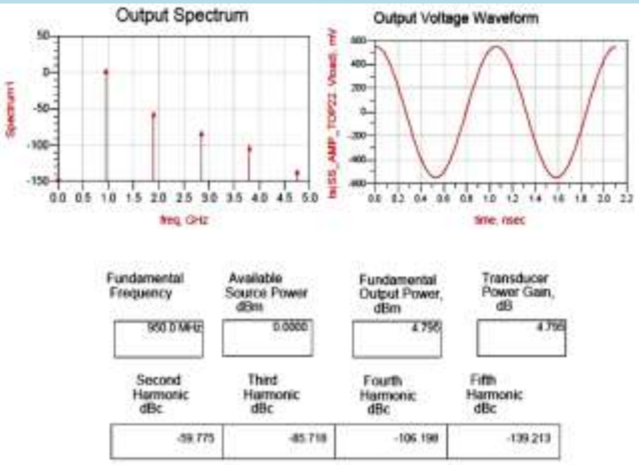

Fig.11. Harmonic Test Results of Amplifier

3.4. One-Tone Test

In order to study the effectiveness of the amplifier design, considering output power and efficiency, one-Tone Test was carried out with power sweep from 0 to 10 with a 5dB step and from 10 to 25 with 1dB step. Simulation results are shown in Fig.12 . Considering 3rd harmonic, it can be seen that there exists a proper difference between fundamental frequency and 3rd harmonic. Fig.13. illustrates input and output waveforms of one-Tone Test. Thus, In order to study the linearization of transistor as the most important issue in multi-user applications, intermodulation terms, are addressed. For this purpose, *Two-Tone Test*is performed. 10kHz Tone spacing with power sweep from 2dbm to 20dbm is considered. Also In this test, the ratio of intermodulation, which is the difference between fundamental frequency and 3rd intermodulation term, that express the ciruit is designed to increase efficiency.

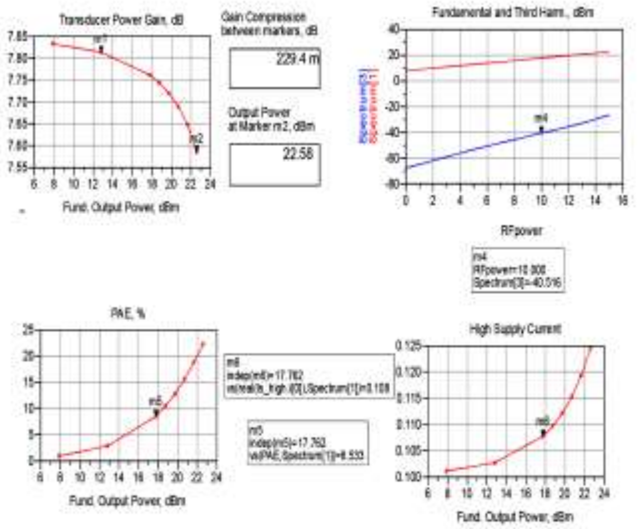

Fig.12. Simulation results of one-Tone Test

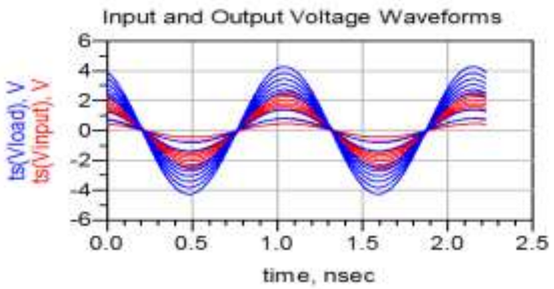

Fig.13. Input and Output Voltage Waveform of one-Tone Test

3.5. Generation of OFDM Signal using IEEE Standard and Amplifier Effect on this Signal

Simulation of modulated OFDM signal with IEEE 802.11a standard is illustrated in Fig.14 . Simulation of this simulation is depicted in Fig.15 .

