Characterization of RF Power Amplifier for Narrow and Wide Band Memory Polynomial Implementations

G. Mohiuddin^{1,*}, M. Mujtaba Shaikh², Safia Amir Dahri², Fozia Panhwar², Kamran Ali Memon², Nuzhat Madina²

¹Department of Electronic Engineering, QUEST, Nawabsah, Pakistan.

²Department of Telecommunication Engineering, QUEST, Nawabsah, Pakistan.

*Corresponding author: mohiuddin.24@iiee.edu.pk

Abstract

Linearly efficient Radio Frequency (RF) power amplifiers have a tremendous role in wireless communication and radar systems as they lie at the front end of most RF systems. In today's world of wireless communication, it is not an easy task to design a RF power amplifier that is linearly efficient. There are two main key challenges that one faces for making RF power amplifier's behavior linearly efficient. First is to characterize RF power amplifier's coefficients smartly. Second is to propose an approach that works on input signal and makes its behavior inverse to that of the designed amplifier behavior so that overall response of the system becomes linear. For countering first challenge, most advanced universally accepted algorithms such as memory polynomial, generalized Hammerstein, cross-term memory polynomial and cross-term Hammerstein are implemented to design RF power amplifier models. For countering second challenge, latest DPD algorithms are implemented which make net response of a system linear. The memory models for modelling RF power amplifier are categorized for narrowband and wideband applications. The narrowband power amplifier models include memory polynomial and cross-term memory polynomial models; whereas wideband power amplifier models include generalized Hammerstein and cross-term Hammerstein models. In this paper, various performance indicators such as Standard Deviation (SD), Third Order Intercept (TOI), Intermodulation Distortion Products (IMD3), Modulation Error Ratio (MER), Spurious Free Dynamic Range (SFDR) and Error Vector Magnitude (EVM) are used to characterize RF power amplifier for both narrow and wide band applications. The simulation results show that under narrowband applications, cross-term memory polynomial model works best as it has least standard deviation and also satisfy other performance parameters up to a desired level with and without digital predistorter algorithm implementation. While for wideband applications, cross-term Hammerstein model satisfies the performance measuring parameters excellently.

Keywords—Memory polynomial, cross-terms, predistortion, harmonic generation, spectral regrowth, power amplifier.

1 Introduction

NORMALLY there is a compromise between linearity and efficiency when we are talking about RF power amplifier's response. If power amplifier is being operated in linear region, than it is less efficient. However in non-linear region, it has high efficiency level [1]. It is supposed to be a highly attractive option to increase efficiency of RF power amplifier because by doing so the efficiency of transmitters and communication systems can also be improved [2]. A designer's approach is to model such an amplifier

which is both linear and efficient. So, to achieve that goal, first of all the correct modelling of power amplifier's coefficients is necessary by implementing best coefficient computational algorithms. Second step is to make net response of amplifier linearly efficient which can be done by implementing some sort of linearity algorithms as shown in Figure 1 [3]. Authors in [1] have compared five Volterra series-based methods for Normalized Mean Square Error (NMSE) and Adjacent Channel Power Ratio (ACPR) with DPD algorithm. The work in [2] is about a unique class of models which has been proposed for Doherty power amplifiers having strong memory effects driven by LTE wideband waveform. Only Cross-term Memory Polynomial model was demonstrated for characterization of RF power with

ISSN: 2523-0379 (Online), ISSN: 1605-8607 (Print)

DOI: <https://doi.org/10.52584/QRJ.1901.03>

This is an open access article published by Quaid-e-Awam University of Engineering Science & Technology, Nawabshah, Pakistan under CC BY 4.0 International License.

Fig. 1: Top: Input/output power characteristic (orange) of a nonlinear power amplifier and the ideal linear characteristic (black). Bot-tom: Input/output power characteristic (orange) of a nonlinear power amplifier showing memory effects, the static DPD characteristic (blue) to achieve the ideal linear characteristic (black) [3].

and without DPD algorithm under different input signals in [3]. The models like Wiener, Classical Wiener, Parallel Wiener, Hammer-stein and Memory Polynomial were proposed in [4]. It had been proved in [4] that by introducing cross-terms (i.e. leading and lagging terms), memory polynomial model's performance can be improved further, so a new model came into being by the name Cross-term Memory Polynomial model. As we know RF power amplifier's behavior is nonlinear and to make net response of the system linear, different techniques were proposed like Feed-forward, Linear Amplification with Nonlinear Components and Digital Pre-distortion [4]. Similarly, only memory polynomial model with or without DPD algorithm was implemented by elaborating its performance on parameters like TOI, EVM, MER, ACPR in [5]. Memory Effects that limit the performance of DPD algorithm were successfully countered by using memory polynomial approach for RF power amplifiers in [6]. By using Memory Polynomials techniques, a digital baseband pre distorter technique was constructed in [7]. A DPD approach modeled on the basis of indirect learning architecture implemented by a recursive predictive error method (RPEM) was discussed in [8]. Gozde Erdogan in [9] proposed different DPD algorithms, almost all of them were based on above discussed characterization models for RF power amplifiers and elaborated

their performance considering the parameters ACPR, IMD3, SFDR and others.

