PRE-DISTORTION DESIGN FOR NON-LINEAR POWER AMPLIFIERS

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ABSTRACT

PRE-DISTORTION DESIGN FOR NON-LINEAR POWER AMPLIFIERS

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Power amplifiers are vital part of communication systems for long distance communication. They are used to amplify the power of incoming signals. The power gain characteristics of these amplifiers show a non-linear behavior for larger input power signals. The non-linear power gain response decreases the efficiency of power amplifier. To alleviate the negative effects of non-linear gain responses of the power amplifiers, researchers model the gain responses and calculate or approximate their inverse called pre-distortions, and the incoming signal is passed through the pre-distortion unit before it is fed to the power amplifier such that the gain responses of the power amplifiers show a linear characteristic.

In this thesis, we first review the well-known pre-distortion methods available in the literature, and then propose a novel approach for pre-distortion design. The proposed approach uses the concept of analog signal reconstruction from its samples. We use $sinc(\cdot)$ function for the modeling of amplifier gain response and pre-distortion design. The proposed method can be seen as the optimum implementation of indirect learning algorithm used for pre-distortion design.

Keywords: Power Amplifier Nonlinearity, Predistortion, Linearization.

ÖZ

DOĞRUSAL OLMAYAN GÜÇ YÜKSELTEÇLERİ İÇİN ÖNBOZMA DİZAYNI

TURAN, Yusuf Berk

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Güç yükselteçleri, özellikle uzak mesafeli iletişim sistemlerinde, kendisine gelen sinyalden yüksek güç elde etmek için kullanılır. Gelen sinyal, güç yükselteci çıkışında doğrusal olmayan bir hale gelebilir ve bozulmaya uğrar. Bu nedenle güç yükselteçlerinden alınan verim azalmaktadır. Bu bozulmaların etkilerini azaltmanın yolu, güç yükseltecinin doğrusallığını kaybettiği doyma bölgesine girmeden önce, doğrusallığını arttırmaktır. Güç yükselteçlerinin doğrusallığını arttırma yöntemine önbozma yöntemi denir.

Bu tez içeriğinde, en çok kullanılan önbozma yöntemlerinden bahsedilmiştir. Bu önbozma yöntemlerine ek olarak önerilen yeni bir yöntem geliştirilmiştir. Önerilen yöntem analog sinyallerin örneklerinden $sinc(\cdot)$ fonksiyonu kullanılarak oluşturulması mantığı üzerine inşa edilmiştir. Bu yöntem ile ilgili simülasyonlar yapılmıştır. Tez içerisinde güç yükselteçlerinin modellerine de yer verilmiştir.

Anahtar Kelimeler: Güç Yükselteç Doğrusalsızlığı, Önbozma, Doğrusallaştırma.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

PA	Power Amplifier
DPD	Digital Predistortion
ILA	Indirect Learning Architecture
DLA	Direct Learning Architecture
IoT	Internet of Things
RF	Radio Frequency
TWTA	Travelling Wave Tube Amplifier
SSPA	Solid-State Power Amplifier
AM	Amplitude Modulation
PM	Phase Modulation
PAE	Power Added Efficiency
FIR	Finite Impulse Response
NMSE	Normalized Mean Square Error
ACPR	Adjacent Channel Power Ratio
ACLR	Adjacent Channel Leakage Ratio
LUT	Look Up Table
DAC	Digital to Analog Converter
ADC	Analog to Digital Converter
LS	Least Squares
IMD	Intermodulation Distortion
PSD	Power Spectral Density

CHAPTER 1

INTRODUCTION

Modern communication systems are improving day by day. Especially with recent technological developments and emerging systems, communication has gained more importance. The components of the communication are the receiver, transmitter and channel. For a qualified communication, the functioning of these basic parts of communication needs to be at high quality. With the advancement of technology, large data sizes necessitate the communication systems to be perfect and qualified. It is very difficult to meet the increasing need. This is because the communication resources are limited. Because of this limit, many communication techniques have been developed and are still in use while meeting the increasing demands.

One of the components used in communication systems is power amplifiers. In this thesis, different power amplifier models are explained. Power amplifiers are used to amplify the input signal. As mentioned earlier, these components need to change and develop in the face of the rapid progress of technology and increasing demands. Power amplifiers, due to their characteristics, distort the input signal when they are in the saturation zone. Thus, a nonlinearity problem arises. In this thesis, information about nonlinearity problem is given. Linearization is necessary to ensure that the communication is perceived on the receiving side correctly and with quality. In power amplifiers, it is important to provide high power efficiency in high power mode. To achieve this, predistortion techniques have been developed. The purposes of these techniques is to prevent distortion of power amplifiers by preventing their entering into the saturation zone. Popular predistortion methods are discussed in the thesis. In addition, a predistortion method has been developed to overcome the problem of nonlinearity.

In this chapter, information about the problem mentioned in the thesis is explained and the organization of the thesis is explained.

1.1. Explanation of the Problem

Linearity is very important for PAs. There are some reasons of PA's nonlinearity for high power efficiency, PA must be in high power mode. After the required input power is supplied, PA enters the compression region. Low level input signals have a constant gain, while high level input signals are saturated, this point where the gain starts to fall is called 1dB point and this point is called 1dB compression point.

In 5G, conveying up to 20 Gbps top data rates and average of 100+ Mbps data rates, the use of power amplifiers in an efficient manner is a critical issue [24]. For big bandwidths, where PA is in non-linear region, the frequency spectrum will be destroyed. These non-linear features of a power amplifier make the proceedings of linearization imminent for high power efficiency modes.

A power amplifier transforms a signal of low power into a signal of high power. There are two desirable characteristics of an energy amplifier: linearity and efficiency. Linearity is essential because when the signal is distorted by a nonlinear element, the frequency spectrum is broadened. It is essential to have efficiency for power amplifiers. DPD is a very useful approach to resolve this issue.

As a result, the aim of this thesis is to move away from non-linearity and provide linearity with predistortion.

1.2. Organization of the Thesis

The thesis contains six chapters. All chapters in the thesis contain information about DPD which may be necessary. In addition, detailed information about DPD is available in the thesis.

Chapter 1 is an introduction for linearity importance of power amplifiers and solution of this problem.

Chapter 2 contains general information about the communication system. Here, general communication networks, details of these communication networks and the interaction of new technologies are mentioned. In addition, basic elements of the communication system are explained. General information about these basic elements is given.

Chapter 3 provides information on power amplifiers. Power amplifier characteristics, nonlinearity problems in power amplifiers, and power amplifier models are mentioned. Power amplifier models are introduced with both memoryless and memory models.

Chapter 4 discusses the learning architecture techniques used to determine digital predistortion. In short, this chapter includes two kinds of learning architecture. These architectures are ILA (Indirect Learning Architecture) and DLA (Direct Learning Architecture). Information about these two learning architectures is also presented in this chapter.

Chapter 5 explains the proposed DPD method and discusses the proposed DPD method with some PA models and simulate some performance metrics. These performance metrics are NMSE, ACPR and PSD. Performance metrics demonstrated with simulation graphics.

Chapter 6 discusses results of all simulations and details the advantages of the proposed approach.

CHAPTER 2

ELEMENTS OF COMMUNICATION SYSTEMS

The purpose of this chapter is to give information about the communication system and components of basic communication systems.

Communication systems closely follow the development of technology. The development of hardware and software technologies and developments in physics provide rapid changes in the communication system. Nowadays, communication is made using different communication techniques everywhere. In particular, the trend towards wireless communication is increasing. The most popular networks in wireless communication are cellular networks and Wi-Fi networks [20]. There are several generations of cellular networks. There is a long course from 1G to 5G in the development from the first to the fifth generation. The technology used in 1G is analogue and FDMA was used (Frequency Division Multiple Access). 2.4Kbps was the average speed and the network communication was wireless. More services and features were launched with 2G such as enhanced voice coverage and capacity and inevitably quality of voice was better than 1G. In the 2G network the speed was improved to 64kbps and first digital norms like GSM (Global System of Mobile), CDMA (Code Division of Multiple Access), and TDMA (Time Division Multiplexing Accessing) were used. 2G technology used circuit switching for voice and packet switching for data. The new age of mobile technologies and their services began with the launch of 3G in 2003. Later, 3G services were launched on mobile devices and smartphones by internet services. 3G was digital voice based and separate digital IP based and included web data email and SMS. W-CDMA was the technology used in 3G. In 3G, the speed was boosted to 2000 kbps and the introduction of the first mobile broadband occurred. The desire to make mobile devices more beneficial and more functionally smarter has been the trend since the introduction of first mobile devices. A smartphone can be considered as a computer without wires that can call and still can be used as a computer but should be fitted in your pocket. The demand to get high speed internet on a smartphone never ceased due to the need of services' and apps' faster internet speed requirements. As a result, in 2011 launch of 4G occurred to be added to current usage along 2G and 3G. 4G's main difference was that it was mainly intended for data, and for multimedia taking IP-based protocol (LTE) as a base. Packet switching was the technology used for switching in 4G. 100,000 kbps was the speed that was achieved by 4G. There are approximately 50 billion devices that will have a connection to the internet by the year of 2020. As a result of this gigantic demand, very fast internet and the transport network's next generation is required. In the year of 2020, answer for all these requirements is 5G which will be entirely functional. The 5G technology has digital voice and data capacity and also bears IoT's (Internet of Things) and AR's (Augmented Reality), VR's (Virtual Reality) distinctive features. With IoT, communication between things using various protocols is beginning from smart cars to smart city grids [22]. With IoT (Internet of Things), smart devices are multiplying and diversifying day by day. IoT makes it possible to control many situations with remote access. Connected systems can include sensors, actuators, smartphones, computers, houses and home/work equipment, automobiles and components of road infrastructure, and various other devices or objects can connect, be monitored or be actuated. Also, cloud technology is also improving day by day. The IoT world's success needs service delivery due to ubiquity, reliability, high-performance, effectiveness, and scalability. To achieve this attribution, the future company and research vision is to combine the ideas of cloud computing and concepts of IoT, i.e., provide an "Everything as a Service" model: specifically, a cloud ecosystem with new features and cognitive IoT skills is given in [21].

Wireless communication means passing information from one source to a one or more receivers without the existence of wires (or electrical conductors). This communication technique is applied to many devices in our day. The goal here is to provide communication between these devices wirelessly and removing the need for cables. Bluetooth is one of the most common wireless communication techniques used around the world. We employ this particular technology when we want to do simplest things such as sending a photograph to our friend through our phone. Bluetooth technology operates on 2.4 GHz frequency band which is open to unlicensed usage and it uses frequency hopping wide spectrum method. The 2.4 GHz frequency band is called ISM (Industrial, Scientific, Medical), and in these areas, which ISM abbreviates, there is no need for licensing, since there is no licensing there are many devices that use this frequency band. This situation increases the effects of interference. For Bluetooth technology, interference is solved using frequency hopping wide spectrum method and employing low power. In order to block interference on a large scale, frequency hopping wide spectrum method allows to communicate over changing frequencies, thus, eliminating the chance of overlapping of two different communications at the same frequency [37].

2.1. Basic Communication System Principle

Communication systems are designed to send messages or information from a source that generates the messages to one or more destinations. As shown in Figure 1 a transmitter, communication channel and a receiver compose a simple communication system. In fact, transmitter, channel and receiver are the heart of a communication system. Communication systems can be one way or two way. As an example; TV or radio broadcasting can be considered as a one-way communication and telephone networks are examples for two-way communication systems. Some functions such as: digitizing, encoding, multiplexing, modulation, RF amplification, could be performed in a communication system [23].

Figure 1: Block Diagram of a Simple Communication System

2.2. Transmitter

The transmitter sends the electrical signal through the physical channel or transforms it into a form that is convenient for transmission. The Federal Communications Commission (FCC), for instance, establishes the frequency range for each transmitting station in radio and television broadcasting. The transmitter must therefore translate the data signal to be transferred into the suitable frequency range that is matched with the transmitter's assigned frequency allocation. Thus, interference that is caused by signals transmitted by various radio stations is eliminated. Similar tasks are conducted in communication systems of telephones, where signals of electrical speech are transferred from many users. In general, the transmitter conducts a method called modulation for the message signal and the channel to be matched. Modulation usually includes the use of the data signal to systematically change either a sinusoidal carrier's amplitude, frequency, or phase. Carrier modulation such as AM, FM, and PM on the transmitter is generally conducted [23].

2.3. Channel

The physical medium is the channel of communication used to deliver the signal to the receiver from the transmitter. Usually, the atmosphere is the channel in wireless transmission. Telephone channels, on the other side, generally use a range of physical media, including wirelines, wires of optical fiber and wireless [23].

