NONLINEAR MODELLING OF RADIO FREQUENCY POWER AMPLIFIER BY USING ARTIFICIAL NEURAL NETWORK

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BY
ASAAD WISAM ANEES AL-HILALI
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Approval of the Graduate School of Natural and Applied Sciences, Atılım University.

Prof. Dr. İbrahim Akman
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I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

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This is to certify that we have read the thesis “Nonlinear Modelling of Radio Frequency Power Amplifier by Using Artificial Neural Network” submitted by “Asaad wisam Anees Al-hilali” and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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I declare and guarantee that all data, knowledge and information in this document has been obtained, processed and presented in accordance with academic rules and ethical conduct. Based on these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ABSTRACT

NONLINEAR MODELLING OF RADIO FREQUENCY POWER AMPLIFIER BY ARTIFICIAL NEURAL NETWORK

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Nowadays large part of modern communication systems can be mostly implemented by digital circuits. As a result of this, at the radio frequency (RF) front end less circuit components are used. One of the important circuit component at RF front-end is RF power amplifier (PA). Moreover, most of the modern communication systems utilize multicarrier modulation schemes and because of this, system performance becomes more sensitive to nonlinear properties of RF PA. Because of these reasons modelling the RF PA behavior become an important issue. In this thesis behavioral model of an RF PA is obtained by using artificial neural network and extracting the third order intercept point (IP3) by post-processing. Additionally, in a similar manner, small signal S-parameters are modeled by artificial neural network in order to obtain a macro-model for RF PA. Results present that using the proposed method, macro-model of an RF PA can be obtained.

Keywords: Nonlinear modelling, radio frequency power amplifier, artificial neural network

ÖZ

RADYO FREKANSI GÜÇ YÜKSELTECİ'NİN DOĞRUSAL OLMAYAN MODELİNİN YAPAY SİNİR AĞLARI İLE OLUŞTURULMASI

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Ekim 2015, 27 sayfa

Son günlerde modern haberleşme sistemlerinin büyük bir bölümü sayısal devreler ile gerçekleştirilmektedir. Bunun sonucu olarak radyo frekansı (RF) ön-ucunda daha az devre elamanının kullanılmasına sebep olmaktadır. RF ön-uçta bulunan devre elamanlarından önemli bir tanesi de RF güç yükseltecidir (GY). Ayrıca modern haberleşme sistemlerinin birçoğu çok taşıyıcılı modülasyon tekniği kullanmaktadır ve bu durum sistem performansını RF GY'nin doğrusal olmayan özelliklerine daha duyarlı hale getirmektedir. Bu sebeplerden dolayı RF GY'nin davranışsal modellenmesini önemli bir konu haline getirmektedir. Bu tezde RF GY'nin davranışsal modeli yapay sinir ağları kullanılarak elde edilmesini ve ardıl işlem sonrası üçüncü derece kesişim noktasının (IP3) belirlenmesini içermektedir. Ayrıca, RF GY için bir makro modelin oluşturulabilmesi için küçük işaret S-parametreleri benzer bir şekilde yapay sinir ağları ile modellenmiştir. Sonuçlar, önerilen metodun RF GY'nin makro modelinin elde edilmesi için kullanılabileceğini göstermektedir.

Anahtar Kelimeler: Doğrusal olmayan modelleme, radyo frekansı güç yükselteci, yapay sinir ağları

DEDICATION

To my parents

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INTRODUCTION

In recent years wireless communication has become of great importance for consumer electronics as well as other areas. Most of the wireless communication systems are based on multicarrier modulation scheme. The drawback of multicarrier modulation systems are that they have high peak to average power ratio (PAPR) which increases system's sensitivity to nonlinear effects. Therefore the radio frequency (RF) power amplifier (PA), which is a highly nonlinear component of the system, becomes the most important subject defining the system performance. Because of these, modelling nonlinear properties of RF PA has become a popular research area in order to figure out the distortive effects of the RF PA on systems. Modelling the nonlinear properties of RF PA is also important for developing linearization techniques.

Conventional approaches have been developed addressing nonlinear modelling RF PA are, e.g. behavioral modelling, equivalent circuit and model reduction techniques [1-3]. The advantage of equivalent circuit models is that a circuit simulator can be used to simulate them along with the other components of the circuit. Also, since the equivalent circuits are developed from physical structures of the devices being modeled, they retrain a certain degree of insight into the device's physical phenomena. Despite this advantage, circuit simulation is difficult and time consuming, because time domain circuit simulators evaluate each parameter for every piece of the circuit over time and this can be quite slow when the simulation requires thousands of iterations [4]. The behavioral modelling technique is currently the major method for system simulation in industrial applications [5]. Measurements based on behavioral modelling has an advantage as it makes it possible to model the desired behavior without knowing the physical insight of the device. However in the case of dramatic changes of the measurements with respect to change of the system level design, reproducing the model from the new measurements requires an automated circuit modelling approach which is difficult to obtain for every microwave device by using the classical modelling approaches.

Since all these approaches have some limitations for microwave circuit modelling, in recent years computer aided design (CAD) approaches based on artificial neural networks (ANNs) have become a popular tool in this area [5-14]. The well-known properties of ANN such as, learning capability which can be used to learn the input-output behavior directly from measured or simulated input-output data of the original circuit instead of developing equivalent topology, accuracy of full-analogue behavior of the circuit, fast evaluation of input to output data of the modelled circuit, makes ANN useful in modelling, simulation and optimization issues.

The use of ANNs for nonlinear microwave circuits modelling has mainly focused on feed forward neural networks (FFNNs) [5-13]. FFNN has been used for global modelling of a microwave circuit to obtain large-signal global modelling simulation of a MMIC (Monolithic Microwave Integrated Circuit) amplifier [10]. To achieve this propose a one hidden layer FFNN whose learning data was obtained from a full-hydrodynamic model of the original device was used. RNNs have been used for macro-modelling of nonlinear microwave circuits to obtain a macro-model which provides fast prediction of the full analog circuits and this model validated by three different analog circuits as practical examples, i.e., power amplifier, mixer, and MESFET [14].