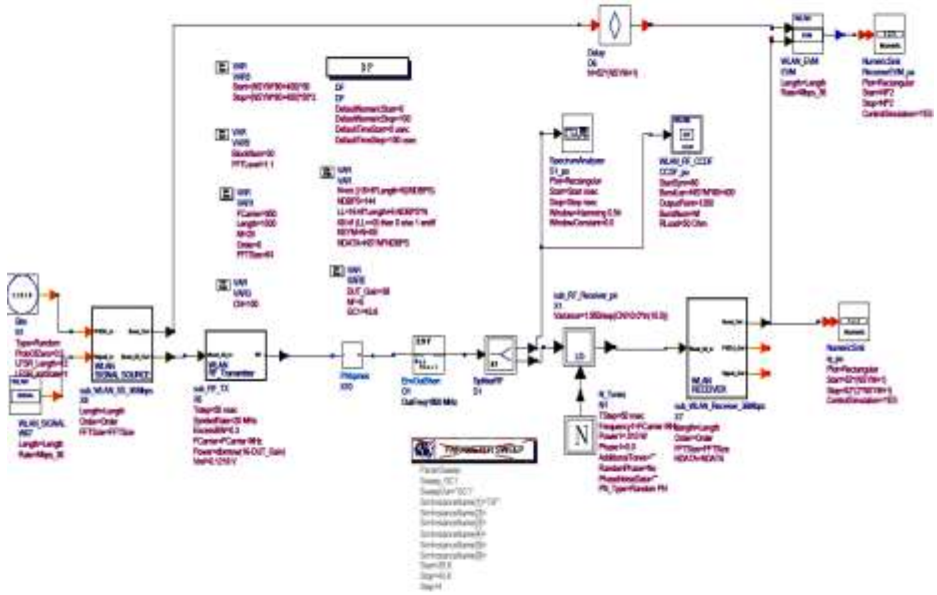

Fig.14. Simulation and test Signal OFDM Adjustments in Amplifier HP-MOS

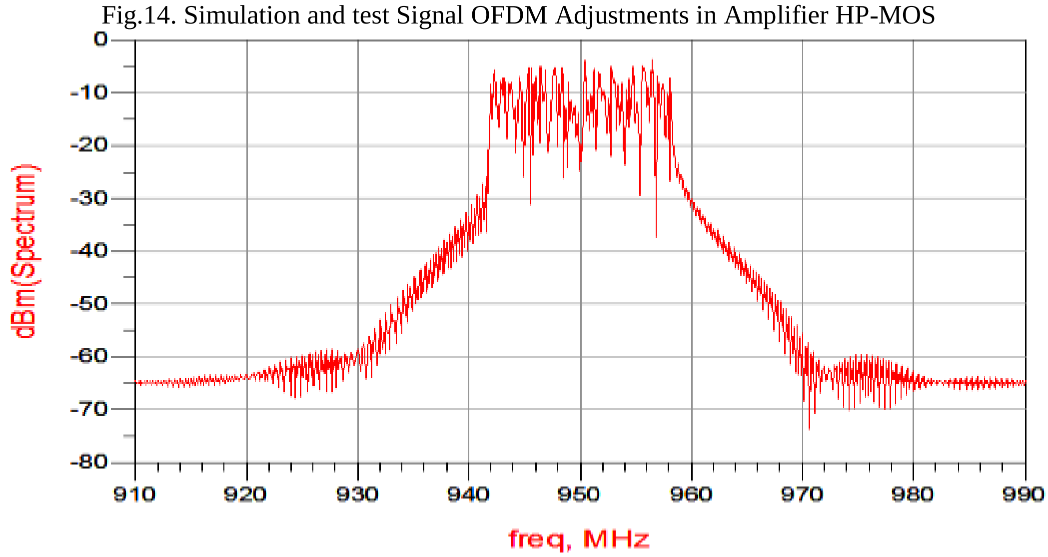

Fig.15. Simulation of Modulated OFDM Signal

Furthermore, in this section, non-linear effect of amplifier on parameters such as CCDF and RF output spectrum are examined using Agilent EESOF ADS. IEEE 802.11a standard uses OFDM-64-QAM signal for increasing data rate its push with regard to man line of power signal has large variations. In order to depict these changes, PAPR measure was proposed. Possibility distribution PAPR is usually expressed as CCDF signal. CCDF is more common than CDF and is obtained by subtraction of CDF (possibility supplement CDF).