The authors have discussed the fundamentals of RF signal techniques in [10]. The often neglected even-order terms in baseband were focused by power amplifier in [11] by deriving explicit passband-baseband pairs for quasi-memoryless polynomial and volterra series. Haoyu Wang, et. al. in [12] proposed an approach for ex-traction of digital predistorter model of RF power amplifiers utilizing only 1-bit resolution analog to digital converters in the observation path to deal with the error signal between input and output signals, the DPD coefficients were estimated then on the basis of direct learning architecture by using measured error signal. The digital predistortion techniques with segmentation were presented in [13] by doing comparative analysis of global DPD with two segmented approaches such as Vector-Switched DPD and Decomposed Vector Rotation DPD with the support of experimentation on a 3 ways Doherty Power Amplifier which is strongly non linear. A joint-polynomial LUT predistorter algorithm was proposed in [14] which offers a better rejection of error vector magnitude distortion and an improved adjacent channel leakage ratio upto 30-40% for wideband code division multiple access at minimum usage of memory. The proposed algorithm in [14] investigates the hermite interpolation LUT method for RF power amplifier. The pruning of Volterra arrangement was performed and approved in [15] in predistorter application, acquiring a decreased intricacy model with agreeable performance. A uniform digital predistortion technique was proposed in [16] for concur-rent multi-band envelope tracking power amplifiers under numerous supply modulation types. Haider Al Kanan and Fu Li in [17] proposed an innovative model which improves the Saleh amplitude to amplitude model applied to the RF Solid State Power Amplifiers. The proposed model deals with the second-order in-termodulation distortion.

An adaptive basis direct learning algorithm was proposed in [18] for the linearization of power amplifiers having improved normalized mean square error and adjacent channel power ratios than the conventional direct learning method. A unique model discussed in [19] was output generalized memory polynomial (OGMP) model using previous output signal to characterize memory effects for digital predistortion of power amplifiers. By using the recursive prediction error minimization method, an algorithm based on adaptive indirect learning architecture of DPD was pro-posed in [20] for linearizing RF power amplifiers used in arising wideband correspondence frameworks. Error vector magnitude and adjacent channel power

ratio were the parameters to evaluate the DPD method proposed in [20]. A low-complexity architecture was presented in [21] for extracting coefficients for digital pre-distortion model of RF power amplifier. An adaptive digital pre-distortion technique was proposed in [22] based on a cascaded arrangement of adaptive indirect learning architecture and static direct learning architecture using a linear interpolation look-up-table. When the variations are occurred in operating conditions then in conventional method it becomes necessary to re-extract all coefficients of power amplifier every time so to avoid that problem it has been proposed in [23] to conduct an off-line pre-training stage one time, by doing so the common features of power amplifier behaviors under dissimilar operating conditions are obtained. The model adaptation process at that point just need to distinguish few changed coefficients, because of which complexity of the model adaptation cycle is also decreased. A modified dynamic deviation reduction (MDDR) based Volterra model for digital predistortion of power amplifiers was proposed in [24].

A method to fabricate digital predistorters that can linearize broad-band power amplifiers utilizing reduced sampling rates was discussed in [25][26]. R. Neil Braithwaite in [27] had discussed the instability mechanisms with recursive least square (RLS) estimator and necessary modifications to correct the problems with the fundamental form of the estimator. The RLS estimator was discussed in perspective of a transmitter with adaptive digital predistortion for compensating non-linearities in the RF power amplifier. The proposed DPD algorithm in [28] was elaborated on the basis of Gegenbauer polynomials adapted for maximum predistorter effectiveness and steadiness under various input signal conditions. In this research, four popularly accepted algorithms named as Memory Polynomial, Cross-term Memory Polynomial, Generalized Hammerstein and Cross-term Hammerstein are individually analyzed for characterizing RF power amplifier with and without implementation of suitable DPD algorithm under two tone and 16 QAM signals. As per literature review, since previous researchers had not demonstrated these four characterization models individually along with implementation of DPD algorithm over the performance measuring parameters of SD, TOI, IMD3, EVM, MER and SFDR. Thus, in this work, comparative analysis between the above four models for both narrow and wide bands is presented. The above four models are examined by varying memory effects and non-linearity order over a range of values and by evaluating the performance measuring parameters as mentioned above. Finally, the best

model for each narrow and wide band is highlighted.

The rest of the paper is structured as follows. Section 2 present the memory structures of the proposed models. Section 3 discuss the coefficient matrix computational algorithms. In section 4, simulation model is discussed. In section 5, performance measuring parameters of power amplifier are considered. In section 6, results are discussed, and finally in Section 7, conclusion is presented.

2 Memory Structures

The memory structures for both narrow and wide bands are discussed in this section. The narrowband power amplifier models include Memory Polynomial and cross-term Memory Polynomial models whereas wideband power amplifier models include Generalized Hammerstein and Cross-term Hammerstein models.