In this study, a new approach based on ANN to obtain a harmonic behavioural model of a RF PA is proposed. This model uses harmonic measurements for different input frequencies and input power levels. Since the harmonic measurements are are based on single tone measurements in order to obtain an accurate nonlinear model a post process based on [15] may be used. In this study not only the harmonics but also the small signal S-parameters are modelled by ANN.

CHAPTER 2

RF PA CHARACTERISTICS

2.1 Nonlinear characteristics of RF PA

In order to describe nonlinearity, firstly linearity should be defined. A linear system can be described by the input-output relationship point of view. Mostly time invariance is included in this definition. This type of system is called as Linear Time Invariant (LTI). Response of an LTI system to a composite input is not only the superposition of the each input component but also the weighted forms of the input components with the same weighting ratios. This principle is illustrated in Figure 1.

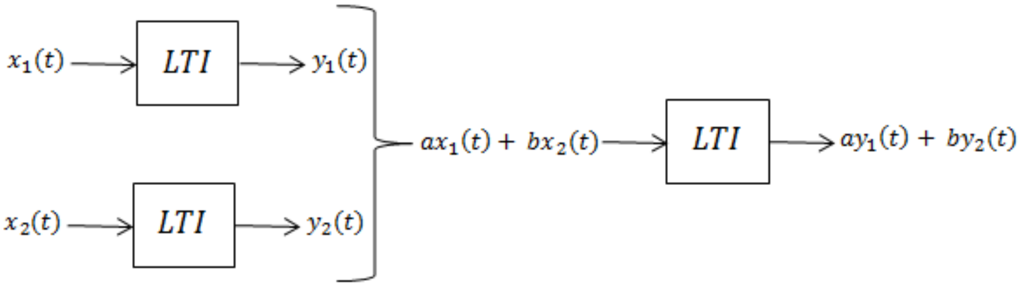

Figure 1. Input-Output Illustration of an LTI System

Any system that does not satisfy this statement can be considered as nonlinear. A simple way of modelling a nonlinear system is by using power series.

$$y(t) = \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t) + \cdots \quad (1)$$

Most of the communication systems are assumed to be linear but these assumptions do not include the distortions caused by nonlinear components. In a communication system the most important component that effect the system performance is the RF PA. These effects are summarizing as harmonic distortions, gain compression, intermodulation and cross modulation.

2.1.1 Harmonics

Harmonics of a nonlinear system can be defined by applying a single-tone as the input of the system. Single tone input can be written as

$$x(t) = A\cos(w_1 t) \quad (2)$$

If this input is used in Equation 1, the output will be expanded as

$$y(t) = \alpha_1 A\cos wt + \alpha_2 A^2 \cos^2 wt + \alpha_3 A^3 \cos^3 wt$$

$$y(t) = \alpha_1 A\cos wt + \frac{\alpha_2 A^2}{2}(1 + A\cos 2wt) + \frac{\alpha_3 A^3}{4}(3\cos wt + \cos 3wt) \quad (3)$$

$$y(t) = \frac{A^2\alpha_2}{2} + \left(\alpha_1 A + \frac{3\alpha_3 A^3}{4}\right)\cos wt + \frac{\alpha_2}{2}\cos 2wt + \frac{\alpha_3 A^3}{4}\cos 3wt$$

This result shows that there are new frequency components, produced by the nonlinear properties of the RF PA. These new components are located at the orders of fundamental frequency. Frequency response of the single tone test is illustrated in Figure 2.

After applying the single tone test signal to a nonlinear system at the output new frequency components located at the order of fundamental frequency are produced. These new components and their amplitudes with respect to nonlinear coefficients of the power amplifier are listed in Table 1.

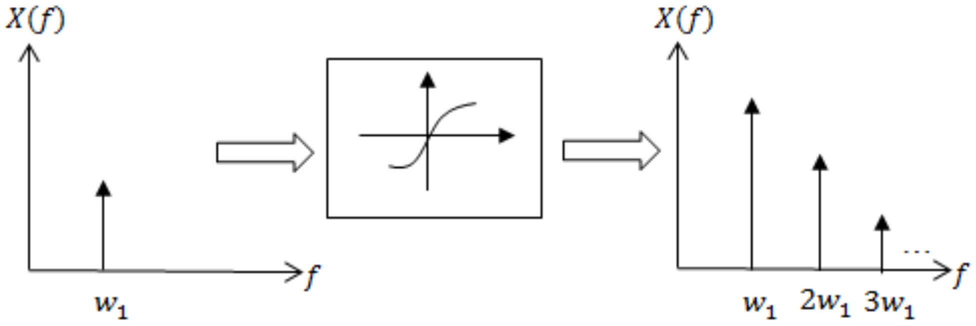

Figure 2. Harmonic Components of Non-linear System

Table 1. The Frequency Components of the 1st, 2nd and the 3rd order with their Amplitude

Harmonics	Frequency w_x	Amplitude
First Harmonic	$-w_2$	$\frac{1}{2}\alpha_1 A_2$
	$-w_1$	$\frac{1}{2}\alpha_1 A_1$
	w_1	$\frac{1}{2}\alpha_1 A_1$
	w_2	$\frac{1}{2}\alpha_1 A_2$
Second Harmonics	$-2w_2$	$\frac{1}{4}\alpha_2 A_2^2$
	$-2w_1$	$\frac{1}{4}\alpha_2 A_1^2$
	$2w_1$	$\frac{1}{4}\alpha_2 A_1^2$
	$2w_2$	$\frac{1}{4}\alpha_2 A_2^2$
Third Harmonics	$-3w_2$	$\frac{1}{8}\alpha_3 A_2^3$
	$-3w_1$	$\frac{1}{8}\alpha_3 A_1^3$
	$3w_1$	$\frac{1}{8}\alpha_3 A_1^3$
	$3w_2$	$\frac{1}{8}\alpha_3 A_2^3$

2.1.2 Gain Compression

Harmonics are not the only result of single tone test but also there are other effects as gain compression has found at the output while increasing the input power of the test signal output power of the nonlinear system traces linearly up to some point. After this point if the input powers still increasing at the output power a compression is occured. In order to define a figure of merit showing the starting point of compression rate, 1 dB gain compression is accepted conventionally. This definition of 1 dB compression point is shown in Figure 3, the ideal line of Gain compression happened when the input power of an amplifier is increased to a level that reduces the gain of the amplifier and causes a nonlinear increase in output power.