2.4. Receiver

The receiver's role is to retrieve the message signal. If a carrier modulation transmits the message signal, the receiver performs the demodulation to obtain the message from the sinusoidal carrier. Since the signal demodulation is performed using the noisy signal, the demodulated signal may contain some distortion. The receiver also conducts several peripheral tasks, including filtering of signal and suppression of noise, in addition to the main function of signal demodulation [23].

CHAPTER 3

POWER AMPLIFIERS

Power amplifiers are used in RF communications to communicate over longer distances. In this chapter, characteristics of power amplifiers, why nonlinearity occurs in power amplifiers, and power amplifier models are discussed.

3.1. Power Amplifiers Characteristics

TWTA (Travelling Wave Tube Amplifier) and SSPA (Solid-State Power Amplifier) can be regarded as a power two basic types of amplifiers. The output power of TWTA is larger and more efficient than the output power of SSPA. If it is looked from a different angle, SSPA is lighter, more linear and more reliable than the TWTA. Thus, at less than 10 GHz frequency, TWTA is being replaced by SSPA [3]. For the modelling of TWTA, "Saleh Model" can be used [4]. In SSPA modelling, a four parameter Ghorbani model is intended for use [1]. Development of RAPP model which has a more realistic profile was also intended for SSPA [2].

The characteristics of a power amplifier can be described by some parameters. Each power amplifier has different AM/AM and AM/PM conversion curves, different efficiency and gains.

3.1.1. AM/AM and AM/PM Conversions

Numerous nonlinearity curves describing the behavior of power amplifiers can be obtained via experimental set ups for power amplifiers. In general, the amplitude transfer characteristics and the phase transfer characteristics define these nonlinearities. These are named as amplifier's amplitude modulation/amplitude modulation conversion (AM/AM) and amplitude modulation/phase modulation (AM/PM) conversion. The relation between the amplitude of the output signal and the amplitude of the input signal is expressed by AM/AM characteristic. When the input power level is much below the saturation point, then AM/AM shows a linear characteristic. In order to see the characteristics of AM/AM in nonlinear region, the input power should be increased beyond the saturation level of the output power. In other words, as the input power increases compression of gain takes place. The relationship between the phase shift of output signal and the amplitudes of input signal is defined by AM/PM characteristic. It should be noted that characteristic of AM/PM is constant in small signal region. When the input power of the power amplifier goes beyond a point such that saturation at the output occurs, phase shift at the output signal becomes more serious. As an example, AM/AM and AM/PM of Ghorbani Model are shown in Figure 7. AM/AM and AM/PM characteristics are important criteria for the analyze of the linearity of power amplifier.

3.1.2. Power Amplifier Efficiency

In order to get a signal at the output of the power amplifier, the amount of required input power is determined using the PA efficiency formula. Two types of parameters help to evaluate PA efficiency. The first one of them is drain efficiency and the second one is called power added efficiency.

Drain efficiency is defined as

$$\mathrm{H} = \frac{P_{out}}{P_{DC}} \tag{3.1}$$

where P_{out} is the amplifier output power and P_{DC} is the DC power consumption.

Power added efficiency (PAE) is defined as the power added by the amplifier ($P_{out} - P_{in}$) divided by the DC power consumption P_{DC}, i.e.,

$$\mathrm{PAE} = \frac{P_{out} - P_{in}}{P_{DC}} = \eta\left(1 - \frac{1}{G}\right) \tag{3.2}$$

where P_{in} is the PA input power and G is the gain of power amplifier.

The power that flows into amplifier input over a settled range of frequency or bandwidth is called input power, P_{in}. For the purposes of an initial testing, concentration of this input power into a single frequency component could be considered.

The power that flows out of amplifier over a settled range of frequency or bandwidth is called output power, P_{out}.

DC power is received from the power supply, P_{DC}. This value can be calculated or measured as the constant bias voltage multiplied by the average DC current at both drain and gate terminals [5].

3.1.3. Power Amplifier Gain

Gain characteristic of PA denotes the ratio between the output power and input power. Normally, it is presented in dB unit, defined by

$$G = 10log\frac{P_{out}}{P_{in}} \tag{3.3}$$

where P_{out} and P_{in} are the output and input powers of PA respectively. The gain is linear when the input power level is low, while it is non-linear when the input power is high.

Constant gain is secured by a power amplifier for input signal at low levels but in the case of high power levels gain decreases due to PA going into saturation. 1 dB compression point means the Decrease of gain by 1 dB from the constant value of gain [6].

3.2. Power Amplifier Nonlinearity

In this part, we will discuss the non-linearity of PAs. A power amplifier has some characteristics and these characteristics are: PA gain, conversions of AM/PM and AM/AM, the efficiency of PA. High power mode for PA must be provided to achieve high power efficiency levels. When the power amplifier has high input power, it enters the compression region. Constant gain is secured by a power amplifier for input signal at low levels but in the case of high power levels gain decreases due to PA going into saturation. As it is mentioned before 1 dB compression point means the decrease of gain by 1 dB from the constant value of gain. 1 dB compression is shown in Figure 2.

The nonlinear behavior of PAs can be divided into two main categories: memoryless and with memory [7]. When memory effects are not regarded, the nonlinearity of the PA is categorized as memoryless nonlinearity. In non-linearity with memory, the output of the PA output does not only rely on present sample of input, but it also relies on the past samples of input. This results in memory effects. Electrical and electro-thermal effects cause the memory effects which are also regarded as the dynamic distortion [8]. The memoryless nonlinearity effects of PAs are generally stronger than the one arising from memory effects.

Memoryless nonlinearity and nonlinearity with memory effect can be analyzed using mathematical models. Taylor polynomial can express the relation between the input and output signals for a memoryless nonlinear amplifier [9] as indicated in (3.4)

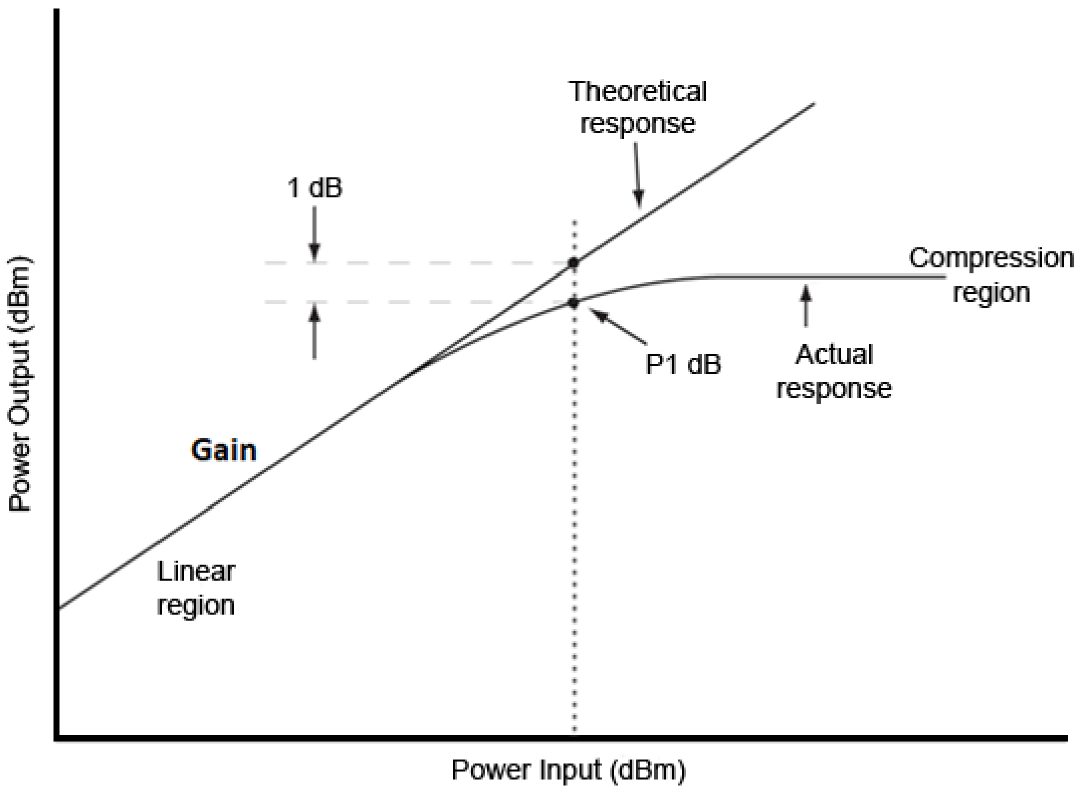

Figure 2: 1 dB Compression [38]

$$V_{out}(t) = a_1 V_{in}(t) + a_2 V_{in}^2(t) + a_3 V_{in}^3(t) + \cdots + a_n V_{in}^n(t) \quad (3.4)$$

where a_1, a_2, a_3 and a_n are the coefficients of Taylor polynomial. In memoryless nonlinearity modeling, memory effect is ignored. The single-tone signal can be expressed as

$$V_{in}(t) = A\cos(2\pi f t) \quad (3.5)$$

where A is the amplitude and f the frequency of the input signal. When we write this expression in Taylor Series, PA's output responses are obtained that contains the original signal and some harmonics. A typical PA characteristic is depicted in Figure 2.

As seen in Figure 3, when input goes into a nonlinear system, it comes out as a nonlinear output. In Figure 4, when the input signal is examined, it is seen that the input signal has two-tone f1 and f2 frequency. In Figure 5, a third-order intermodulation distortion at the output of a nonlinear system is observed.

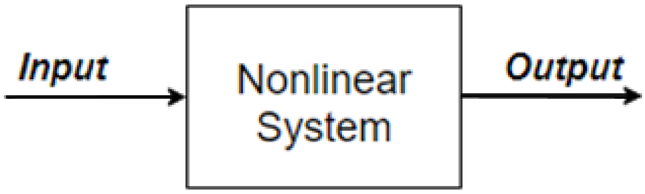

Figure 3: Block Diagram of Nonlinear System

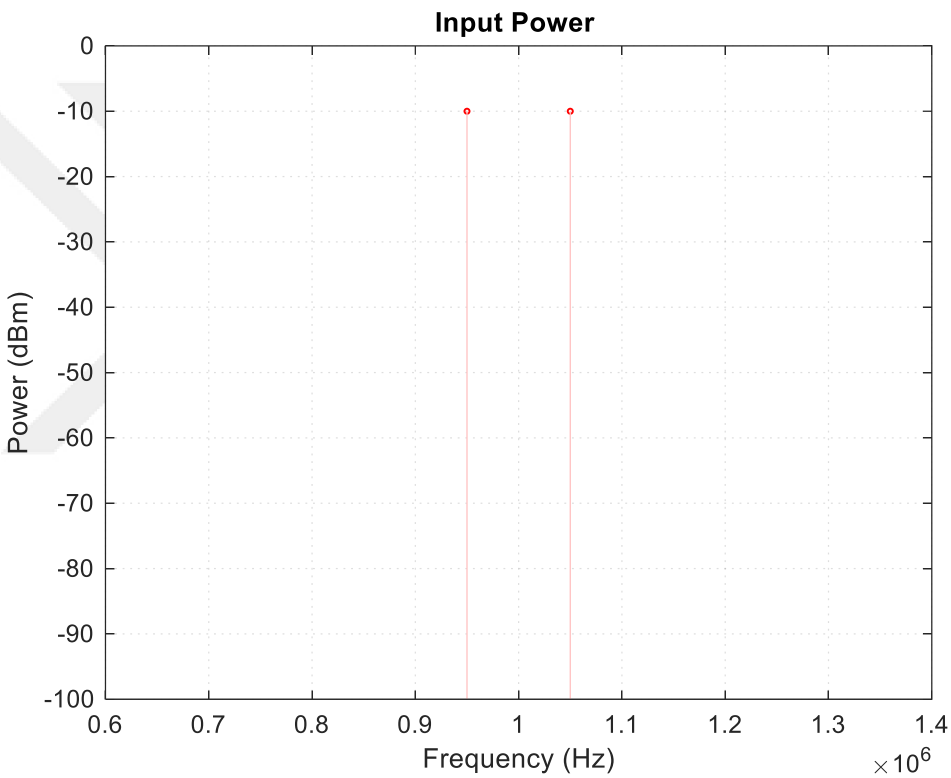

Figure 4: Input Power of Nonlinear System [36]