2.1 Memory Polynomial

This narrowband memory polynomial implementation is operated on the envelope of the input signal. It does not generate new frequency components. It captures in-band spectral regrowth. This model is used to create a narrowband power amplifier operating at high frequency [5]. The memory polynomial model can be implemented as follows [4],

$$y_{MP}(n) = \sum_{k=0}^{K-1} \sum_{m=0}^{M-1} a_{km} x(n-m) |x(n-m)|^k \quad (1)$$

where m and k represent memory depth and non-linearity order or degree length respectively. Thus Memory Polynomial algorithm has a significant role for pre-distortion of power amplifiers operating under typical conditions [6], [7].

2.2 Generalized Hammerstein

This wideband memory non-linearity implementation is operated on the envelope of the input signal. It generates frequency components that are integral multiples of carrier frequencies and captures in-band spectral regrowth. If the degree of nonlinearity increases, it simultaneously increases the number of out-of-band frequencies generated. The wideband power amplifiers operating at low frequency model can be created by using this model [5]. Thus, the Generalized Hammerstein model can be implemented as follows [4],

$$y_{MP}(n) = \sum_{k=0}^{K-1} \sum_{m=0}^{M-1} a_{km} x^k(n-m) \quad (2)$$

where m and k represent memory depth and non-linearity order or degree length respectively.

2.3 Cross-term Memory Polynomial

This narrowband memory polynomial implementation is operated on the envelope of the input signal. It does not generate new frequency components. It captures in-band spectral regrowth. This model is used to create a narrowband power amplifier which is operating at high frequency. Leading and lagging memory terms are included in this model. The expression for Cross-term Memory Polynomial implementation can be given by [4],

$$y_{CT-MP}(n) = \sum_{k=0}^{K_a-1} \sum_{l=0}^{L_a-1} a_{kl} x(n-l) |x(n-l)|^k + \sum_{k=1}^{K_b} \sum_{l=0}^{L_b-1} \sum_{m=1}^{M_b} b_{klm} x(n-l) |x(n-l-m)|^k + \sum_{k=1}^{K_c} \sum_{l=0}^{L_c-1} \sum_{m=1}^{M_c} c_{klm} x(n-l) |x(n-l+m)|^k \quad (3)$$

where K_a and L_a are representing the number of coefficients for aligned signal and envelope, K_b , L_b and M_b are representing the number of coefficients for signal and lagging envelope and K_c , L_c and M_c are denoting the number of coefficients for signal and leading envelope. The notable benefit of the Cross-terms Memory Polynomial model is that the coefficients are appeared in linear form. Therefore, any suitable type of least-squares algorithm can be used to estimate all of the coefficients.

2.4 Cross-Term Hammerstein

This wideband implementation is operated on the envelope of the input signal. It generates frequency components that are integral multiples of carrier frequencies and captures in-band spectral re-growth. When the order of non-linearity is increased, the number of out of band frequencies generated is also increased. Normally, the wideband power amplifiers operating at low frequency are created by using this algorithm [5]. This model can be implemented as follows,

$$y_{CT-M}(n) = \sum_{k=0}^{K_a-1} \sum_{l=0}^{L_a-1} a_{kl} x(n-l) x(n-l)^k + \sum_{k=1}^{K_b} \sum_{l=0}^{L_b-1} \sum_{m=1}^{M_b} b_{klm} x(n-l) x(n-l-m)^k + \sum_{k=1}^{K_c} \sum_{l=0}^{L_c-1} \sum_{m=1}^{M_c} c_{klm} x(n-l) x(n-l+m)^k \quad (4)$$

where K_a and L_a are representing the number of coefficients for aligned signal and envelope, K_b , L_b and M_b are representing the number of coefficients

for signal and lagging envelope and K_c , L_c and M_c are denoting the number of coefficients for signal and leading envelope.

3 Coefficient Matrix Computational Algorithms

The algorithms to extract coefficient matrices for both narrow and wide band models are discussed in this section. Each sub-section describes the computational algorithm for the respective model while taking care of its memory structure.

3.1 Memory Polynomial

In Memory polynomial model, at any instant of time, the output signal is the sum of all the elements of the following discussed complex matrix [5] having dimensions memory depth (mem) x voltage order (deg),

$$\begin{bmatrix} C_{11}V_0 & C_{12}V_0 & \dots & C_{1,deg}V_0|V_0|^{d-1} \\ C_{21}V_1 & C_{22}V_1|V_1| & \dots & C_{2,d}V_1|V_1|^{d-1} \\ \vdots & \vdots & & \vdots \\ C_{m,1}V_{m-1} & C_{m,2}V_{m-1}|V_{m-1}| & \dots & C_{m,d}V_{m-1}|V_{m-1}|^{d-1} \end{bmatrix}$$

where m and d represent the memory depth and voltage order, respectively. The number of rows represent the number of memory terms and the number of columns represent the degree of non-linearity in above discussed matrix. The amount of delay is denoted by the signal subscript.