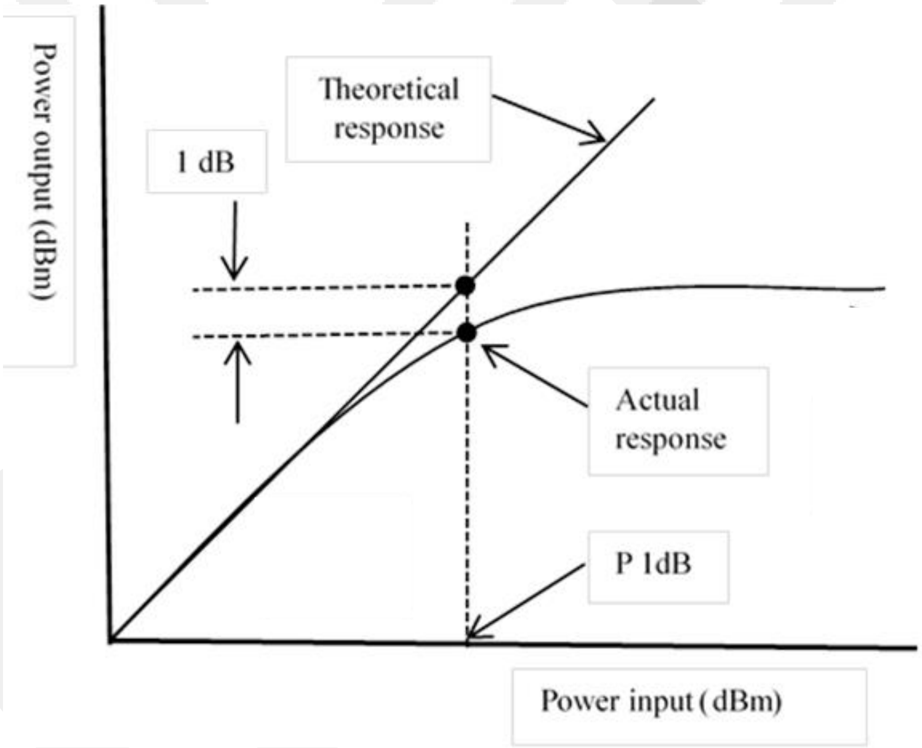

Figure 3. 1dB Compression Point

In order to describe it mathematically, Equation 2 should be considered for the fundamental frequency. As shown in equation 4, the amplitude of the fundamental frequency is

$$A_1 = \left(\alpha_1 A + \frac{3\alpha_3 A^3}{4}\right) \tag{4}$$

It's noticed that this gain is not only related with the first degree nonlinear coefficient α1 but also it is related with the third order nonlinear coefficient α_3. Third order nonlinear coefficient α_3 is mostly negative and it is obvious that increasing the input amplitude A result as a decreasing in the amplitude of fundamental frequency component [16].

2.1.3 Intermodulation

Up to now the test signal is single tone test, but mostly the input of the non-linear system is multi tone, and there are new consequences in order to consider, one of them is intermodulation. Intermodulation is generated by applying multi-tone signals with different frequencies to a non-linear system and the result show new components that are not harmonic distortion of the input frequencies called as intermodulation as shown in Figure 4.

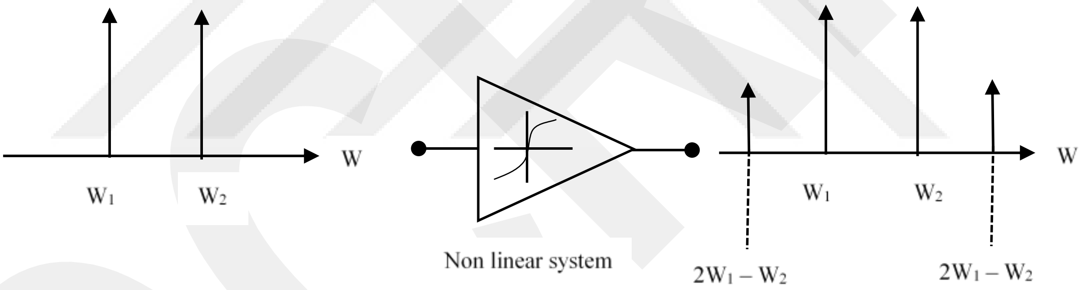

Figure 4. Intermodulation

In order to describe intermodulation mathematically

From equation (2) assuming

$$x(t) = A_1 \cos w_1 t + A_2 \cos w_2 t \tag{5}$$

By applying $x(t)$ in equation (3) the result will be

$$y(t) = \alpha_1(A_1 \cos w_1 t + A_2 \cos w_2 t) \quad + \alpha_2(A_1 \cos w_1 t + A_2 \cos w_2 t)^2$$

$$+\alpha_3(A_1 \cos w_1 t + A_2 \cos w_2 t)^3 \tag{6}$$

The problem for all the engineering in all the specialist is the nonlinearity, the goal form this test to make the system more linear. As a result of the effect of the nonlinear system on the tone it gives also the harmonic distortion, intermodulation, cross modulation and gain compression.