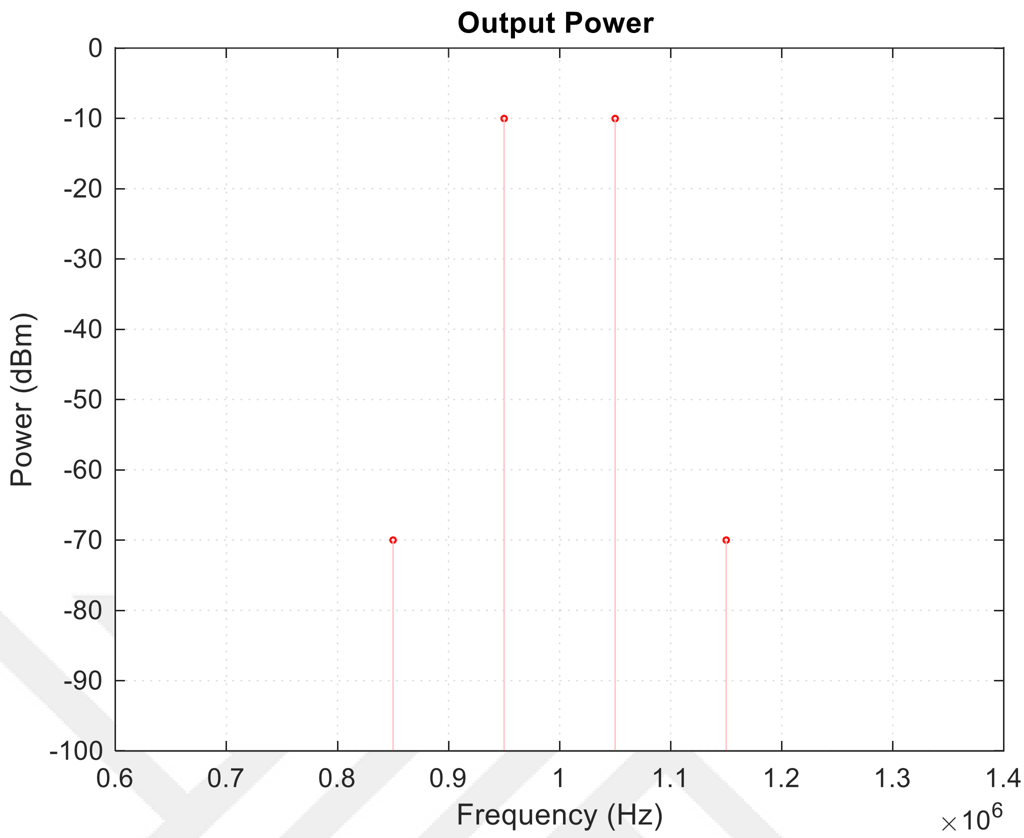

Figure 5: Output Power of Nonlinear System [36]

The Volterra series is a series of mathematics capable of representing a non-linear system with memory effects [10]. Discrete time Volterra series are in used in digital systems and they can be expressed as [11]:

$$y(k) = \sum_{n=0}^{\infty} y^{(n)}(k) \tag{3.6}$$

$$y^{(n)}(k) = \sum_{j_1=-\infty}^{\infty} \sum_{j_2=-\infty}^{\infty} \dots \sum_{j_n=-\infty}^{\infty} h^{(n)}(j_1, j_2, \dots, j_n) x(k-j_1) x(k-j_2) \dots x(k-j_n) \tag{3.7}$$

where $h^{(n)}$ are the kernels of the system, x is the input, and y is the output.

3.3. Power Amplifier Models

This Chapter introduces some Power Amplifier Models. PA models are divided into two main categories which are memoryless and some memory based models. We will first explain the memoryless PAs. For memoryless PA models, it is simple to estimate their parameters and measurements required to estimate the parameter are quite simple to perform. Then, memory based PA models are explained. In memory based PA models, the amplifier shows frequency-dependent behavior when the input signal's bandwidth is comparable to the amplifier bandwidth.

3.3.1. Polynomial Model

For narrow-band system, memoryless PA models are employed due to the insignificance of the memory effects. The polynomial model exhibits memoryless PA behavior. Amplitude conversion function of the polynomial model can be expressed as

$$y(t) = \sum_{k=1}^{N} a_k \, x(t)|x(t)|^{k-1} \tag{3.8}$$

and phase conversion function of polynomial model is expressed as

$$\Phi_k(t) = |x|^{k-1} \, x \tag{3.9}$$

In even terms of order improvement of accuracy takes place. (3.8) has even order terms [12]. But this increases the complexity. Therefore, even terms can be ignored [13]. Below, odd order polynomial model is presented,

$$y(t) = \sum_{k=0}^{N} a_k \, x(t)|x(t)|^{2k} \tag{3.10}$$

where, $y(t)$ is the output signal and $x(t)$ is the input signal. The coefficients a_k can be estimated using least squares approximation.

3.3.2. Saleh Model

Saleh model was presented by Adel A. M. Saleh and this model is used for modeling the behaviors of TWTA (Traveling wave tube amplifiers) [4]. Amplitude (AM/AM conversion) and phase (AM/PM conversion) functions are expressed as

$$y(A) = \frac{a_a A}{1 + \beta_a A^2} \tag{3.11}$$

$$\Phi(A) = \frac{a_\Phi A^2}{1 + \beta_\Phi A^2} \tag{3.12}$$

where A is the amplitude of the signal and $a_a, \beta_a, a_\Phi, \beta_\Phi$ are coefficients. In Figure 6, Saleh Model AM/AM and AM/PM conversion is observed. When the amplitude curve is observed, it can be said that as the power increases, nonlinearity also increases.

3.3.3. Ghorbani Model

Ghorbani model was presented for modelling Solid State Power Amplifiers (SSPA). The Ghorbani model has a very similar approach to the Saleh model, the amplitude (AM / AM conversion) and phase (AM / PM conversion) functions are given as [1],

$$y(A) = \frac{a_0 A^{a_1}}{1 + a_2 A^{a_1}} + a_3 A \tag{3.13}$$

$$\Phi(A) = \frac{b_0 A^{b_1}}{1 + b_2 A^{b_1}} + b_3 A \tag{3.14}$$

where A is the amplitude of the signal and $a_0, a_1, a_2, a_3, b_0, b_1, b_2, b_3$ are coefficients.

In Figure 7, Ghorbani model AM/AM and AM/PM conversion is observed. When the amplitude curve is observed, it can be said that as the power increases, nonlinearity also increases in similarity with the Saleh model.

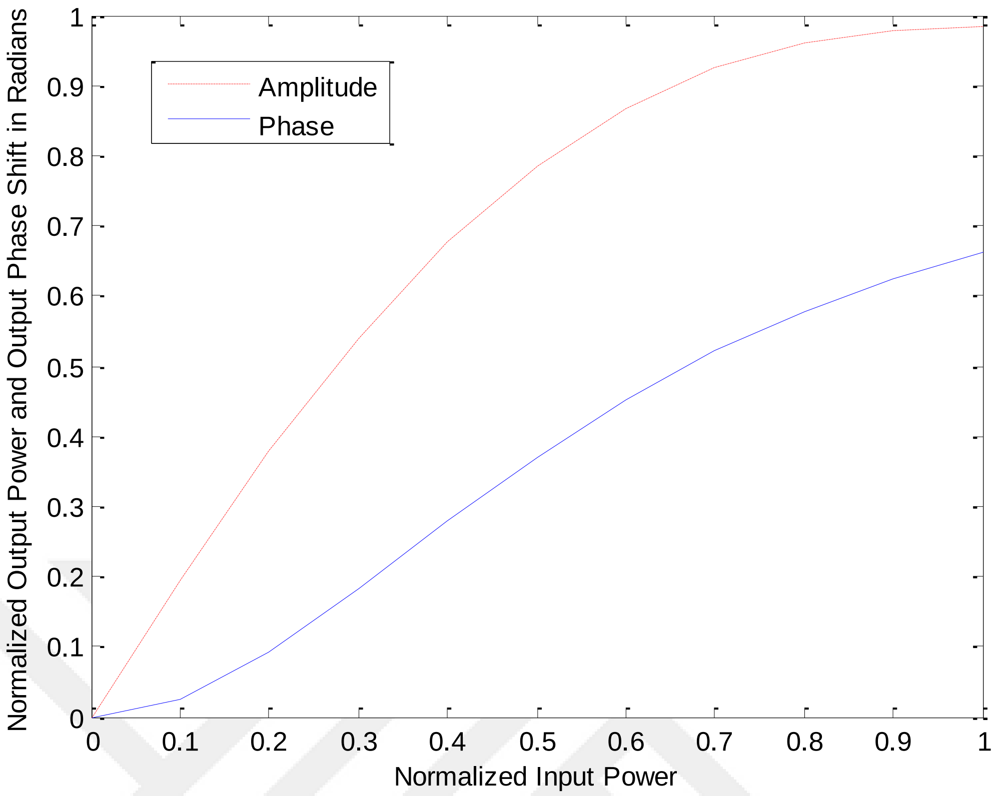

Figure 6: Saleh Model AM/AM and AM/PM Conversion

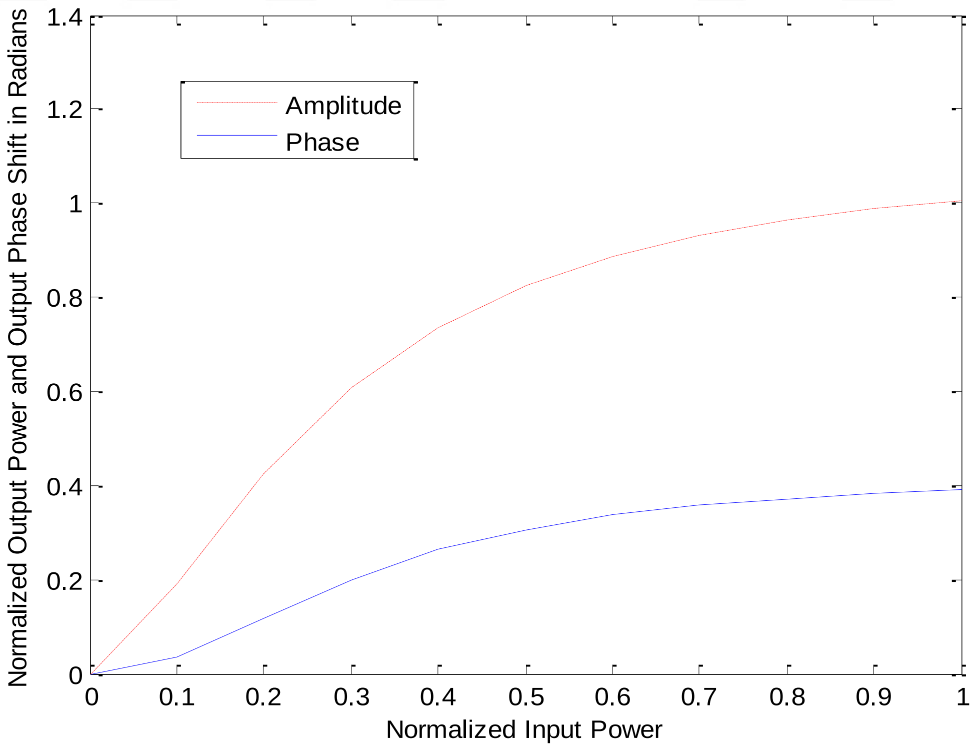

Figure 7: Ghorbani Model AM/AM and AM/PM Conversion

3.3.4. Rapp Model

The Rapp model was presented by Christopher Rapp with a different approach from the Saleh and Ghorbani models. SSPAs exhibit a more linear behavior than TWTA in small signal regions. Output signal becomes clipped for large inputs. The phase (AM/PM conversion) is assumed to be small enough. So, the phase can be ignored. The amplitude (AM/AM conversion) and phase (AM/PM conversion) functions are expressed as

$$y(A) = v \frac{A}{\left[1 + \left(\frac{v\,A}{A_0}\right)^{2p}\right]^{\frac{1}{2p}}} \tag{3.15}$$

$$\Phi(A) \approx 0 \tag{3.16}$$

where v is the small signal gain, A_0 is the limiting output amplitude (saturation voltage) and meter p is the smoothness of the transition from the linear region to the limiting region. As shown in the Figure 8, for smoothness factor $p = 3,$ nonlinearity is improved as opposed to Ghorbani Model [2].