3.2 Generalized Hammerstein

In Generalized Hammerstein model, at any instant of time the output signal is the sum of all elements of the following matrix [5] having dimensions memory depth (mem) x voltage order (deg),

$$\begin{bmatrix} C_{11}V_0 & C_{12}V_0^2 & \dots & C_{1,d}V_0^d \\ C_{21}V_1 & C_{22}V_1^2 & \dots & C_{2,d}V_1^d \\ \vdots & \vdots & & \vdots \\ C_{m,1}V_{m-1} & C_{m,2}V_{m-1}^2 & \dots & C_{m,d}V_{m-1}^d \end{bmatrix}$$

3.3 Cross-term Memory Polynomial

In this model, at any instant of time the output, signal is the sum of all elements of a matrix specified by the element-by-element product such as:

$$C \cdot * M_{CTM}$$

where C is a complex coefficient matrix having following dimensions:

$$\text{Memory Depth}(m) \times \{\text{Memory Depth}(m) \cdot (\text{VoltageOrder}(d) - 1) + 1\}$$

Model	Characterization Data	Type of Coefficients	In-band spectral Regrowth	Out-of-Band Harmonic Generation
Memory Polynomial	Bandpass (I, Q)	Complex	Yes	No
Generalized Hammerstein	True passband	Real	Yes	Yes
Cross-term Memory Polynomial	Bandpass (I, Q)	Complex	Yes	No
Crossterm Hammerstein	True passband	Real	Yes	Yes

TABLE 1: Characteristics of memory structure [5]

M_{CTM} can be obtained by the product of below discussed matrices.

$$\begin{bmatrix} V_0 \\ V_1 \\ \vdots \\ V_{m-1} \end{bmatrix} \begin{bmatrix} 1 & |V_0| & |V_1| & \dots & |V_{m-1}| & |V_0|^2 & \dots & |V_{m-1}|^2 \\ \dots & |V_0|^{d-1} & \dots & |V_{m-1}|^{d-1} & \dots & |V_0|^{d-1} & \dots & |V_{m-1}|^{d-1} \end{bmatrix}$$

The number of rows denote the number of memory terms; whereas, the number of columns is proportional to the degree of non-linearity and the number of memory terms. The amount of delay is represented by the signal subscript. Here, the cross terms are represented by the additional columns that do not appear in the Memory Polynomial model [5].

3.4 Cross-term Hammerstein

The output signal in this model is the sum of all the elements of a matrix specified by the element-by-element product at any instant of time such as,

$$C \cdot * M_{CTH}$$

where C is a complex coefficient matrix having following dimensions:

$Memory\ Depth(m) \times \{Memory\ Depth(m) \cdot (Voltage\ Order(d) - 1) + 1\}$
 M_{CTH} can be obtained by the product of below discussed matrices:

$$\begin{bmatrix} V_0 \\ V_1 \\ \vdots \\ V_{m-1} \end{bmatrix} \begin{bmatrix} 1 & V_0 & V_1 & \dots & V_{m-1} & V_0^2 & \dots & V_{m-1}^2 & \dots & V_0^{d-1} & \dots & V_{m-1}^{d-1} \end{bmatrix}$$

The number of rows are equal to the number of memory terms and the number of columns is proportional to the degree of nonlinearity and the number of memory terms in the above matrix. The amount of delay is represented by the signal subscript. Here, cross terms are represented by the additional columns that do not appear in the Generalized Hammerstein model [5].

4 Simulation Model

After extracting coefficients of RF power amplifier, the DPD algorithm is implemented to increase transmitter linearity. It is being placed before the power amplifier for pre-distorting the signal which is being transmitted. The DPD characteristic is designed to be inverse of the power amplifier's characteristic so that the two effects cancel one another and net response is linear overall. The Simulink block diagram in Fig. 2 is tested initially by applying two tone signal and obtained results of performance measuring parameters with and without enabling DPD algorithm are noted. Then a modulated waveform such as a 16QAM signal is applied. The effects of DPD algorithm are also observed in this case, by measuring the difference in EVM, MER, TOI, IMD3 and SFDR before and after the DPD algorithm is applied. For getting respective results for each model, the model of power amplifier's block in Simulink block diagram can be changed in accordance with the respective characterization model of power amplifier.

5 Performance Measuring Parameters of RF Power Amplifier

The parameters used for performance measurement of RF power amplifier are discussed in this section. The best model for each narrow and wideband is explored on the basis of performance measuring indicators as discussed in subsections 5.1, 5.2, 5.3, and 5.4.

5.1 Standard Deviation

It can be defined as, the proportion of scattering of a bunch of information from its mean. The higher the scattering, the more noteworthy will be the greatness of deviation from its mean. The formula of standard deviation can be given as:

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \mu)^2} \quad (5)$$

5.2 Inter-Modulation Products (IMD3), Third order intercept point (TOI) and Spurious Free Dynamic Range (SFDR)

When the power amplifier is operated under large signal conditions then that leads the power amplifier to work in non-linear region. This deviation from linearity produce distortions such as a number of harmonics and inter-modulation products at the output when a power amplifier is excited with n-tone signal, where n is greater than 1. Let a two-tone signal is applied to the input as [9]:

$$V_i(t) = \cos(2\pi f_1 t) + \cos(2\pi f_2 t) \quad (6)$$

The 2nd order products includes 2nd order harmonics ($2f_1, 2f_2$) and 2nd order inter-modulation products ($f_2 + f_1, f_2 - f_1$). The 3rd order products include 3rd order harmonics ($3f_1, 3f_2$) and 3rd order inter-modulation products ($2f_2 + f_1, 2f_2 - f_1, 2f_1 + f_2, 2f_1 - f_2$) as mentioned in Figure 3 [9]. The amplitude of the harmonics decreases with increasing order of harmonics. Since, ($2f_1, 2f_2, 3f_1, 3f_2$) can be filtered out easily so there distortion is minimized. While, ($f_2 + f_1, f_2 - f_1, 2f_2 + f_1, 2f_1 + f_2$) can be easily filtered too as they are far away from the tones. The problem occurs for ($2f_2 - f_1, 2f_2 - f_1$) because both of them lie within the bandwidth and are very near to the tones. These problematic inter-modulation products are called inter-modulation distortion (IMD_3). To solve that problem, a mathematical concept has been introduced called third order intercept point which tells us about the linearity of the device. The IP3 point cannot be measured directly, but it can be determined from the measurement data at much smaller power levels in order to avoid overload and daage of the device under test [10]. TOI can be given as:

$$TOI = P_{tone} + \frac{\Delta P}{2} \quad (7)$$

In Fig. 4, the third order intercept point (P3) is the output power level at which both of the extended slopes of third order harmonic and fundamental signal meet with each other. The fundamental and third order harmonic levels at this power are equal. It is understood that operation at third order intercept point is impossible since the output power normally saturates below this level. If in-put signal level is decreased by 1dB, then that will definitely decrease level of fundamental tone by 1dB. Similarly, if there is a decrease of 1dB in input signal level then that will decrease levels of all third order product by 3dB. That proves if the input power is decreased by one-third of the distance in decibels from P3 to noise floor, the third order harmonic will drop to noise level. This

specific output power range for fundamental signal is called spurious-free dynamic range (SFDR), which can be estimated as [9]:

$$SFDR(dB) = \frac{2}{3}[P_3 - P_{NOISE}] \quad (8)$$

The third order intercept power and spurious-free dynamic range are proportional to each other. If one is high the other will be high too, which means unwanted inter-modulation products are sup suppressed more. This is an important approach for calculating the linearity of a power amplifier [9].

5.3 Error Vector Magnitude (EVM)

Error vector magnitude tells us that how accurately the wireless system is transmitting symbols with in the constellation. Informally, EVM tells the difference between the positions of ideal constellation points and the actual constellation points. EVM is actually the average amplitude of error signal normalized to the peak signal amplitude. It can be expressed as:

$$EVM(dB) = 10\log_{10}(P_{error}/P_{reference}) \quad (9)$$

$$EVM(\%) = \sqrt{(P_{error}/P_{reference})} \times 100\% \quad (10)$$

5.4 Modulation Error Ratio (MER)

The modulation error ratio is used to quantify the performance of a wireless system. MER has a close relationship with EVM, but it is calculated from average power of signal. It can be expressed as:

$$MER(dB) = 10\log_{10}\left(\frac{P_{signal}}{P_{error}}\right) \quad (11)$$

$$MER(\%) = \sqrt{\frac{P_{error}}{P_{signal}}} \times 100\% \quad (12)$$

6 Results & Discussion

The RF power amplifier modelling is done by using actual component characteristics. The RF component imperfections as well as strategies were explored to create a model by fitting to collect-ed RF power amplifier data. The Power amplifier model was then placed alongside a model of a DPD algorithm within a closed loop. The data rate at which the coefficients extracted was 15.36 MHz while keeping the bandwidth at 50 MHz. In Simulink block diagram of each model, the up conversion and down conversion frequencies are 2.7 MHz and 50 MHz respectively.

While modelling the RF power amplifier, it is very important to set memory depth (M) and non-linearity

Fig. 2: Simulink block diagram of a simple behavioral model of an RF transmitter, an observer receiver path and an adaptive DPD algorithm tested with a two-tone signal / baseband signal [3].

Fig. 3: Spectrum of inter-modulation distortion products [9]

Fig. 4: Harmonics growth as a function of input power [9]

order (K) values. Initially, $M=5$ and $K=5$ are chosen for DPD algorithm. While extracting power amplifier's coefficients, the range of values for memory depth and non-linearity order has been set in a way that M ranges from 3 to 10 and K is taken from 1 to 10. Keeping the value of memory depth equal to 3, the value of K is varied from 1 to 10. In that situation, the power

Fig. 5: Error vector magnitude representation

amplifier coefficients were extracted for observation of standard deviation value along with response curves.