The second and third order intermodulation products shown in Table 2.

Table 2. Second and third order intermodulation products.

Intermodulation products	**Frequency w_x**	**Amplitude**
Second Order Intermodulation Products	$-w_1 - w_2$	$\frac{1}{2}\alpha_2 A_1 A_2$
	$w_1 - w_2$	$\frac{1}{2}\alpha_2 A_1 A_2$
	$w_2 - w_1$	$\frac{1}{2}\alpha_2 A_1 A_2$
	$w_1 + w_2$	$\frac{1}{2}\alpha_2 A_1 A_2$
Third Order Intermodulation Products	$-2w_1 - w_2$	$\frac{3}{8}\alpha_3 A_1^2 A_2$
	$2w_1 - w_2$	$\frac{3}{8}\alpha_3 A_1^2 A_2$
	$2w_2 - w_1$	$\frac{3}{8}\alpha_3 A_1 A_2^2$
	$2w_1 + w_2$	$\frac{3}{8}\alpha_3 A_1^2 A_2$

2.2 Small signal S-parameters

Scattering parameter, also called S-parameter (‘s’ in s-parameter refers to scattering) belong to the two port parameters used in two port theory. S-parameters are complex (magnitude and phase) because of the input signal are changed by the network. S-parameters are important in microwave design because they are easier to work with and to easy to measure at high frequencies than other kinds of two port parameters. They are conceptually simple, analytically convenient and capable of providing detailed insight into a measurement and modelling problem. However, it must keep in mind that -like all other two port parameters, S-parameters are linear by default, they represent the linear behaviour of the two port.

$$\begin{bmatrix} |b_i|^2 \\ |b_2|^2 \end{bmatrix} = \begin{bmatrix} |S_{11}|^2 & |S_{12}|^2 \\ |S_{21}|^2 & |S_{22}|^2 \end{bmatrix} * \begin{bmatrix} |a_i|^2 \\ |a_2|^2 \end{bmatrix} \tag{7}$$

$|a_i|^2$ Power wave traveling towards the two port gate

$|b_i|^2$ Power wave reflected back from the two port gate

$|S_{11}|^2$ Power reflected from port 1

$|S_{12}|^2$ Power transmitted from port 1 to port 2

$|S_{21}|^2$ Power transmitted from port 2 to port 1

$|S_{22}|^2$ Power reflected from port 2

S-parameter refers to RF ‘voltage out versus voltage in’ in the most basic sense. S-parameter comes in matrix, with the number of rows and columns equal to the number of ports. For the S-parameter subscripts (ij), j is the port that is excited (the input port), and (i) is the output port.

CHAPTER 3

NEURAL NETWORK

Artificial neural network (ANN) or simply neural network (N.N) is an information processing system which was influenced by human brain function. It's offers a new way to solve many modelling and design problems in many fields. It has the ability to learn from observation and generalize arbitrary input-output relationships. Although neural network technique has been used for a long time, the introduction of neural network to RF and microwave field is only done in recent years. It offers a new way to solve many modelling and design problems in this field. ANN can be trained with given input-output information through a learning process involving storage of such information in the form of synaptic weights of the network. The fact that neural networks can learn arbitrary, continuous, multi-dimensional and nonlinear input-output relationships from corresponding data has resulted in their use in diverse areas of engineering such as bio-medical, control engineering, pattern recognition, and speech processing.

Neural networks have been used to model a wide variety of RF/microwave components and circuits such as transmission line components, bends vias, CPW components, spiral inductors, FETs HBTs, HEMTs, waveguides, laser diodes, embedded resistor, filters, amplifiers, mixers and antennas.

A variety of neural network structures have been used for RF/microwave applications including feed forward neural networks, e.g. multi-layer perceptron's (MLP)neural networks, Radial Basis Function (RBF) networks , wavelet networks etc., and neural networks with feedback, e.g. Recurrent Neural Networks (RNN). Research in the RF/microwave-ANN area recently led to the creation of state-of-the-art knowledge-neural-network structures, which advocate incorporation of existing engineering knowledge in the form of empirical equations/models or equivalent circuits into the neural network internal structure. Neural networks with knowledge including knowledge based neural networks, difference method, prior knowledge input network, and space mapped neural networks have been shown to outperform conventional neural network structures (without knowledge) in high-frequency modelling and design.

3.1 Neural Network Structure

A common neural network structure has at least two standard components, namely, the processing elements and the correlation between them. The processing elements are called neurons and the connections between the neurons are known as links. The precept task of a neuron is to operate information, and is therefore characterized by a mathematical function called neuron activation function. Every link has a weight parameter supported with it. Each neuron receives stimulus from other neurons connected to it, processes the information, and produces an output. Neurons that receive stimuli from outside the network are called input neurons while neurons whose outputs are externally used are called output neurons. Neurons that receive stimuli from other neurons and whose outputs are stimuli for other neurons in the network are known as hidden neurons. Different neural network structures can be constructed by using different neurons (i.e., neuron activation functions) and by connecting them differently as shown in Figure .