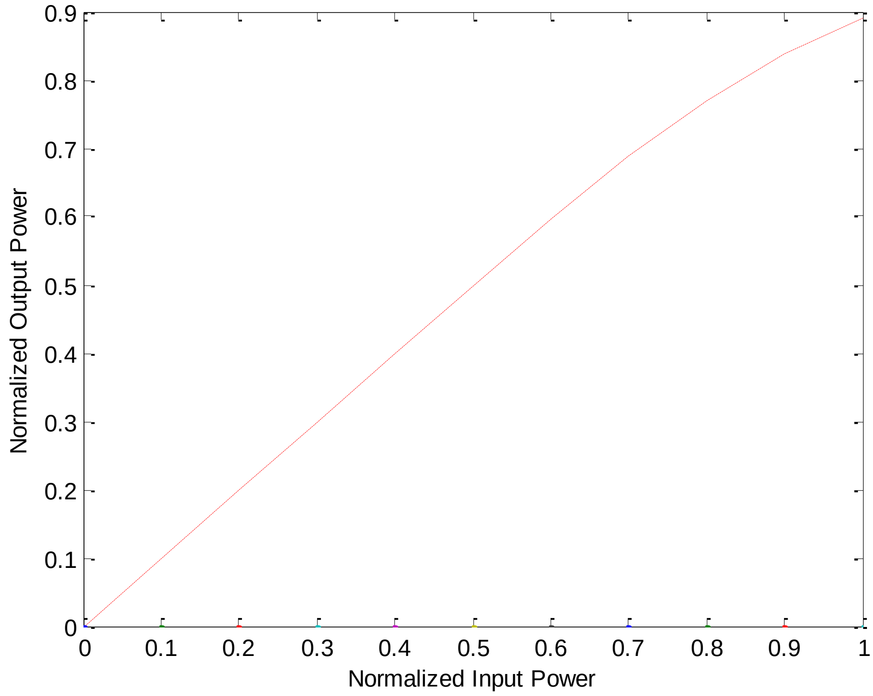

Figure 8: Rapp Model AM/AM and AM/PM Conversion

3.3.5. White Model

White model was presented for the accurate modelling of amplitude and phase characteristics of Ka-band (26-40 GHz) SSPAs [14]. The amplitude and phase conversions functions are expressed as

$$y(A) = a_0(1 - e^{-a_1 A}) + a_2\, A\, e^{-a_3 A^2} \tag{3.17}$$

$$\Phi(A) = \begin{cases} b_0\left(1 - e^{-b_1(A-b_2)}\right), & A \geq b_2 \\ 0, & A < b_2 \end{cases} \tag{3.18}$$

where $y(A)$ is the output amplitude and A is the normalized input amplitude. The parameter a_0 represents the saturation level, a_1 is the linear region gain, a_2 and a_3 are used to match the high linearity. $\Phi(A)$ is the output phase shift and this is controlled by b_0, b_1 and b_2 parameters. b_0 is the magnification, b_1 is the steepness and b_2 controls the shift along the input power axis. The parameters $a_0, a_1, a_2, a_3, b_0, b_1$ and b_2 can be obtained by least squares curve fitting. In Figure 9, White Model AM/AM and AM/PM conversion is observed.

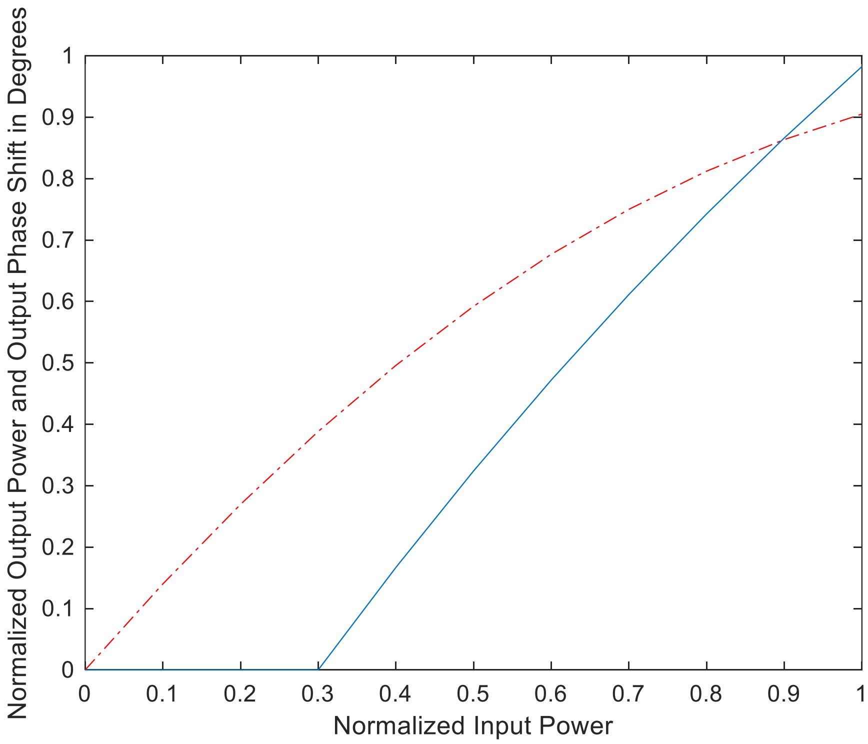

Figure 9: White Model AM/AM and AM/PM Conversion

3.3.6. Volterra Series Model

Volterra series models were presented by Vito Volterra for the nonlinear power amplifiers with memory effects which can be characterized by the Vito series expansion. Mathematical expression of Volterra model is given as

$$y(k) = h_0 + \sum_{p_1 = 1}^{\infty} h_1(p_1)x(k - p_1) \tag{3.19}$$
$$+ \sum_{p_1=0}^{\infty}\sum_{p_2=0}^{\infty} h_2(p_1, p_2)x(k - p_1)x(k - p_2)$$
$$+ \sum_{p_1=0}^{\infty}\sum_{p_2=0}^{\infty} \dots \sum_{p_n=0}^{\infty} h_n(p_1, p_2, \dots, p_n)x(k - p_1)x(k - p_2)\dots x(k - p_n)$$
$$+ \dots$$

where $h_n(p_1, p_2, \dots, p_n)$ represent the Volterra kernels [15].
Volterra model can be written in a simpler form as

$$y(k) = h_0 + \sum_{p=1}^{\infty} h_n[x(k)] \tag{3.20}$$

where $h_n[x(k)]$ is expressed as

$$h_n[x(k)] = \sum_{p_1=0}^{\infty}\sum_{p_2=0}^{\infty} \dots \sum_{p_n=0}^{\infty} h_n(p_1, p_2, \dots, p_n)x(k - p_1)x(k - p_2)\dots x(k - p_n) \tag{3.21}$$

The total multiplication amount required for the Volterra model is a complexity measure, referred to as $C(N, M)$ which is calculated as

$$C(N, M) = \sum_{n=1}^{N} \frac{(M - 1 + n)!}{(n - 1)!\,(M - 1)!} \tag{3.22}$$

where N is the nonlinearity order and, M is the memory [16].-

3.3.7. Memory polynomial model

Memory polynomial model was presented to simplify Volterra Series model. Memory polynomial model is defined as

$$y(n) = \sum_{p=0}^{P-1}\sum_{r=0}^{R-1} a_{pr}x(n-r)|x(n-r)|^{p} \quad (3.23)$$

where a_{pr} are coefficients of the model, P and R are the memory sizes. There are a number of other PA memory polynomial models proposed in [18].

3.3.8. Generalized memory polynomial model

Generalized memory polynomial model was presented for another simple Volterra Series model. It is obtained by combining the delayed memory polynomial model version with the memory polynomial model using both positive and negative cross-term time shifts. This cross-term model has the advantage that the coefficients appearing in linear form just like in the case in memory polynomial [17], and the model is given as

$$\begin{aligned} y(n) = & \sum_{p=0}^{P_a-1}\sum_{r=0}^{R_a-1} a_{pr}x(n-r)|x(n-r)|^{p} \\ & + \sum_{p=1}^{P_b}\sum_{r=0}^{R_b-1}\sum_{s=1}^{S_b} b_{prs}x(n-r)|x(n-r-s)|^{p} \\ & + \sum_{p=1}^{P_c}\sum_{r=0}^{R_c-1}\sum_{s=1}^{S_c} c_{prs}x(n-r)|x(n-r+s)|^{p} \end{aligned} \quad (3.24)$$

where P_a and R_a are the number of coefficients for aligned signal and envelope from memory polynomial, P_b, R_b and $S_b$are the number of coefficients for aligned signal and delayed envelope, and P_c, R_c, S_c are the number of coefficients for signal and leading envelope.

3.3.9. Hammerstein Model

Hammerstein Model is a simplified Volterra Model. The model employs a memoryless nonlinear model and finite impulse response (FIR) filter. Block diagram of Hammerstein model is shown in Figure 10. Mathematical expression of this model in combined form is given as [17] [19]

$$y(n) = \sum_{m=0}^{M-1} h(m) \sum_{k=1}^{K} a_k x^k(n-m) \tag{3.25}$$

Mathematical expressions of this model in separate forms are given as

$$z(n) = \sum_{k=0}^{K} a_k\, x(n)|x(n)|^k \tag{3.26}$$

$$y(n) = \sum_{m=0}^{M} h_m\, z(n-m) \tag{3.27}$$

where a_k and h_m are the coefficients of model, K is the order of nonlinearity and M is the memory size.

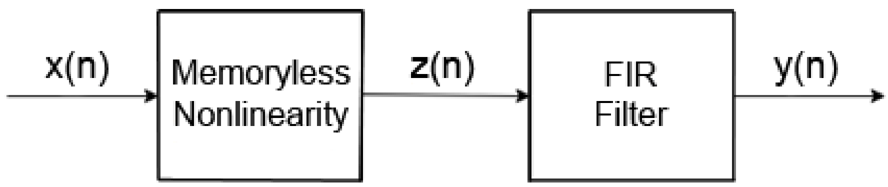

Figure 10: Block Diagram of Hammerstein Model

As mentioned before, this model is divided into two parts. In Figure 10, $x(n)$ is the input signal of model, $z(n)$ is the output of the memoryless nonlinear part and $y(n)$ is the output of the model which is the output of the FIR filter.

3.3.10. Wiener Model

Wiener Model, just like the Hammerstein Model, is a simplified Volterra Model consisting of two separate blocks. The model is the opposite of the Hammerstein Model. Mathematical expression of this model in combined form is given as [17]

$$y(n) = \sum_{k=1}^{K} a_k \left[\sum_{m=0}^{M-1} h(m)x(n-m) \right]^k \tag{3.28}$$

Mathematical expressions of this model in separate form are given as

$$z(n) = \sum_{m=0}^{M} h_m \, x(n-m) \tag{3.29}$$

$$y(n) = \sum_{k=0}^{K} a_k \, z(n)|z(n)|^k \tag{3.30}$$

where a_k and h_m are the coefficients of model, K is the order of nonlinearity and M is the memory.

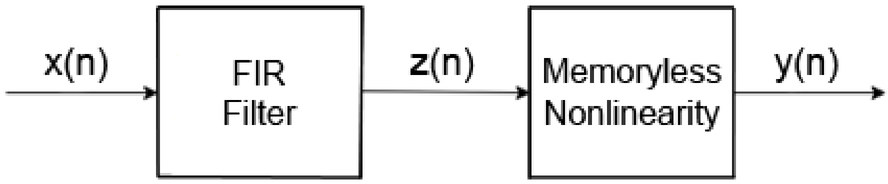

Figure 11: Block Diagram of Wiener Model

In Figure 11, $x(n)$ is the input signal of model, $z(n)$ is the output of the FIR filter part and $y(n)$ is the output of the model which is the output of the memoryless nonlinear part.

CHAPTER 4

DIGITAL PREDISTORTION (DPD)

In this chapter, DPD is explained in details. Section 4.1 gives the general logic and details of the digital predistortion. Predistortion implementation techniques are explained in subsection 4.1.1. In Section 4.2., some performance metrics related to predistortion are given, NMSE (normalized mean square error) and ACPR (adjacent channel power ratio) are described. In section 4.3, learning architectures are explained.

4.1. General Logic of Digital Predistortion

Predistortion is a method of obtaining linear amplification and high power efficiency. It enables the amplifier to function at a large values of input power by correcting the distortion which occurs due to the nonlinearity. Predistortion is a must issue for power amplifiers since beyond the point of saturation, any increment in input power does not result in any further increment in the output power. Therefore, predistortion is employed before the power amplifier. The predistortion unit produces a distortion on the input signal, and the distorted signal is fed to the power amplifier whose gain shows a linear characteristic to the predistorted input signal. The predistortion operation is illustrated in Figure 12.