Later on, memory depth has been changed for its multiple values. Again, by keeping value of memory depth equal to 4, the value of K has been varied from 1 to 10. Similarly, the coefficients of power amplifier have been brought out and the standard deviation values along with response curves and variations in results have been noticed. The same process is repeated until memory depth value approaches to 10. In this way, 80 results of each model have been obtained. The second step followed is to find the result having least standard deviation. At the least deviated value for the specific model it is very important to note memory depth and non-linearity order both. If standard deviation result occurs at higher value of M, then its value at an acceptable level of M and K has been taken into account where latency factor and abnormal response of output can be reduced as much as possible. Once a suitable value of SD is found for an acceptable level of memory depth then that value of M is fixed and K is started to vary from 1 to 10. When an acceptable

value of non-fitted coefficients, third order intercept value, spurious free dynamic range, error vector magnitude and modulation error ratio with and without implementation of DPD algorithm are obtained then that specific value of K is also fixed. In this way, out of all 320 results for the performance measuring metrics, optimized results for each model have been acquired.

In narrow band, two models i.e. memory polynomial and cross term memory polynomial have been implemented. After optimization of extracted coefficients of power amplifier, cross term memory polynomial model is found to be superior in terms of standard deviation which is 2.67% whereas SD of memory polynomial model achieved to be 4.24% from the real power amplifier's behavior. The wide band models include Generalized Hammerstein and Cross-term Hammerstein. Similarly, after optimization of extracted power amplifier's coefficients, SD acquired for generalized Hammerstein and cross term Hammerstein models are 13.46% and 13.04% respectively. Thus, Cross term Hammerstein model is superior to Generalized Hammerstein model. TABLE 2 shows optimized values (in terms of standard deviation) for each model.

In case of narrowband models, when two tone input signal is applied, the obtained TOI value for memory polynomial model is 38.39 dBm. When cross terms are introduced, TOI value has improved from 38.39 dBm to 39.86 dBm. Similarly, IMD3 values are suppressed more by introducing cross terms. Thus, IMD3 values have suppressed from -34.68 dBc to -39.59 dBc and from -39.75 dBc to -40.96. SFDR obtained in memory polynomial model is 0.30 dBc while in cross term memory polynomial model it is 0.31 dBc with slight improvement. After assessing the obtained values of all the parameters, cross term memory polynomial model is considered to be excellent for narrowband as shown in Table 3.

In case of wide band, when two tone input signal is set out, the obtained TOI value for Hammerstein model is 33.01 dBm. By introducing cross-terms the TOI value has improved from 33.01 dBm to 55.78 dBm. Similarly, IMD3 values are also suppressed more. Consequently, IMD3 values have got suppressed from -30.63 dBc to -88.29 dBc and from -28.30 dBc to -81.65 dBc. SFDR acquired in Generalized Hammerstein model is 0.09 dBc whereas it is 0.21 dBc in Cross-term Hammerstein. After evaluating the achieved results of all performance measuring parameters, Cross term Hammerstein model is found to be suitably fitted for wide band as shown in Table 3.

In case of two tone input signal when DPD algorithm is enabled, the performance measuring metrics as shown in TABLE 4 of each model have improved

Model Type	Standard Deviation (Optimized)
Memory Polynomial	4.2384%
Crossterm Memory Polynomial	2.6702%
Generalized Hammerstein	13.4644%
Crossterm Hammerstein	13.0494%

TABLE 2: Model type vs. standard deviation

results than without implementing the DPD algorithm as illustrated in TABLE 3. For narrow band Cross-term Memory Polynomial model to be recognized as better model whereas for wideband Cross-term Hammerstein model is studied as the advantageous model.

In case of narrowband, when an input signal of 16QAM is applied, EVM and MER obtained in memory polynomial are 18.9% and 14.5dB respectively. By introducing cross-terms EVM and MER have revamped to 18.4% and 14.7dB respectively. In case of wideband under a 16QAM input signal, achieved EVM and MER are 14.3% and 16.9dB. When the Cross-terms are introduced, EVM and MER have escalated to 4.8% and 26.3dB. By examining the attained values of all performance indicators, cross term memory polynomial model has reflected to be pre-eminent for narrowband. The performance measuring indicators for each model without DPD algorithm for 16QAM signal are shown in Table 5.

When a 16QAM signal is set out and DPD algorithm is enabled, the performance measuring metrics of each model as shown in TABLE 6 have progressed results than without implementing the DPD algorithm illustrated in TABLE 5. For narrowband case, Cross term Memory Polynomial model has to be identified as the suitable model whereas for wide band the most suitable model is Crossterm-Hammerstein as per the observed performance indicators.

It is scholarly accepted fact that by introducing cross terms, system's response becomes better [1], [3], [4], [5]. Thus, by analyzing our results, it has been found that the considered performance measuring parameters for the cross-terms involved models in both narrowband wide bands have improved which validates the above mentioned fact.