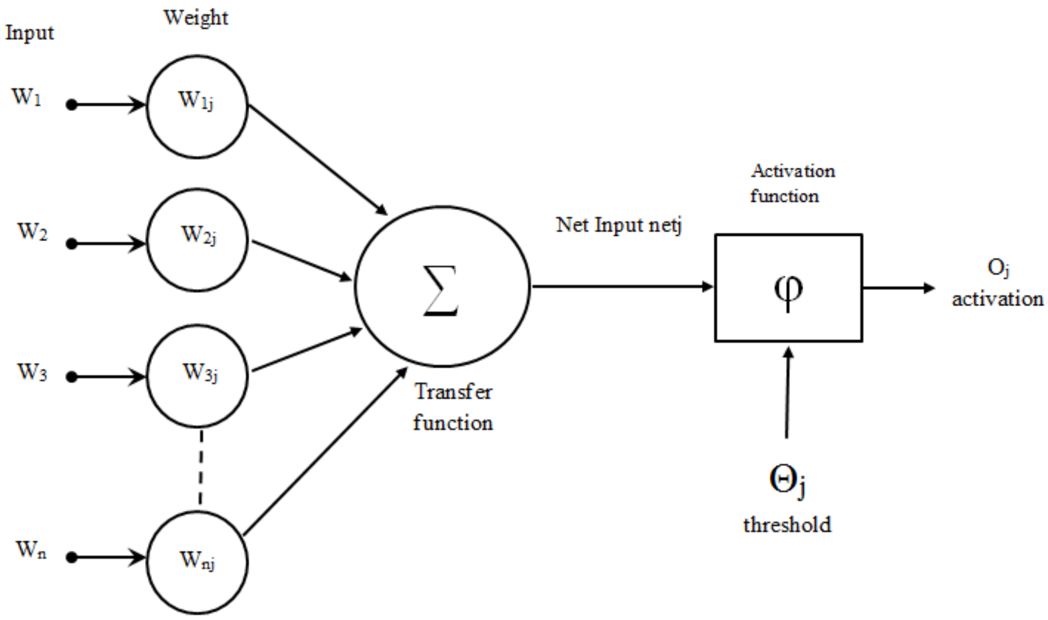

Figure 5. Neural Network Structure

3.2 Multilayers Perceptron (MLP)

The most popular type of neural networks is the multilayer perceptron, Artificial neural network based on MLP are feed forward nets with one or more layer of nodes between its input and output layers, and due to the nonlinearity activation function with each nodes the MLP is capable of forming arbitrarily complex decision function in the pattern space .

The construction of multi layers of nodes in which each layer is connected to hidden layer or series of hidden layers containing nodes. The first layer of nodes activates the input variables while each of the nodes within the hidden layers processes using a nonlinear activation function. The MLP requires the user to train the network (i.e., arrange the number of hidden layers and neurons within hidden layers) using a "training" set of data to provide supervised learning. The MLP is particularly valuable in the forecasting of important events even when employing extremely chaotic nonlinear datasets.7 Multilayer perception (MLP) is a popular neural network structure .The neurons are organized in layers therefore neural network is known as multilayer perceptron neural network. There are three types of layers: (1) input layer, (2) output layer, and (3) hidden layer as shown in Figure 6. The interconnections between neurons of different layers are known as links or synapses. Each neuron is correlated with a weight parameter. The input neurons receive stimuli from outside the network. The neurons of hidden layers receive the signal and compute responses and send the information to the output neurons. Thus the response of the model is determined by the inputs and weight parameter of the network.

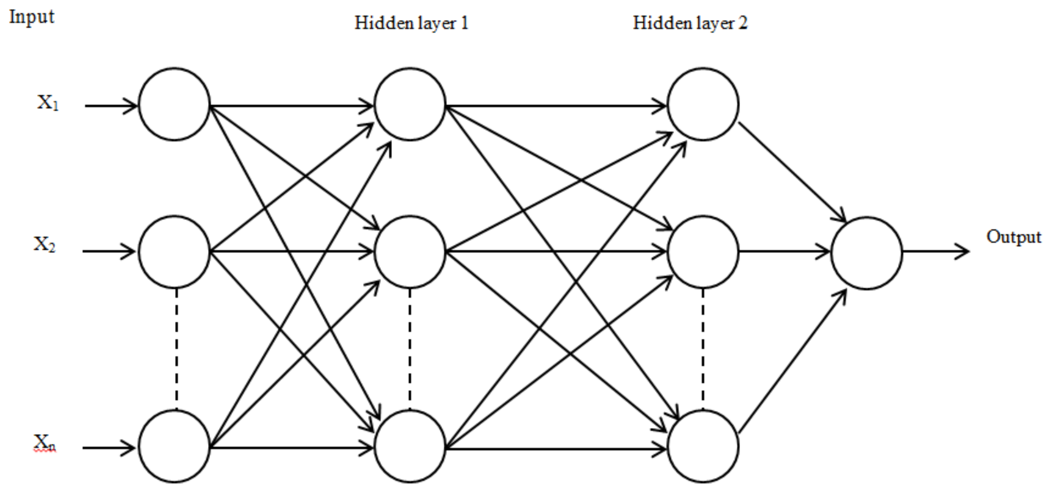

Figure 6. Multilayer Perceptron Structure

Artificial neural network based on MLP are feed-forward nets with one or more layer of nodes between its input and output layers, and due to the nonlinearity activation function with each nodes the MLP is capable of forming arbitrarily complex decision function in the pattern space. A multilayer perceptron (MLP) is introduced, which fulfills the following requirements. The hardware solution should be application independent, which makes it usable for several problems during runtime. This can be achieved by high flexibility. High flexibility can be guaranteed by a highly parameterizable design. The neurons (also called perceptron in this case) transfer function can be freely chosen, which makes it adaptable to different scenarios. Additionally, an easy integration of the MLP into existing infrastructures is important.

CHAPTER 4

EXPREMINTAL WORK

In chapter two, when a single tone applied to a nonlinear system one of the results for the output is harmonics are important since they give an opinion about nonlinear coefficients amplitude.

4.1 Harmonics Measurement

In this chapter measuring the harmonics distortion is observed as shown in Figure 7.