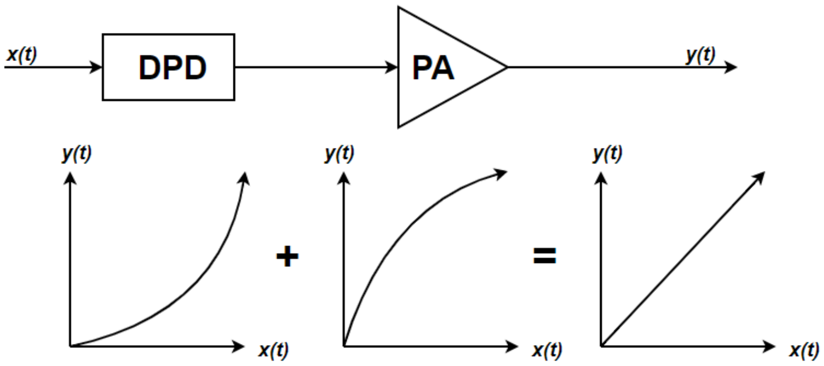

Figure 12: Illustration of Digital Predistortion

The linearization performance depends directly on how accurately the power amplifier's AM / AM and AM / PM responses are modeled. With poor modeling, there will also be poor linearization.

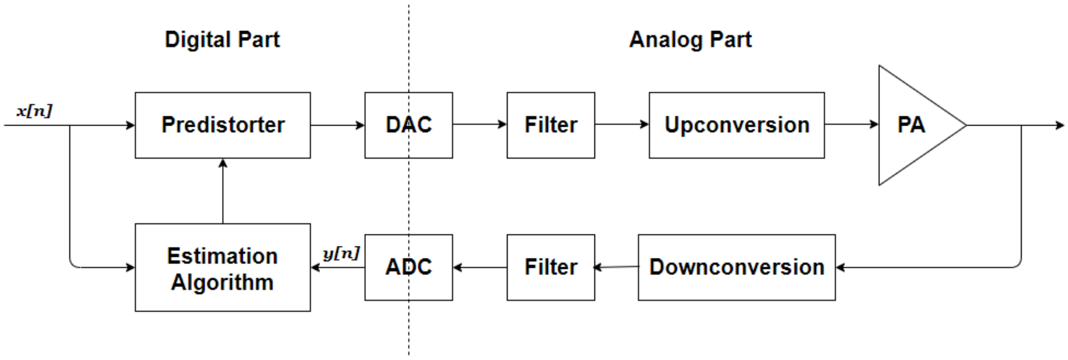

Figure 13: Basic Prodistortion Architecture

The baseband samples go through the predistor and the predistor's output is sent to the DAC which passed through a lowpass filter, and then upconversion is applied to the filter output before the power amplifier. The output of the power amplifier is splitted into two components: one for antenna transmission and one for predistorter feedback. Downconversion occurs in the latter part, after that passing through lowpass filter and sampling by ADC is carried out. An estimation algorithm is used for the evaluation of the coefficient used in predistorter model. In general, characteristics (AM/AM and AM/PM responses of the power amplifier) curves are learned by predistorter by the use of the feedback path. The data that is sent and received from the power amplifier by predistorter is known by training data. By the use of this information, it adapts and distorts the baseband samples to compensate for the distortion of the power amplifier. In terms of adaptability, the predistorter technique is made a strong technique by the employment of the feedback path. However, it introduces the issue of stability and the complexity of hardware and software. The issue of stability must be considered and predistorters must be prevented from entering into unstable operation.

4.1.1. Predistortion Implementation Techniques

There are two most commonly used predistortion implementation techniques. These are predistorter based on LUT (Look Up Table) and predistorter based on polynomials. Figure 14 shows the block diagram of LUT based predistortion. As seen in this figure, a look-up table contains complex coefficients. Depending on its amplitude, multiplication of the incoming signal with the coefficients included in LUT is performed. The input signal is adjusted using the look-up table which contains coefficients modeling the amplifier's inverse characteristic. Thus, the predistorter and the power amplifier produces a linear gain [25].

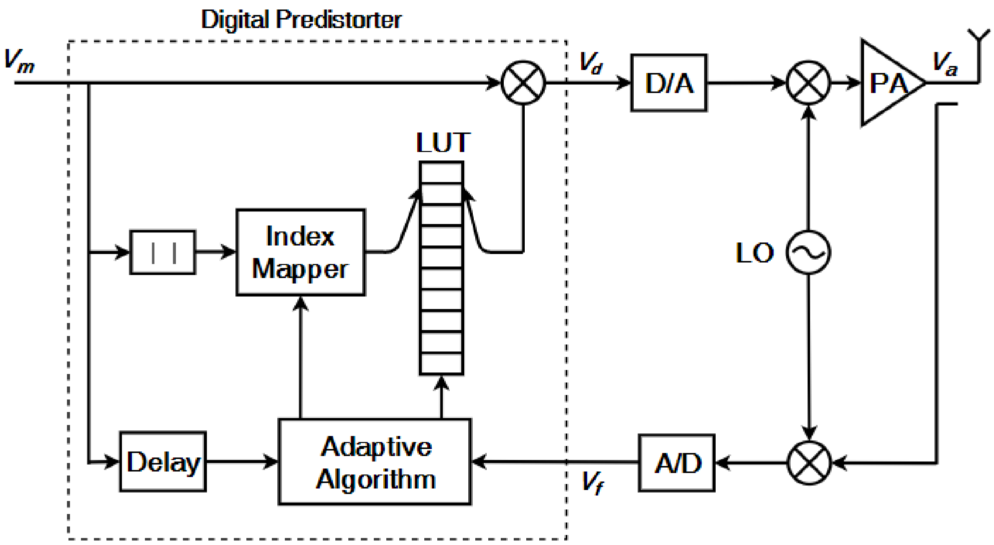

Figure 14: Block Diagram of LUT Based Predistortion [27]

In polynomial modelling of predistortion, a polynomial function is used and the polynomial coefficients are adapted such that the combined characteristic of power amplifier and the predistorter is linear. The performance of the predistortion relies on the order of the polynomial. In particular, in the neighboring frequency band, 5th order polynomials are needed to suppress IMD (Intermodulation Distortion) products [26]. Figure 15 shows the block diagram of a communication system employing polynomial predistorter.

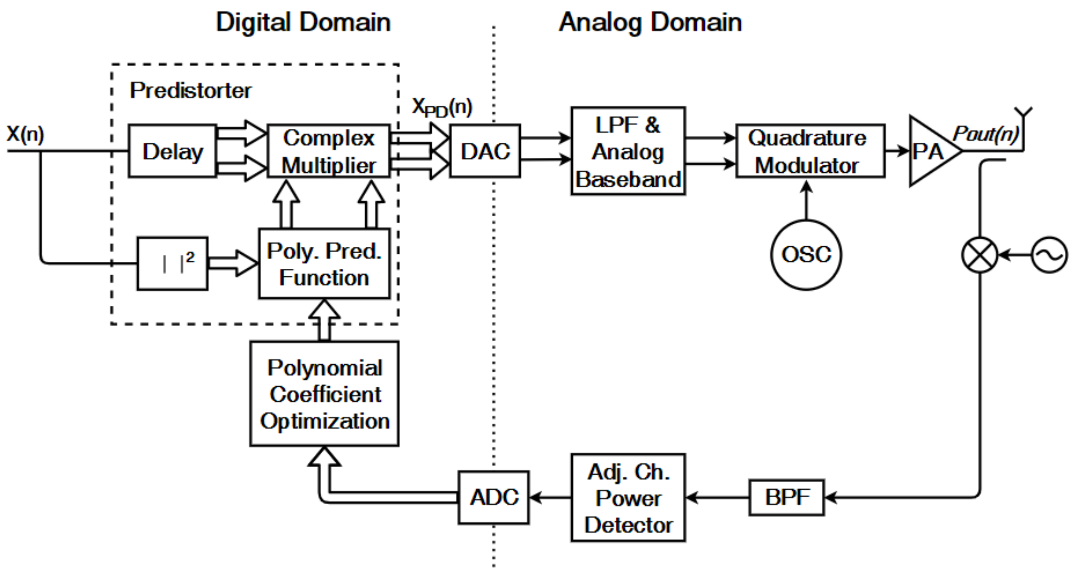

Figure 15: Block Diagram of Communication System Employing Polynomial Based Predistortion [28]

4.2. Performance Metrics

Many different predistortion methods have been proposed in the literature. There are some performance metrics to compare the performance of these methods. Under this heading, the most commonly used performance metrics for power amplifier behavior and predistortion are presented.

4.2.1. Normalized Mean Squared Error

The normalized mean square error (NMSE) is a performance criterion frequently used in linearization of power amplifiers (PA) to quantify the quantity of distortion at the PA output [29]. The normalized mean square error (NMSE) is defined as

$$NMSE = \frac{\sum_{n=0}^{N-1} |y(n) - \hat{y}(n)|^2}{\sum_{n=0}^{N-1} |y(n)|^2} \tag{4.1}$$

where $y(n)$ indicates the signal measured at the output of the PA and $\hat{y}(n)$ denotes the output of the mathematical model. Because the in-band error dominates the NMSE, it is used for evaluating the model's in-band efficiency.

4.2.2. Adjacent Channel Power Ratio (ACPR)

Adjacent channel power ratio (ACPR) is a measurement of signal spreading through neighboring channels caused by power amplifier nonlinearities. ACPR is defined as the ratio of the out-of-band signal power in the adjacent channel to the in-band signal power as,

$$ACPR(B) = \frac{\int_{f_0-3B}^{f_0-B} S_0(f)df + \int_{f_0+B}^{f_0+3B} S_0(f)df}{\int_{f_0-B}^{f_0+B} S_0(f)df} \tag{4.2}$$

where $[-B, B]$ is the desired bandwidth, and $S_0(f)$ is the power spectral density of the amplified signal $s_0(t)$ [30].

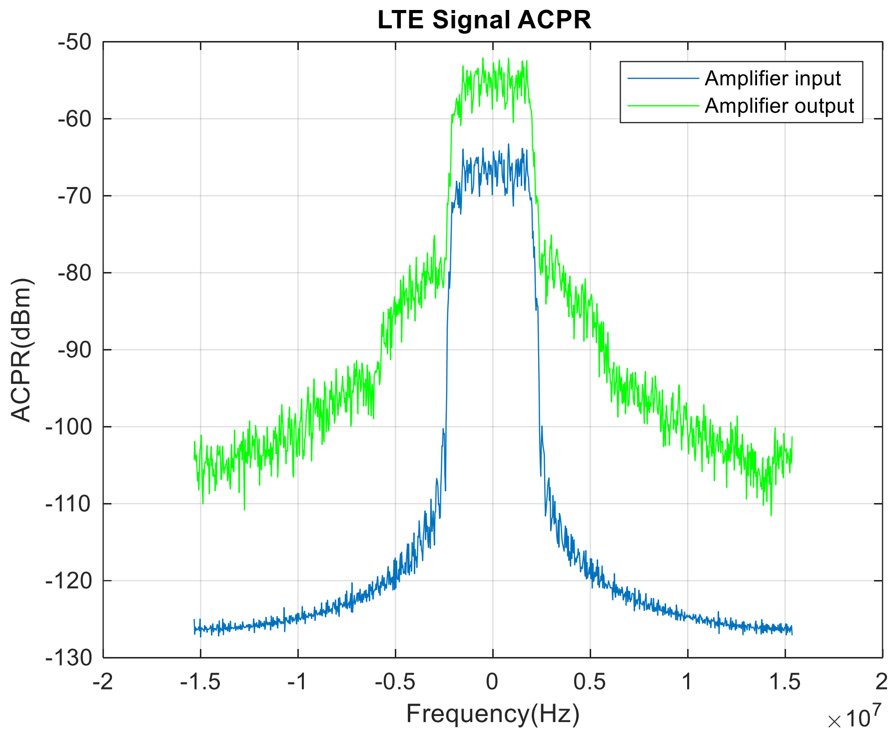

Figure 16: LTE Signal ACPR [34]

4.2.3. Adjacent Channel Leakage Ratio (ACLR)

The adjacent channel leakage ratio (ACLR) is a performance metric of DPD. It measures the power leaked into the adjacent channels with respect to the signal power in the main channel [31]. The ACLR is defined as,

$$ACLR = \max_{k=1,2}\left[\frac{\int_{(adjacent)_k}|S(f)|^2}{\int_{channel}|S(f)|^2}\right] \quad (4.3)$$

where $S(f)$ denotes the power spectrum of the output signal $s(n)$. Integration in the numerator is taken over the adjacent channels, and the integration in the denominator is taken over the transmission channel. ACLR is expressed in dB. In Figure 17, an analysis of LTE signal ACLR is depicted.