7 Conclusion

In this research, four popular algorithms named as Memory Polynomial, Generalized Hammerstein, Cross-term Memory Polynomial and Cross-term Hammerstein have been taken into account for computation of power amplifier's coefficients using actual component characteristics. Since the response of power amplifier is non-linear so in order to make its net

Optimized Models	M	K	TOI (dBm)	IMD3 (dBc)	SFDR (dBc)
Memory Polynomial	3	5	38.39	-34.68, -39.75	0.30
Cross-term Memory Polynomial	3	4	39.86	-39.59, -40.96	0.31
Generalized Hammerstein	3	5	33.01	-30.63, -28.30	0.09
Cross-term Hammerstein	3	2	55.78	-88.29, -81.65	0.21

TABLE 3: Performance indicators without DPD (2 Tone Signal)

Optimized Models	M	K	TOI (dBm)	IMD3 (dBc)	SFDR (dBc)
Memory Polynomial	3	5	41.37	-41.05, -45.94	0.41
Cross-term Memory Polynomial	3	4	41.77	-43.56, -45.16	0.42
Generalized Hammerstein	3	5	41.66	-53.1, -34.87	0.41
Cross-term Hammerstein	3	2	57.14	-73.16, -76.72	0.42

TABLE 4: Performance indicators with DPD (2 Tone signal)

Optimized Models	M	K	RMS EVM (%)	AVG MER (dB)	SFDR (dBc)
Memory Polynomial	3	5	18.9	14.5	0.41
Cross-term Memory Polynomial	3	4	18.4	14.7	0.42
Generalized Hammerstein	3	5	14.3	16.9	0.41
Cross-term Hammerstein	3	2	4.8	26.3	0.42

TABLE 5: Performance indicators without DPD (16QAM Signal)

Optimized Models	M	K	RMS EVM (%)	AVG MER (dB)	SFDR (dBc)
Memory Polynomial	3	5	4.7	26.5	0.41
Cross-term Memory Polynomial	3	4	3.2	30.0	0.42
Generalized Hammerstein	3	5	3	30.5	0.41
Cross-term Hammerstein	3	2	1.7	35.2	0.42

TABLE 6: Performance indicators with DPD (16QAM Signal)

response linear, a linearity algorithm known as DPD has been implemented. The responses of all four models for extracting power amplifier's coefficients were observed with and without implementation of DPD algorithm. Various performance indicators like Standard Deviation (SD), Third Order Intercept (TOI), Intermodulation Distortion Products (IMD3), Modulation Error Ratio (MER) and Spurious Free Dynamic Range (SFDR) have been used to characterize RF power amplifier for both narrow and wide band applications. It is investigated through the simulation results that under narrowband applications, Cross-term Memory Polynomial model is outstanding as it has least standard deviation and is also satisfying other performance indicators up to appreciable level with and without DPD algorithm implementations. While for wideband applications, Cross-term Hammerstein model satisfies the performance measuring parameters excellently. Thus, the considered performance measuring parameters for the cross-terms involved models in both narrow and wide bands have improved which validates the fact that by introducing cross terms, system's response becomes better.

Acknowledgement

The authors are very thankful to the Electronic Engineering Department, QUEST, Nawabshah and Quaid-e-Awam University of Engineering, Science and Technology (QUEST), Nawabshah, Sindh, Pakistan for their support and encouragement for this research work.

References

- [1] Ibrahim Can Sezgin, "Different Digital Predistortion Techniques for Power Amplifier Linearization," Master's Thesis, Electrical and Information Technology Faculty of Eng., LTH, Lund Univ., Sweden, 2016.
- [2] O. Hammi, "Augmented Twin-Nonlinear Two-Box Behavioral Models for Multicarrier LTE Power Amplifiers," The Scientific World Journal, vol. 2014, Article ID 762534.
- [3] Model RF Power Amplifiers and Increase Transmitter Linearity with DPD Using Matlab, <https://www.mathworks.com/campaigns/offers/modeling-rf-power-amps-with-dpd.html>. 2018
- [4] Morgan, et.al., "A Generalized Memory Polynomial Model for Digital Predistortion of RF Power Amplifiers," IEEE Transactions on Signal Processing, vol. 54, no. 10, pp. 3852–3860, Oct. 2006.
- [5] Power amplifier, <http://www.mathworks.com/help/simrf/ref/poweramplifier.html>, 2021.
- [6] J. Kim and K. Konstantinou, "Digital predistortion of wideband signals based on power amplifier model with memory," Electron. Lett., vol. 37, pp. 1417–1418, Nov. 2001.
- [7] L. Ding, G. T. Zhou, D. R. Morgan, Z. Ma, J. S. Kenney, J. Kim, and C. R. Giardina, "A robust digital baseband predistorter constructed using memory polynomials," IEEE Trans. Commun., vol. 52, no. 1, pp. 159–165, Jan. 2004.