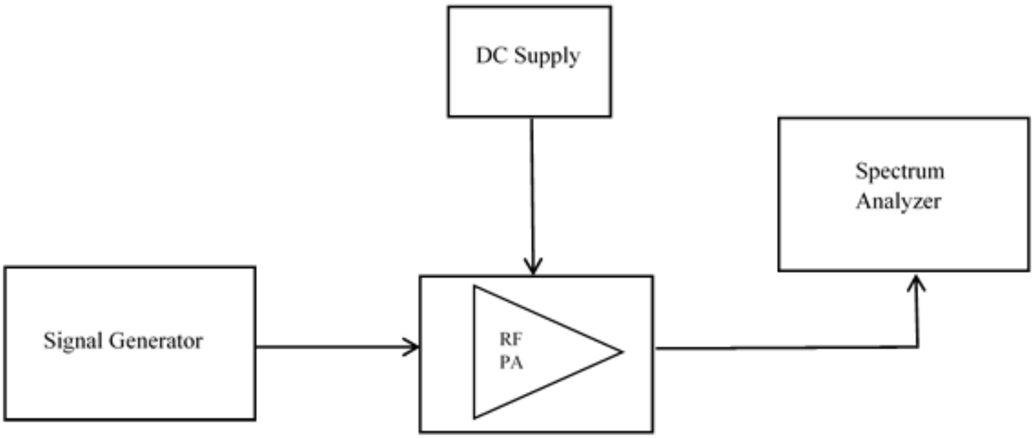

Figure 7. Harmonic Distortion Measurement Circuit

This figure is consist of PSG-L series signal generator, triple output D.C power supply ,RF PA , and PSA series spectrum analyzer .The RF PA used to measure the harmonic distortion working from 1.8 GHz to 2.8 GHz.

Firstly, the setup for the D.C power supply is 5V. Measurements are carried out by sweeping the frequency and power of the input signal by adjusting the signal generator. Frequency of the signal generator is swept from 1.8 GHz to 2.8 GHz by 100 MHz step. Similarly power of the input signal is swept from -20 dBm to 20 dBm

by 1 dBm step. Output power of the RF PA for each input set is measured up to 10^{th} harmonic. The total size of the measurement is (4510).

Training and test sets of N.N are generated from these measurements.

4.2 Small Signal S-parameter Measurement

Small signal s-parameter are measured by using vector network analyzer (VNA) as shown in Figure 8.

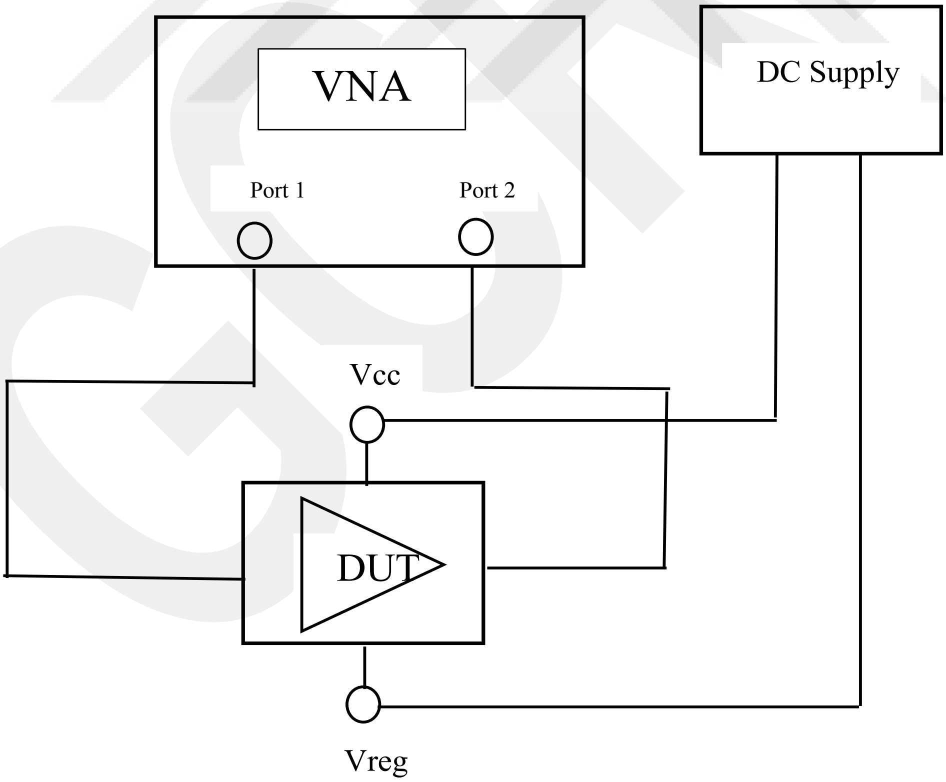

Figure 8. S-parameter Measurement Circuit

Regulation voltage Vreg, is used for controlling the output power of the RF PA. In these measurements frequency is swept from 2.4 GHz to 2.5 GHz at 51 points and Vreg. is swept from 1 V to 1.7 V with 0.1 V step.

CHAPTER 5

TEST RESULTS AND DISCUSSION

In this research, after finishing harmonic and S-parameter measurements in RF laboratory, the next step is to model them using neural network approach (multilayer perceptron method) In this chapter, harmonic and S-parameter measurement results and the modelling details and results will be explained and given.

5.1 Modelling Harmonics and Results

Modelling harmonics starts by dividing the harmonic measurements in to two sets, training set and testing set. The neural network structure used to model these sets constructed from three layers (two hidden layers and one output layer). To obtain training set and testing set results three scenarios have done for the same structure by changing the number of the neurons in the hidden layers. These changes are made to observe the progress in the training set and testing set results. Training set and testing set need to be model must be arranged in to input-output pairs. The input-output pairs in the training set used for model development, while the input-output pairs in the testing set used for validation. The training set and testing set contain of two inputs represented by frequency and input power signal, and ten outputs represented by the harmonics as shown Figure 9.