CCDF diagram is shown in Fig.16 for this signal in the absence of amplifier and in the presence of amplifier with residue power of 5dB. Horizontal axis indicates power signal higher than power signal in terms of dB, while vertical axis demonstrates possibility percentage.

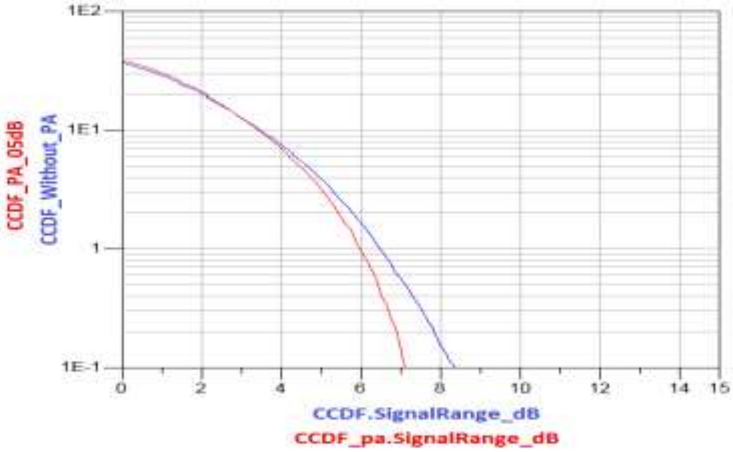

Fig.16. CCDF for two cases in the absence of amplifier and in the presence of with residue power ddB

Also, output spectrum of modulator and amplifier without digital pre-distortion is shown in Fig.17 and Fig.18 .