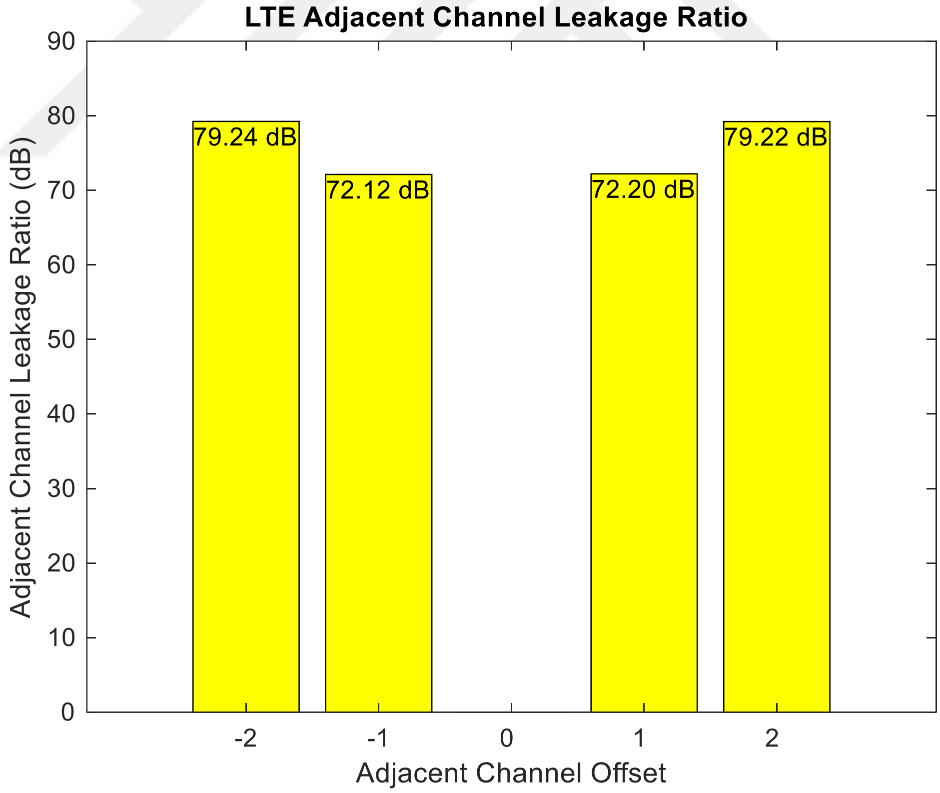

Figure 17: LTE Signal ACLR [35]

4.3. Learning Architecture

The learning architectures of the digital predistorter is divided into two main categories. These are direct learning architecture (DLA) and indirect learning architecture (ILA). In DLA approach, the behavior of PA model is predefined and determination of its co-efficients is performed in the next step, and using the inverse of PA model, the predistorter is designed. In ILA approach, first, a postdistorter model is presumed, the PA output is taken as a postdistorter input. Then estimation algorithms such as Least Squares (LS) are used to estimate the postdistorter. Lastly, the postdistorter is used before the PA as its predistorter [32]. The ILA and DLA techniques are explained in this chapter.

4.3.1. Indirect Learning Architecture

In ILA, the postdistorter design is performed first. Usually, modelling of the postdistorter is achieved using a memory polynomial [33]. The output of the postdistorter in [32] is expressed as

$$z_p(n) = \sum_{k=0}^{K} \sum_{l=0}^{L} a_{kl} \Phi_{kl}[z(n)] \tag{4.4}$$

where $z(n) = \frac{y(n)}{G_0}$, G_0 is the desired gain, a_{kl} are the complex valued coefficients, $\Phi_{kl}[z(n)] = z(n-k)|z(n-k)|^{2l}$, K is the memory depth and $2l+1$ is the largest nonlinearity order. For a perfect system, $z_p(n) = x(n)$ equality is required. Figure 18 represents block diagram of ILA.

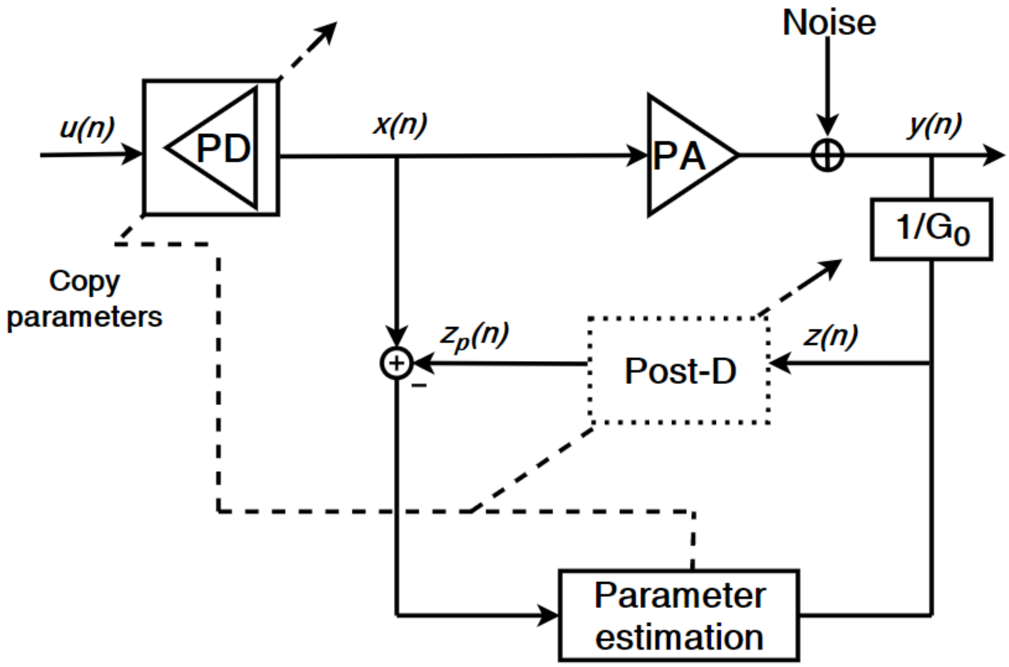

Figure 18: Block Diagram of ILA [32].

4.3.2. Direct Learning Architecture

The design of the digital predistortion using DLA consists of two stages. In the first stage, the behavior model of PA must be identified. A memory polynomial can be used for the modeling of PA. The model for PA is described in [32] as

$$y(n) = \sum_{p=0}^{P}\sum_{q=0}^{Q} c_{pq}\Phi_{pq}[x(n)] \tag{4.5}$$

where c_{pq} are the coefficients of the model, $\Phi_{pq}[x(n)] = x(n-p)|x(n-p)|^{2q}$, P is the memory depth and $2q+1$ is the largest nonlinearity order. Calculating the inverse of the PA model, the design of the predistortion is achieved. Figure 19 represents the block diagram of DLA.

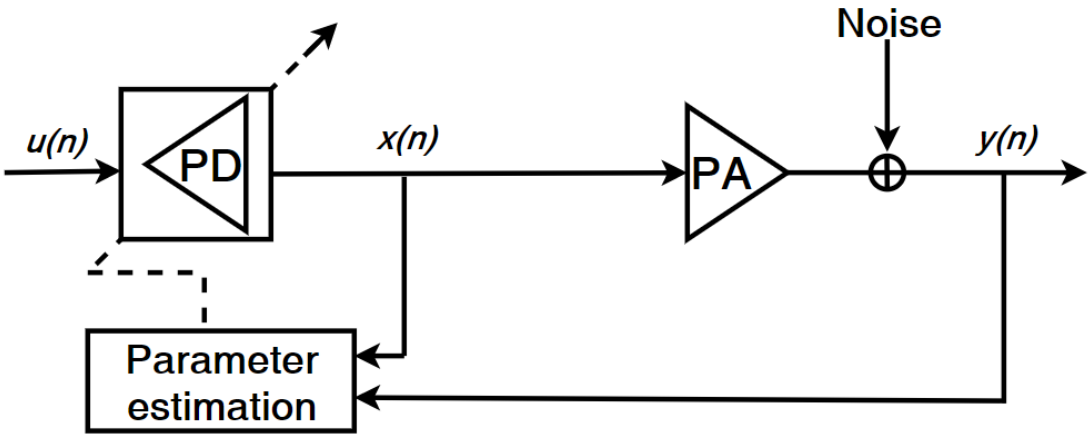

Figure 19: Block Diagram of DLA [32].

Chapter 5

Proposed DPD Method

In this chapter, the proposed DPD method is explained. The proposed DPD method is simulated with modeled PA and compared to other PA models. In addition, some performance metrics were used to analyze the proposed DPD method. These performance metrics are normalized mean square error (NMSE), adjacent channel power ratio (ACPR) and power spectral density (PSD). Detailed information about the performance metrics can be found in chapter 4.

5.1. The Proposed DPD Method

The proposed method is based on the $sinc$ function. This method also can be called DPD with reconstruction. The mathematical expression of $sinc$ function (5.1) and its graph is given in Figure 20.

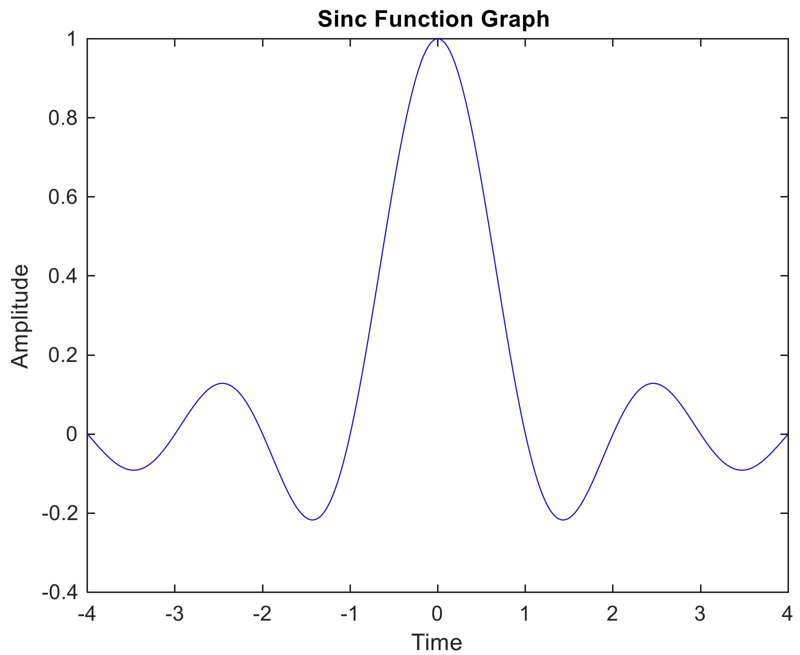

Figure 20: Sinc Function Graph

$$sinc(t) = \frac{\sin(\pi * t)}{\pi * t} \tag{5.1}$$

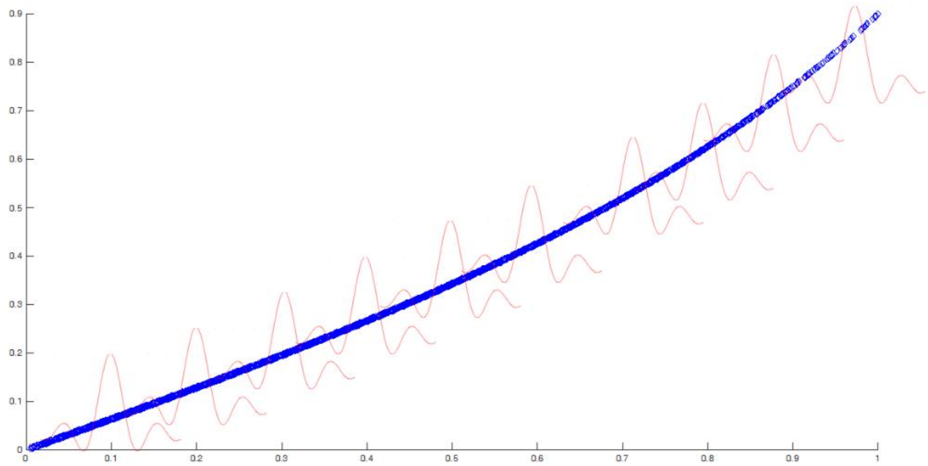

Figure 21: The Shifted and Scaled Sinc Functions Used for Reconstruction

In our proposed approach, we consider the reconstruction of a signal from its samples. For this purpose, we consider the horizontal axis as the input of a nonlinear function and the vertical axis as the output of the nonlinear function. The digital data along the horizontal axis is considered as the sampling instants of the nonlinear function, i.e., signal. The digital data along the vertical axis is considered as the sample values taken from the nonlinear function.