- [8] L. Gan, “Adaptive Digital Predistortion of Nonlinear Systems,” Ph.D. Thesis, Electrical and Information Eng., Graz Univ. of Technology, Austria, 2009.
- [9] Gozde Erdogdu, “Linearization of Rf Power Amplifiers by using Memory Polynomial Digital Predistortion Technique,” Master’s Thesis, Electrical and Electronics Engineering, Middle East Technical Univ., Turkey, June 2012.
- [10] F. Caspers, P. Kowina, “RF Measurement Concepts,” CAS Proc., pp. 101–156, 2014.
- [11] Harald Enzinger, “Behavioral Modeling and Digital Predistortion of Radio Frequency Power Amplifiers,” PhD dissertation, Doctoral School of Information and Communications Eng., Graz Univ. of Tech., Austria, 2018.
- [12] Haoyu Wang, Gang Li, Chongbin Zhou, Wei Tao, Falin Liu, and Anding Zhu, “1-Bit Observation for Direct Learning Based Digital Pre-distortion of RF Power Amplifiers,” IEEE Transactions on Microwave Theory and Techniques, vol. 65, no. 7, pp. 2465 - 2475, Jan. 2017.
- [13] Genevieve Baudoin, “On Segmented Predistortion for Linearization of RF Power Amplifiers,” Radio Eng., vol. 29, no. 1, pp. 2465 - 2475, Apr. 2020.
- [14] Dinaagaren Selvadurai, Roslina M. Sidek, Khalid Al-Hussaini and Borhanuddin M. Ali, “A Hermite Interpolated LUT for RF Power Amplifiers,” Pertanika J. Sci. Technol., vol. 25, pp. 299 - 306, Apr. 2017.
- [15] Becerra, J.A., Madero-Ayora, M.J., Reina-Tosina, J., and Crespo-Cadenas, C., “Digital predistortion of power amplifiers using structured compressed-sensing Volterra series,” Electron. Lett. vol. 53, no. 2, pp. 89–91, Jan. 2017.
- [16] Qianyun Lu, Fan Meng, Na Yang, and Chao Yu, “A Uniform Digital Predistorter for Concurrent Multi-Band Envelope Tracking RF Power Amplifiers With Different Envelopes,” IEEE Transactions on Microwave Theory and Techniques, vol. 66, no. 9, pp. 3947 - 3957, Aug. 2018.
- [17] Haider Al-Kanan and Fu Li, “A Simplified Accuracy Enhancement to the Saleh AM/AM Modeling and Linearization of Solid-State RF Power Amplifiers,” Electronics, vol. 9, no. 11, pp. 1 - 13, Oct. 2020.
- [18] Cuiping Yu, Ke Tang and Yuanan Liu, “Adaptive Basis Direct Learning Method for Predistortion of RF Power Amplifier,” IEEE Microwave and Wireless Components Lett., vol. 30, no. 1, pp. 98-101, Nov. 2019.
- [19] Cuiping Yu, Guangjiang Wang and Yuan’an Liu, “Low complexity output generalized memory polynomial model for digital predistortion of RF power amplifiers,” International Journal of RF and Microwave Computer-Aided Engineering, vol. 28, no. 8, pp. 1-7, Sept. 2018.
- [20] Duc Han Le, Van-Phuc Hoang, Minh Hong Nguyen, Hien M. Nguyen and Duc Minh Nguyen, “Linearization of RF Power Amplifiers in Wideband Communication Systems by Adaptive Indirect Learning Using RPEM Algorithm,” Mobile Networks and Applications, vol. 25, no. 7, pp. 1988–1997, Apr. 2020.
- [21] Noel Kelly and Anding Zhu, “Direct Error-Searching SPSA-Based Model Extraction for Digital Predistortion of RF Power Amplifiers,” IEEE Transactions on Microwave Theory and Techniques, vol. 66, no. 3, pp. 1512-1522, 2018.
- [22] Han Le Duc, Bruno Feuvrie, Matthieu Pastore and Yide Wang, “An Adaptive Cascaded ILA- and DLA-Based Digital Predistorter for Linearizing an RF Power Amplifier,” IEEE Transactions on Circuits and Systems, vol. 66, no. 3, pp. 1031 - 1041, Oct. 2018.
- [23] Yue Li, Xiaoyu Wang and Anding Zhu, “Complexity-Reduced Model Adaptation for Digital Predistortion of RF Power Amplifiers With Pre-training-Based Feature Extraction,” IEEE Transactions on Microwave Theory and Techniques, vol. 69, no. 3, pp. 1780-1790, Dec. 2020.
- [24] Zhao Li, Cuiping Yu, and Yuan’an Liu, “A Modified Dynamic Deviation Reduction Based Volterra Model for Digital Predistortion of RF Power Amplifiers,” Proc. IEEE Symp. Electromagnetic Compatibility (ISEMC ’06), 2019.
- [25] Yue Li, Xiaoyu Wang and Anding Zhu, “Sampling Rate Reduction for Digital Predistortion of Broadband RF Power Amplifiers,” IEEE Transactions on Microwave Theory and Techniques, vol. 68, no. 3, pp. 1054-1064, Oct. 2019.
- [26] Ke Li and Hairan Shi, “A Generalized Sampling Based Method for Digital Predistortion of RF Power Amplifiers,” Proc. International Conference in Communications, Signal Processing, and Systems, pp. 953-959, 2020.
- [27] R. Neil Braithwaite, “Fixed Point Considerations for Digital Predistortion of a RF Power Amplifier Using Recursive Least Square (RLS) Estimation,” Proc. IEEE Topical Conference on RF/Microwave Power Amplifiers for Radio and Wireless Applications (PAWR), pp. 125-127, Jan. 2019.
- [28] Manel Manai, Hanen Chenini, Afef Harguem, Nouredine Boulejeff and Fadhel M. Ghannouchi, “Robust Digital Predistorter for RF Power Amplifier Linearization,” IET Microwaves Antennas Propagation, vol. 14, no. 7, pp. 649–655, April 2020.