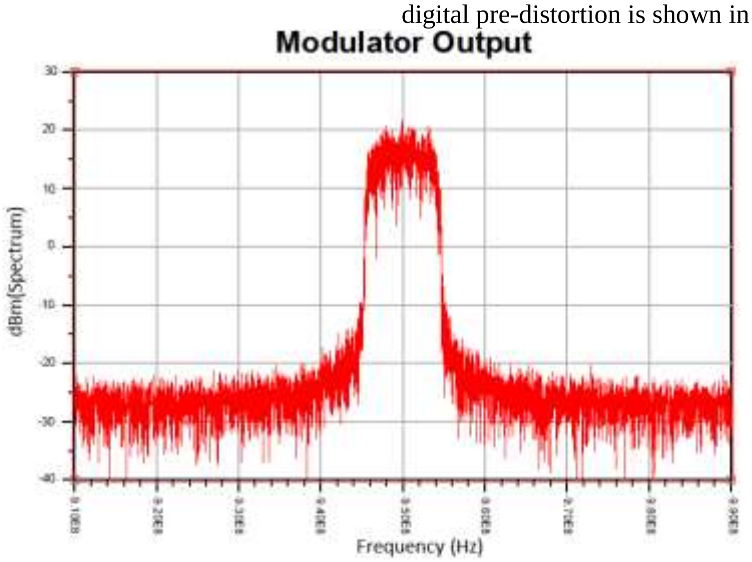

Fig.17. Modulator Output without digital-Pre-distortion

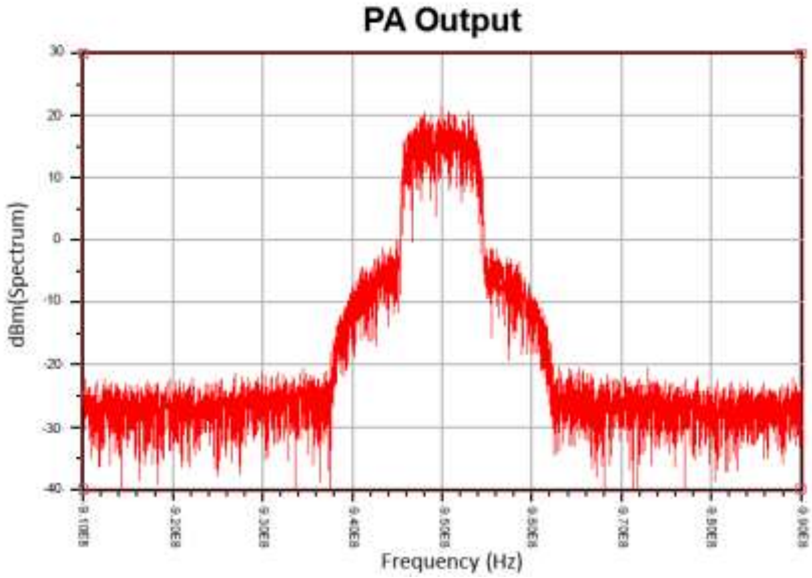

Fig.18. Amplifier Output without digital-Pre-distortion

3.6. Input signal and Feedback Signal in time Domain

Fig.19 illustrates input signal amplitude in terms of sending symbols in time domain. In addition, output feedback signal used for error calculation and pre-distortion update is depicted in terms of input symbols in Fig.20 .

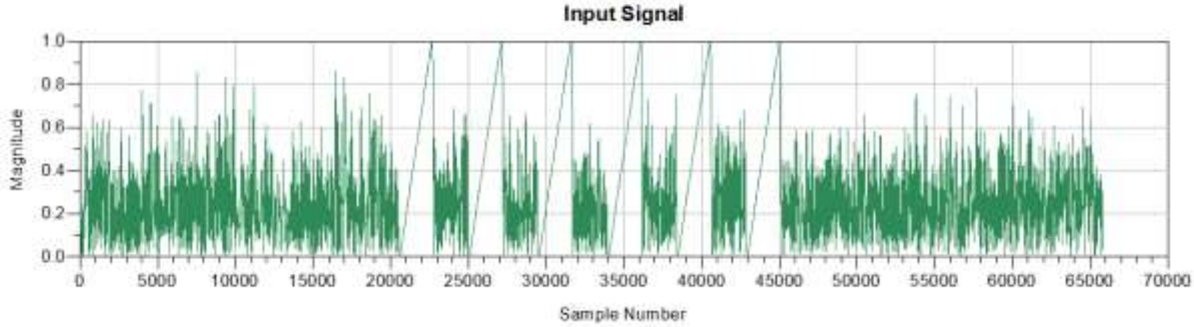

Fig.19. Input Signal in Time Domain

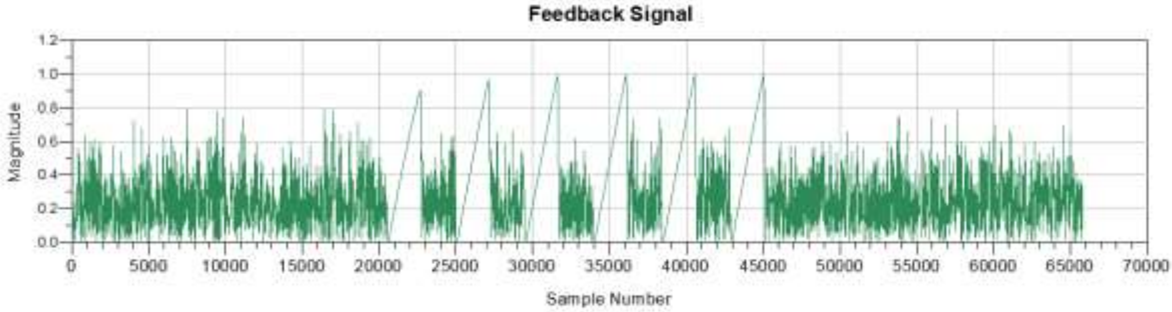

Fig.20. Feedback Signal in Time Domain

3.7. Look-up Tabled based on Proposed Method

In this method, transmitted signal has an iterative pattern in the each pulse cycle iteration. This only requires first cycle error data to store in memory. Unless the user change signal adjustment, this issue by RF applications with 2-D memory (I and Q as the address words), lead to deceased LUT size. In addition, methods including multi-level LUT and complex-gain-based DPD algorithms can reduce memory size. The capacity of used memory for updating error and application of distortion on input is 256. In Fig.21 and Fig.22 the used memories for each symbol are shown. Fig.23 and Fig.24 depict size and phase of look up table for symbols. In addition, signal correlation is illustrated in Fig.25 for signal delay of input and feedback.