The reconstruction of the nonlinear function is achieved using

$$\sum_{n=1}^{N} y[n] * \ sinc\left[\frac{(x - x[n])}{T_s}\right] \tag{5.2}$$

where $y[n]$is the output sample, x is the input parameter, $x[n]$ is the input sample, T_s is sampling period and N is the length of the input array, i.e., number of sampling instants. If the sampling period is not known, an approximate value can be determined using the absolute value of the minimum difference between consecutive instants along the horizontal axis.

The main advantage of this method is that the method can achieve optimum values with sinc function. Thus, a model that can fit to real measurement data can be obtained.

Changing the roles of horizontal and vertical axises, the design of the predistortion can be performed using the proposed method. In Figure 22, the input-output characteristic of the PA obtained via measurement data, and its mathematical modeling using the reconstruction approach is depicted. Switching the axises of the PA characteristic, and modeling it using the reconstruction approach as depicted in Figure 23, we obtain the predistortion model for PA. In practical systems, the input signal first passes through the DPD block and then the output of the DPD block is fed to the PA. In this way, we obtain a linear relation between the input and output of the PA.

Using the proposed predistortion modeling, we get the linear PA model depicted in Figure 24.

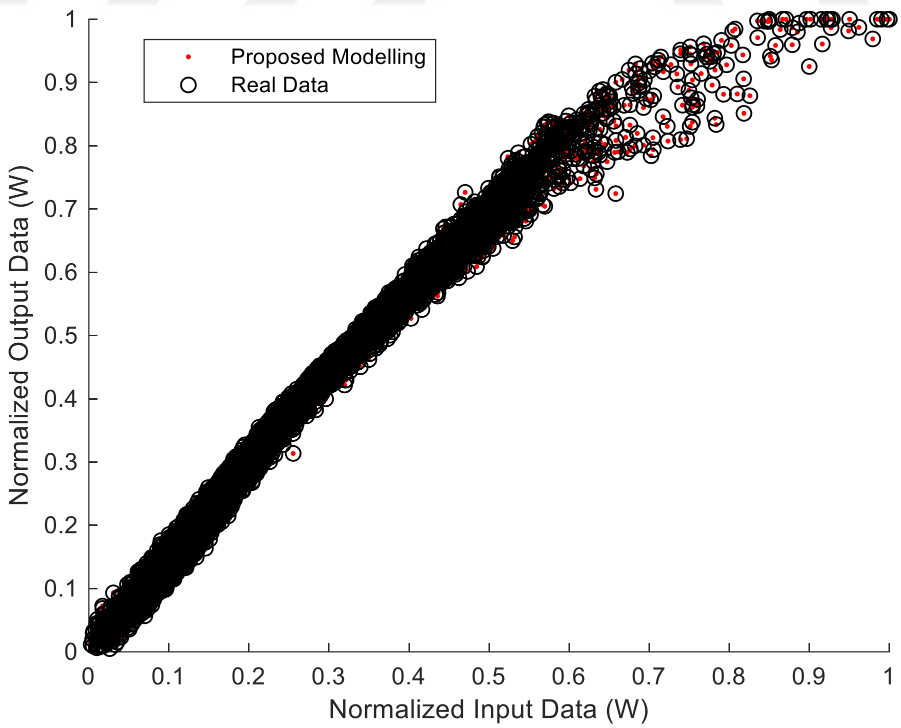

Figure 22: PA AM/AM Modeling

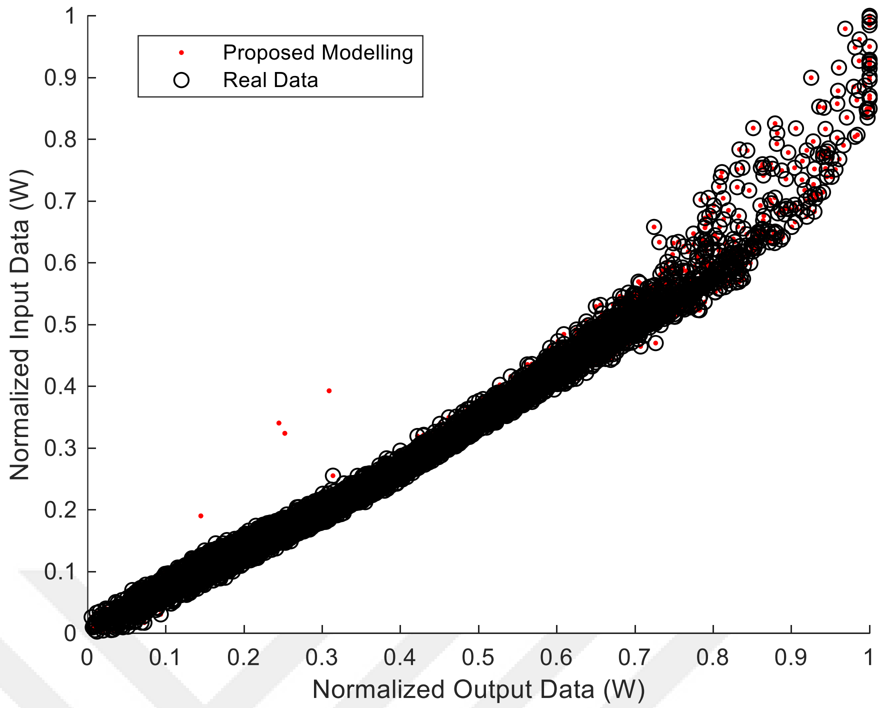

Figure 23: PA Predistortion Modeling

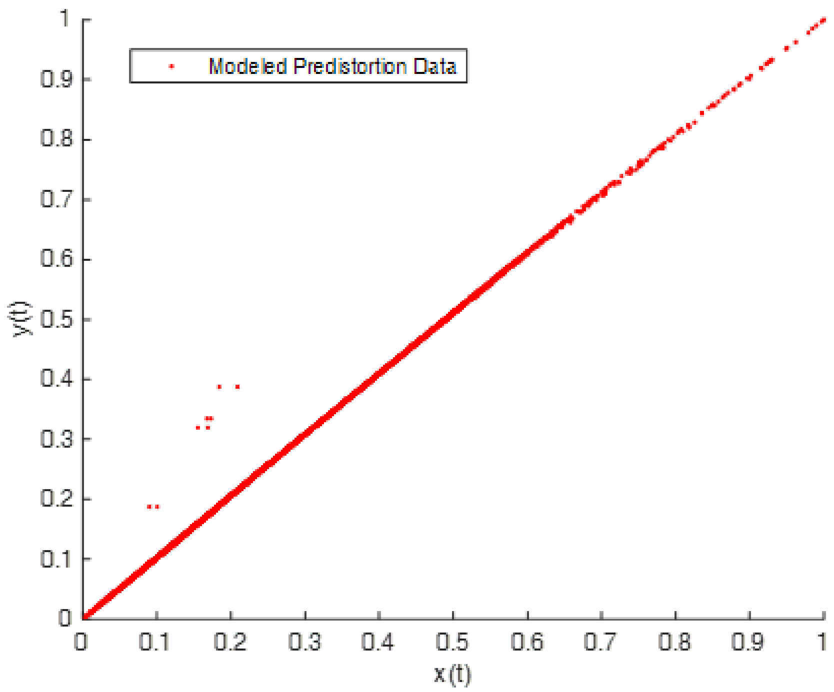

Figure 24: PA AM/AM Characteristic with Predistorded Data

If we use Saleh model for PA, we obtain the model shown in Figure 25 for AM/AM conversion of PA, and the model in Figure 26 for the predistortion.

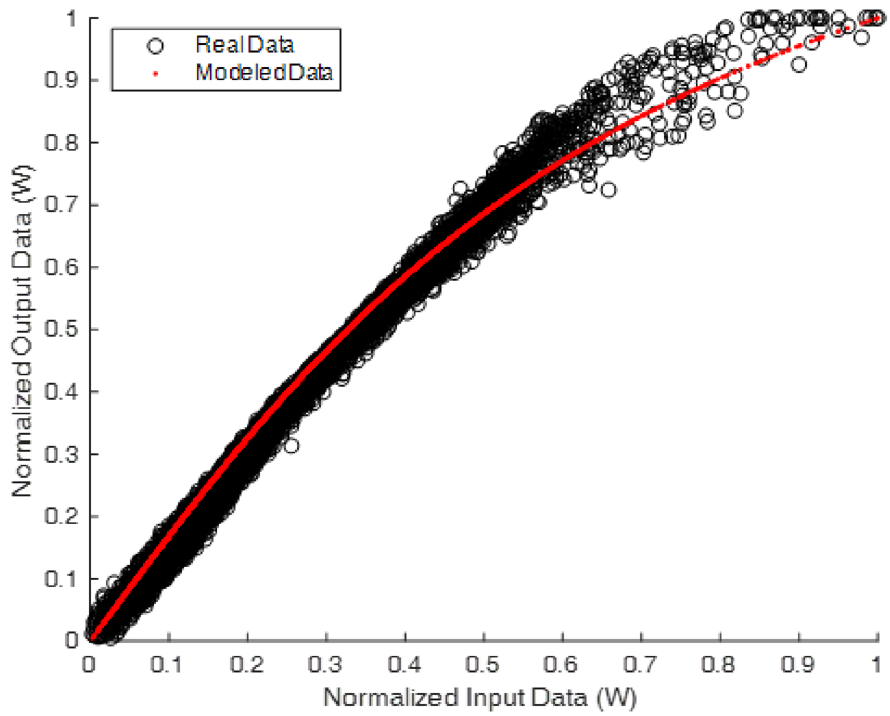

Figure 25: Inverse Saleh Model PA AM/AM Conversion

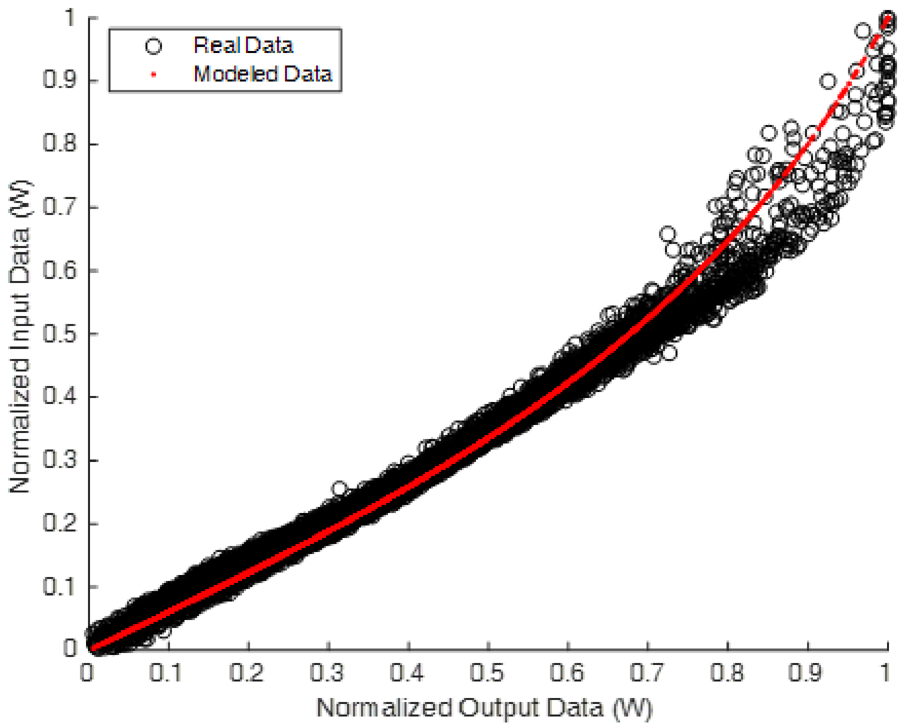

Figure 26: Saleh Model PA AM/AM Conversion

5.2. Performance Analyses

The performance of the predistortion is analyzed using some performance metrics. These performance metrics are normalized mean square error (NMSE), adjacent channel power ratio (ACPR) and power spectral density (PSD).

5.2.1. Normalized Mean Square Error (NMSE)

This performance metric was applied to PA models used which are, Saleh and Ghorbani PA models. Measurement data set includes 10000 samples.