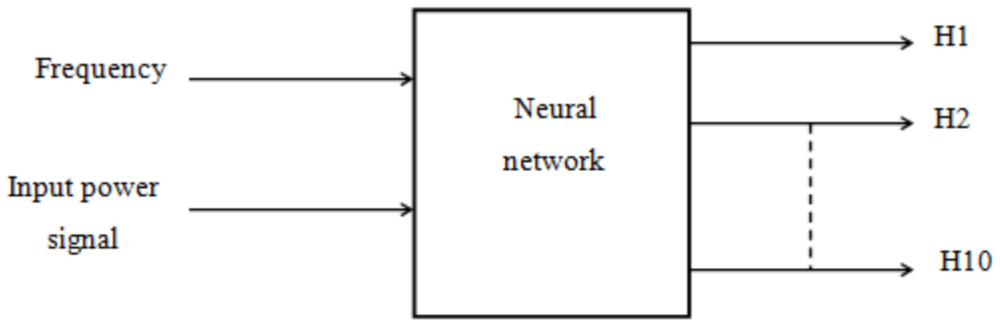

Figure 9. Modelling Structure For Harmonics

Each of the frequency and the input power signal represent the input for the neural network while the output represented by the harmonics. Table 3 and Table 4 shows the input parameter for each of training set and testing set.

Table 3. Training Set Input

Input parameter	Start	Step	End
Frequency	1.8 GHz	200 MHz	2.8 GHz
Input power signal	20 dBm	-1dBm	-20 dBm

Table 4. Testing Set Input

Input parameter	Start	Step	End
Frequency	1.9 GHz	200 MHz	2.7 GHz
Input power signal	20 dBm	-1dBm	-20 dBm

The train set input has 6 frequencies; each frequency has 41 input power signal as shown below

$$\left[\begin{bmatrix} F_{1.8\,GHz} & \cdots & F_{1.8\,GHz} \\ P_{20\,dBm} & \cdots & P_{-20\,dBm} \end{bmatrix} \cdots \begin{bmatrix} F_{2.8\,GHz} & \cdots & F_{2.8\,GHz} \\ P_{20\,dBm} & \cdots & P_{-20dBm} \end{bmatrix}\right] \qquad (8)$$

The size of the matrix in (8) is 2*246. Each column represents the input. For each training set input it has 10 harmonics, the total number for the harmonics in the training set is 2460 harmonics as shown below

$$\left[\begin{bmatrix} F_{1.8\,GHz} & & F_{1.8\,GHz} \\ P_{20\,dBm} & & P_{-20\,dBm} \\ H_1 & \cdots & H_1 \\ \vdots & & \vdots \\ H_{10} & & H_{10} \end{bmatrix} \cdots \begin{bmatrix} F_{2.8\,GHz} & & F_{2.8\,GHz} \\ P_{20\,dBm} & & P_{-20\,dBm} \\ H_1 & \cdots & H_1 \\ \vdots & & \vdots \\ H_{10} & & H_{10} \end{bmatrix}\right] \qquad (9)$$

The size of the matrix in (9) 10*246. Each column corresponds to the output. In other words, the output is desired harmonics corresponding to each column in (8).After preparing the train input set, and applying it to the network the error average and Standard deviation results will be shown in three scenarios as shown in Table 5. The number of the layers in each scenario is assumed to be 3, however the changed had been made in the number of the neurons in each layer to reach to acceptable approximation of the harmonics. In the first scenario the number of the neurons for each layer is 10, second scenario 20 neurons and the third scenario 30 neurons.

Table 5. Average Error and Standard dev. For Training Set

Harmonics	scenario one		scenario two		scenario three	
	Average Error	Standard dev.	Average Error	Standard dev.	Average Error	Standard dev.
H1	2.658	1.866	2.057	1.693	1.206	0.958
H2	3.835	5.778	3.792	6.837	2.132	7.343
H3	2.201	2.242	2.809	2.804	1.772	2.156
H4	3.135	2.559	2.736	2.717	1.838	2.122
H5	3.501	9.041	4.845	7.795	5.894	8.371
H6	4.94	11.566	6.787	12.08	9.058	14.881
H7	3.951	8.139	8.768	10.393	2.639	9.326
H8	3.637	9.139	7.006	9.357	7.257	9.785
H9	2.759	2.656	2.384	2.207	1.736	2.125
H10	2.935	2.713	3.019	2.879	1.753	2.275

Based on the performance of the N.N for each scenario, Table 6 shows the performance of the N.N for each scenario in terms of average error and standard dev. for training set. As can be seen from the table the best result is obtained for scenario 3. Even if scenario 3 is the best, still have higher error for H5, H6 and H8, this can be attributed to dynamic behavioral of the harmonics and the other harmonics approximation are acceptable.

The testing set input has five frequencies; each frequency has 41 input power signals as shown below

$$\left[\begin{bmatrix} F_{1.9\,GHz} & \cdots & F_{1.9\,GHz} \\ P_{20\,dBm} & \cdots & P_{-20\,dBm} \end{bmatrix} \cdots \begin{bmatrix} F_{2.7\,GHz} & \cdots & F_{2.7\,GHz} \\ P_{20\,dBm} & \cdots & P_{-20dBm} \end{bmatrix}\right] \qquad (10)$$

The size of the matrix in (10) is 2*205. Each column represents the input.

For each testing set input it has 10 harmonics, the total number for the harmonics in the testing set is 2050 harmonics as shown below

$$\left[\begin{bmatrix} F_{1.9\,GHz} & & F_{1.9\,GHz} \\ P_{20\,dBm} & & P_{-20\,dBm} \\ H_1 & \cdots & H_1 \\ \vdots & & \vdots \\ H_{10} & & H_{10} \end{bmatrix} \cdots \begin{bmatrix} F_{2.7\,GHz} & & F_{2.7\,GHz} \\ P_{20\,dBm} & & P_{-20\,dBm} \\ H_1 & \cdots & H_1 \\ \vdots & & \vdots \\ H_{10} & & H_{10} \end{bmatrix}\right] \qquad (11)$$

The size of the matrix in (11) 10*205. Similarly with (2), each column corresponds to the output. In other words, the output is desired harmonics corresponding to each column in (10) as shown Table 6.