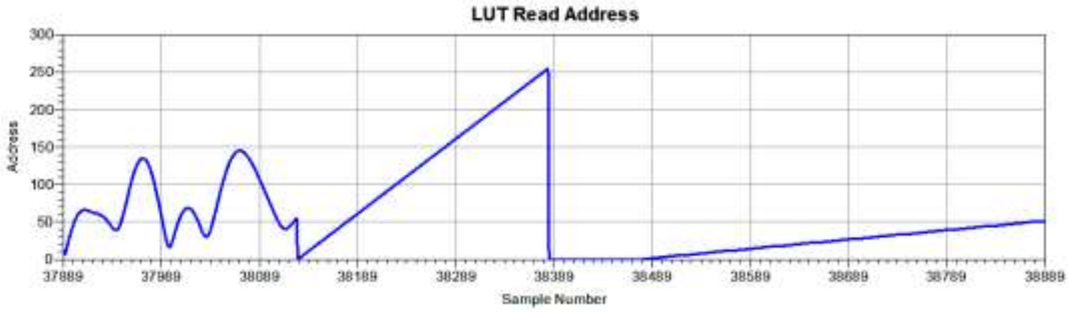

Fig.21. Reading address of look-up table based on proposed estimated method

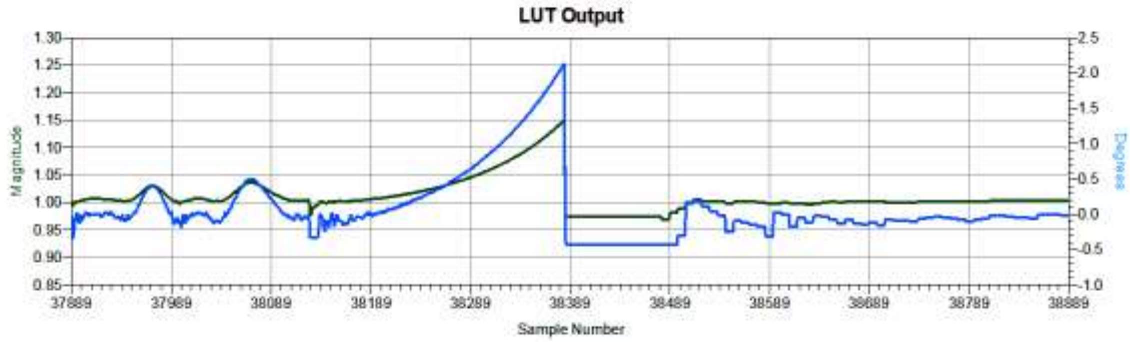

Fig.22. Output of look-up table based on proposed estimated method

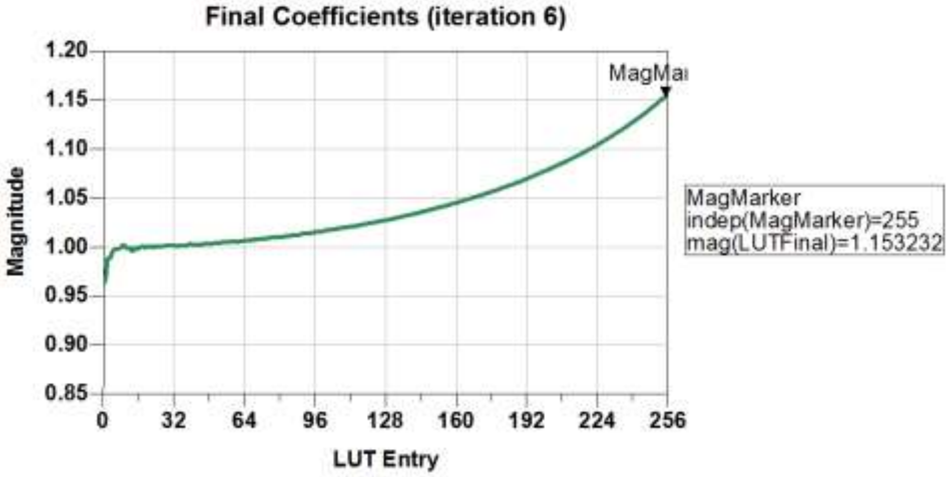

Fig.23. Size of look up table based on proposed estimated method

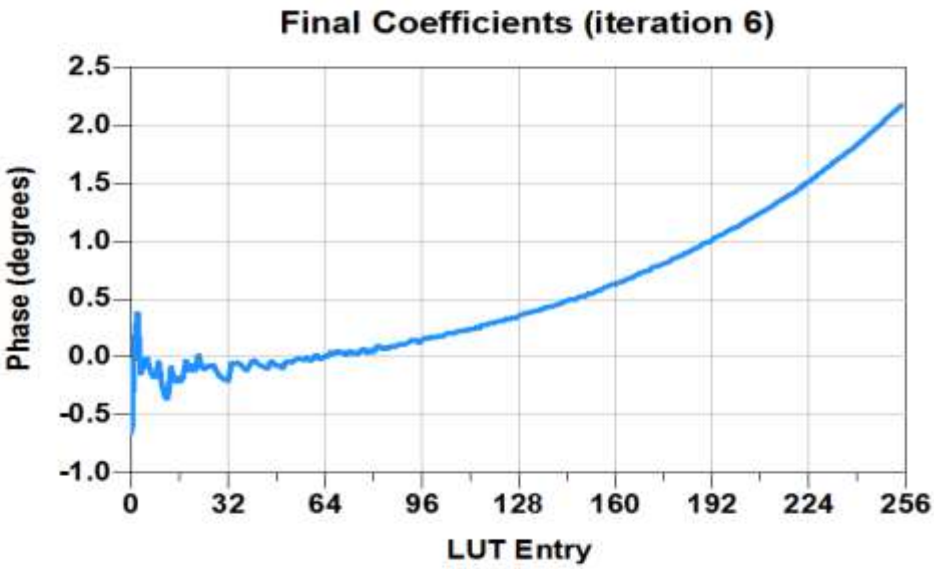

Fig.24. Phase of look up table based on proposed estimated method

Index	CoarseAdjustDelay	FineAdjustDelay
65791	2	4

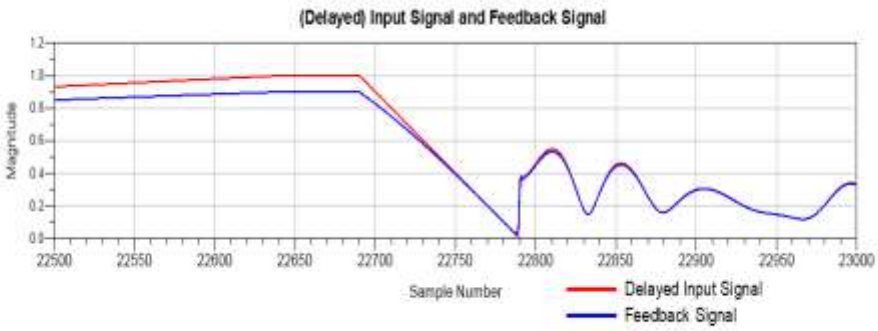

Fig.25. Signal correlation of input and feedback

3.8. Modified Output Spectrum based on Proposed Adaptive Method

Fig.26 and Fig.27 show output spectrum of amplifier before and after application of proposed digital pre-distortion (DPD), respectively. Modulator output is transmitted to the amplifier by applying of digital pre-distortion system. This, after utilization of distorted input, amplifier output is obtained without distortion of extra harmonics. As can be seen, output spectrum improves linearization of transmitted signal in the presence of pre-distortion system and decreases inappropriate harmonics.