Parameters of PA models are selected in such a way to fit to the real data. The obtained NMSE results are as:

- ❖ Modeled PA NMSE = 0.0039
- ❖ Saleh PA Model NMSE = 0.0062
- ❖ Ghorbani PA Model NMSE = 0.0051

5.2.2. Adjacent Channel Power Ratio (ACPR)

Figure 27 shows Modeled PA ACPR analysis graphic. Detailed information about Adjacent Channel Power Ratio is given in Chapter 4 and results and discussions are given in Chapter 6.

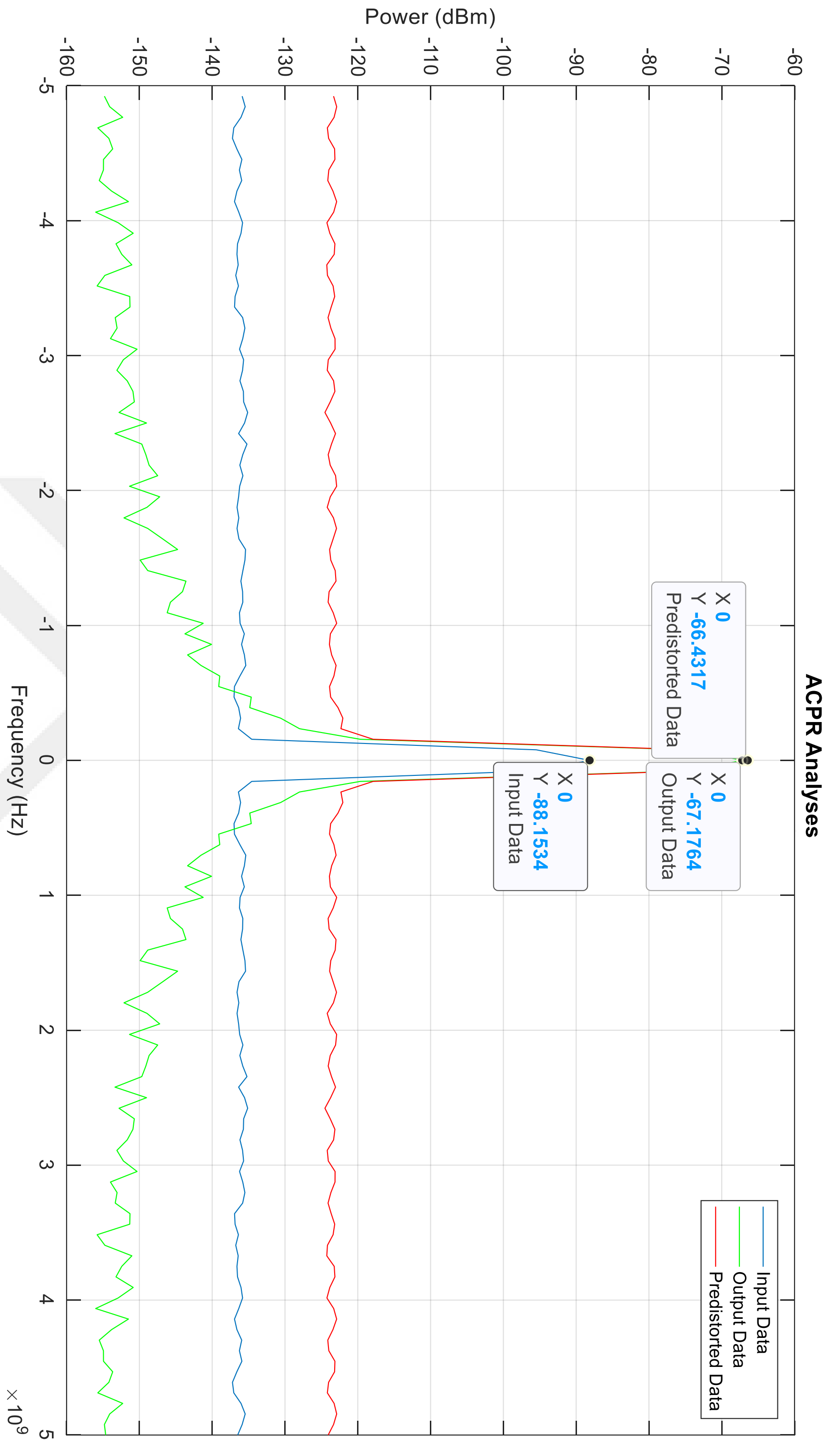

Figure 27: Modeled PA ACPR Analysis

5.2.3. Power Spectral Density (PSD)

This performance metric was applied to modeled PA and obtain Figure 28 which is the Modeled PA PSD analysis graphic. Results and discussions are given in Chapter 6.

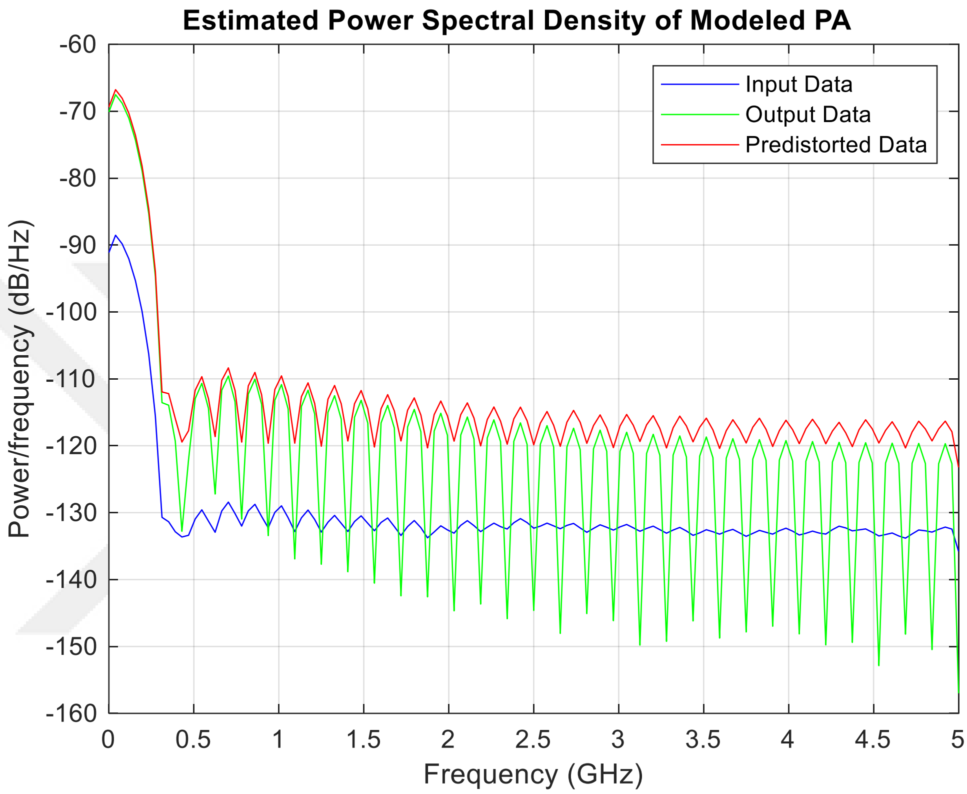

Figure 28: Modeled PA PSD Analysis

Chapter 6

Results and Discussions of Proposed DPD Method

Power amplifiers are vital parts of any communication system. With increased transmission speeds, the compensation of the non-linear effects of the power amplifiers gained more importance considering the past. Predistortion is a method to alleviate the negative effects arising from the non-linear characteristics of the power amplifiers. In predistortion approach, the signal received from the antenna is passed through a system before it is fed to the power amplifier such that the input-output characteristic of the power amplifier is forced to be linear or close to the linear.

In this thesis work, we first review the predistortion techniques available in the literature. Subsequently, we propose a new approach for the design of predistortion. The proposed approach considers the use of the concept of analog signal reconstruction from its digital samples. In this approach, to model the power amplifier input-output characteristic, we consider the digital inputs of the power amplifier as time instants, although they are not time, and the output values of the power amplifier as the samples taken from a continuous time signal and perform reconstruction operation using a sinc filter. We modeled real data available in MATLAB for the characterization of a power amplifier using our proposed approach, and it is seen that the proposed approach performs very well considering the other mathematical models such as Saleh model. To the best of authors' knowledge, this approach is never used in the literature and it is a novel approach to model the power amplifiers input-output characteristics.

The proposed method fits substantially to the real data. In particular, when the sampling period is reduced and the sampling is increased during reconstruction, it almost completely fits the real data. This is clearly seen in Chapter 5 when you look at Figure 22 and Figure 23. Figure 25 and Figure 26 also show Saleh's compatibility to fit on real data. The proposed method fits better on real data than Saleh. As shown in

Figure 29, the difference between the real data consisting of 10000 data samples and the modeled data obtained by the proposed method is taken. Out of 10000 data samples, approximately 9992 of them fit exactly on the real data.

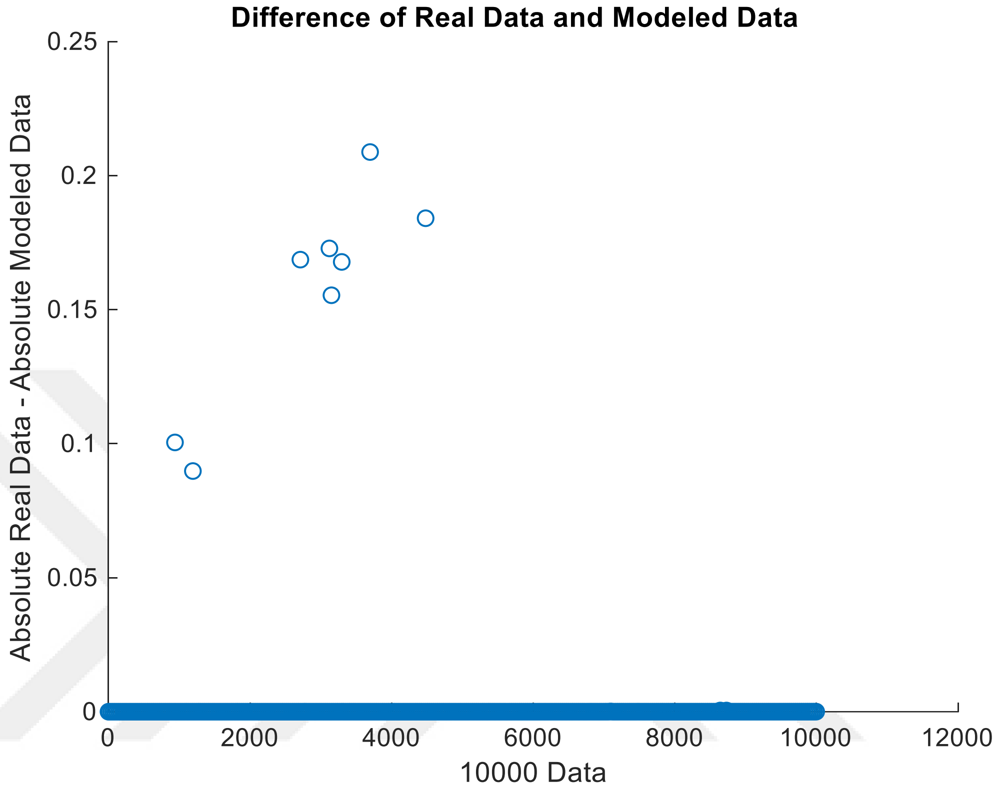

Figure 29: Difference of Real Data and Modeled Data

Normalized mean square error can be used to check the accuracy of any model used for PAs. If a model has a very low NMSE, then it is well performing. We used a real data set including 10000 data samples and NMSE of the proposed model is measured as 0.0039. NMSE of Saleh model is 0.0062 and NMSE of Ghorbani model is 0.0051. These results show that the proposed PA model is performing well. Also, linear characteristic is obtained for PA, using the predistortion designed via the proposed method.

Adjacent channel power ratio (ACPR) is a measurement of signal spreading through neighboring channels caused by power amplifier nonlinearities. When the ACPR analysis graphs are examined, it is seen that the predistorted signal which is produced using the proposed DPD method has a high power level. This is normal because the data is exposed to nonlinearity twice.

The power spectral density analysis graphs are examined, just like ACPR, the power level is higher due to nonlinearity process but linearity is achieved in predistortion.

As a result, when the simulation data is analyzed, the proposed DPD method fits substantially to the real data. Especially, the proposed method fits on the real data with a very high percentage using the sinc function. All results achieved linearity. Linearity is provided by the proposed DPD method. Also, its applicability is easier than other DPD methods mentioned in the thesis. The proposed method eliminates the complex models and complex predistortion structure.

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