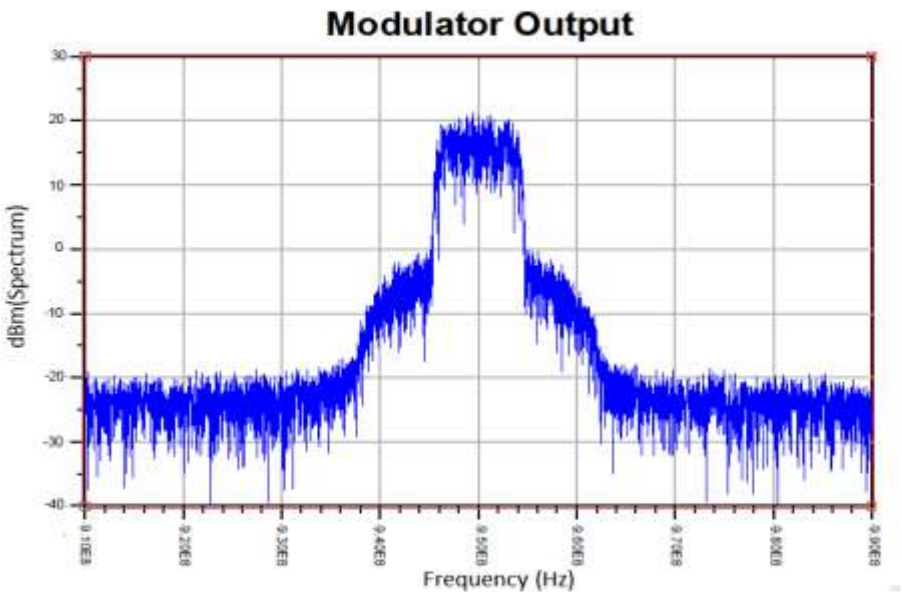

Fig.26. Amplifier output before applying DPD system

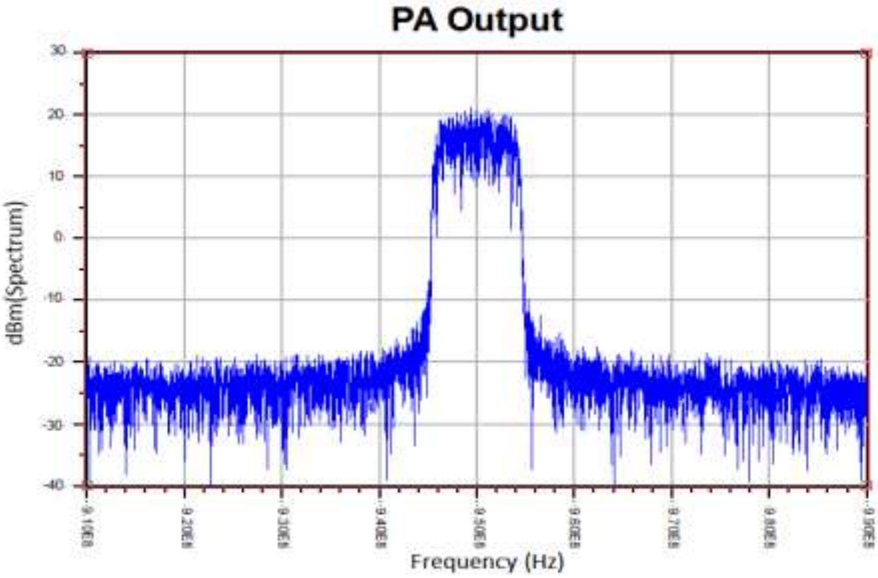

Fig.27. Amplifier output after applying DPD system

3.9. Results of the current study compared with other references

In this section, the results obtained from combined method presented in the current paper, compared with results some of the references. In [22], According to the results that benefited from a new hybrid method based on analog pre-distortion base techniques from third and fifth inter-modulation and second harmonic injection, concluded that additional harmonics have been weakened, But it can be observed that the harmonics have not been weakened completely in the system. Fig.28. In paper [4], a whole overview of the most important determining issues in pre-distortion and transmitter architecture presented using three methods of LINC and ET and PT in the base-band (BB) signal processing and FPGA design. Results indicate reduced additional harmonics and improved linearity of the system. But use of three methods simultaneously led to increased computational complexity of the system .Fig.29. It should be emphasized that besides the elimination of additional harmonics and eliminated the linearity of system those methods which reduce the computational complexity should be used and in this paper, we achieved the desired results.

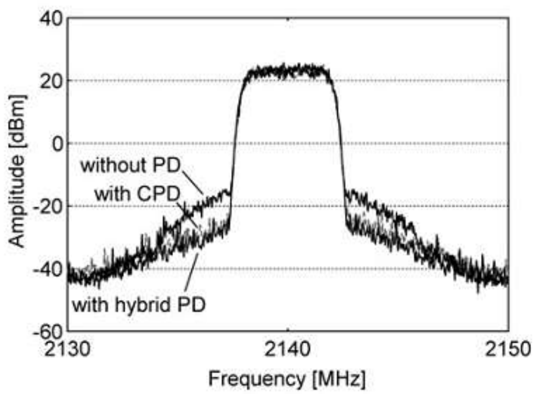

Fig.28. Output power spectra for W-CDMA signal [22]

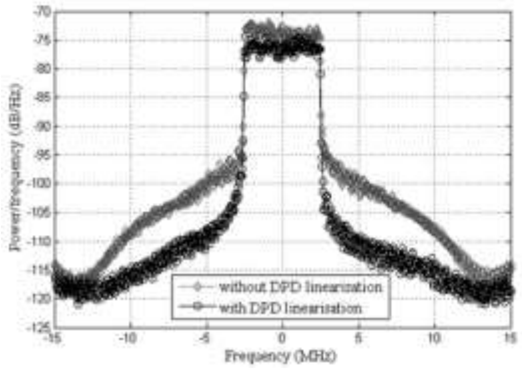

Fig.29. Output power spectra for a class AB PA [4]

4. Conclusion

In this paper, a new technique based on the combination of polynomial method and look-up table was proposed. This leads to as much as reduced hardware in implementation in order to have high response speed. With the aid of Agilent EESOF ADS software, the effect of power amplifier such as OFDM signal parameters, i.e., frequency spectrum and CCDF, were examine. Furthermore, in this paper, a novel linearization pre-distortion method in power amplifier based on LMS technique, as an adaptive one, was use. Consequently, in order to estimate modulator output of OFDM system, coefficients related to Look-up table by LMS technique were estimated as forward program with the least error value. The results of this method were demonstrated both in Look-up table and output signal frequency spectrum. As output spectrum improves linearization of transmitted signal and eliminated inappropriate harmonics. The results indicated high efficacy of the proposed method. ADS software was used as a simulation tool of power amplifier in OFDM system, while final results of signal was obtained by MATLAB. On the other hand, for Linearization of pre-distortion in power amplifiers, techniques combined with adaptive filters and artificial intelligence algorithms can be used to properly to eliminate harmonics, and to improve estimates of polynomials using other types series like wavelet functions or Bessel series instead of power Series, With a higher degree of orthogonality and active matching circuits employed to improve linearity and reduce distortion of power amplifier and I will continue to work on them in the future.

Appendix

LMS: Least Mean Square
DPD : digital predistorter
OFDM : Orthogonal Frequency-Division Multiplexing
PAPR : Peak to Average Power Ratio
DSP : Digital Signal Processing
Lut: look-up table
RF : Radio Frequency
FPGA : Field-Programmable Gate Array
SED-DPD : slow envelope dependent digital predistorter
PA : Power Amplifier
IMD : intermodulation distortoin
QAM : quadrature amplitude modulation
MS-DPD : mixed-signal digital predistorter
PLUME : Parallel-LUT-MP-EMP
2-D-MSP : Two-Dimensional Memory Selective Polynomial
GMP : generalized memory polynomial
TNTB : twin nonlinear two-box
FTNTB : Forward twin nonlinear two-box
RTNTB : reverse twin nonlinear two-box
PTNTB : parallel twin nonlinear two-box
CCDF: Complementary Cumulative Distribution Function
CDF: Cumulative Distribution Function
DAC : Digital to analog converter
ADC : Analog to Digital converter
ACPR: Adjacent Channel Power Ratio
CPD : cuber predistortion
ET : Envelope tracking
LINC : linear amplification with non-linear component
BPC : basic predistortion cell
PT : polar transmitters
MSE : mean square error

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