Based on the performance of the N.N for each scenario, Table 6 shows the performance of the N.N for each scenario in terms of average error and standard dev. for testing set. As can be seen from the table the best result is obtained for scenario 3. Even if scenario 3 is the best, still have higher error for H5, H6 and H8, this can be attributed to the dynamic behavioral of the harmonics and the other harmonics approximations are acceptable.

Table 6. Average Error and Standard dev. For Testing Set

Harmonics	scenario one		scenario two		scenario three	
	Average Error	Standard dev.	Average Error	Standard dev.	Average Error	Standard dev.
H1	7.93	13.860	6.127	14.209	8.312	14.566
H2	11.191	13.014	10.135	14.544	7.133	11.907
H3	5.760	5.905	10.728	8.136	7.597	6.529
H4	10.470	12.663	8.720	13.240	8.629	12.098
H5	13.016	46.017	14.313	44.207	21.264	47.929
H6	14.161	18.941	14.179	19.375	23.647	28.756
H7	14.273	15.517	15.408	15.891	7.791	12.158
H8	11.553	10.411	15.968	20.788	33.511	28.84
H9	11.152	13.834	9.716	14.257	8.297	14.264
H10	9.912	12.499	10.358	13.714	7.369	11.982

5.3 Modelling S-parameter And Results

As the same method in modelling harmonics, modelling S-parameter start by dividing each port into two sets, training set and testing set. The neural network is used to approximate the measurements comprised of four layers, three hidden layers and one output layer. In S-parameter modelling one scenario have been done to obtain training set and testing set results. The scenario has 30 neurons in each hidden layer. As previously mention training set and testing set need to be model must be arranged in to input-output pairs. The input-output pairs in the training set used for model development, while the input-output pairs in the testing set used for validation. The training set and testing set contain of two inputs represented by frequency and voltage, and one output represented by the S-parameters as shown in figure 10. The S-parameters as its mention before contain of two ports (magnitude and phase), so each port has its own training set and testing set.

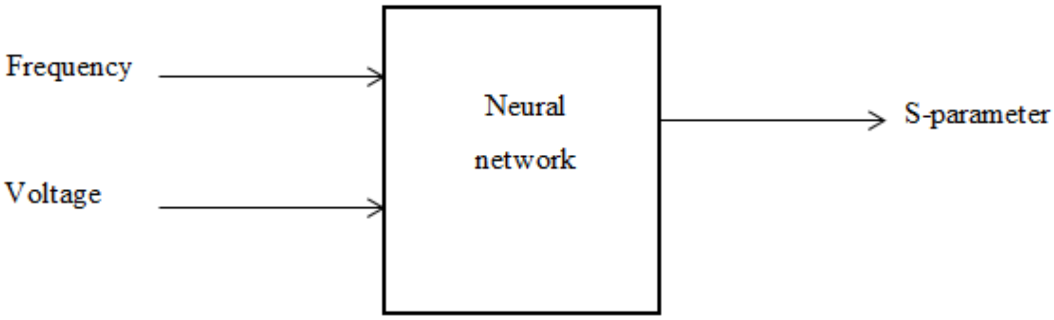

Figure 10. Modelling Structure For The S-parameter

Table 7 and Table 8 are shown the input parameter for each of training set and testing set (magnitude and phase).

Table 7. Training Set Input (Magnitude and Phase)

Input parameter	Start	Step	End
Frequency	2400000000 Hz	4000000 Hz	2500000000 Hz
Voltage	1.1 V	0.2 V	2.7 V

The training set input for (magnitude and phase) has 9 voltages; each voltage has 26 frequencies as shown below

$$\left[\begin{bmatrix} F_{2.4\,GHz} & \cdots & F_{2.5\,GHz} \\ V_{1.1\,V} & & V_{1.1\,V} \end{bmatrix} \cdots \begin{bmatrix} F_{2.4\,GHz} & \cdots & F_{2.5\,GHz} \\ V_{2.7\,V} & & V_{2.7\,V} \end{bmatrix}\right] \tag{12}$$

The size of the matrix in (12) is 2*234. Each column represents the input. The total number for the S-parameter in the training set is 234 as shown in 13 and 14 for each of (magnitude and phase).

$$\left[\begin{bmatrix} F_{2.4\,GHz} & \cdots & F_{2.5\,GHz} \\ V_{1.1\,V} & & V_{1.1\,V} \\ |S_{11}| & & |S_{11}| \end{bmatrix} \cdots \begin{bmatrix} F_{2.4\,GHz} & \cdots & F_{2.5\,GHz} \\ V_{2.7\,V} & & V_{2.7\,V} \\ |S_{11}| & & |S_{11}| \end{bmatrix}\right] \tag{13}$$

$$\left[\begin{bmatrix} F_{2.4\,GHz} & & F_{2.5\,GHz} \\ V_{1.1\,V} & \cdots & V_{1.1\,V} \\ \angle S_{11} & & \angle S_{11} \end{bmatrix} \cdots \begin{bmatrix} F_{2.4\,GHz} & & F_{2.5\,GHz} \\ V_{2.7\,V} & \cdots & V_{2.7\,V} \\ \angle S_{11} & & \angle S_{11} \end{bmatrix}\right] \tag{14}$$

Table 8.Testing Set Input (Magnitude and Phase)

Input parameter	Start	Step	End
Frequency	2400000000 Hz	4000000 Hz	2496000000 Hz
voltage	1 V	0.2 V	2.6 V

The testing set input for (magnitude and phase) has 9 voltages; each voltage has 25 frequencies as shown in (15)

$$\left[\begin{bmatrix} F_{2.4\,GHz} & \cdots & F_{2.496\,GHz} \\ V_{1\,V} & & V_{1\,V} \end{bmatrix} \cdots \begin{bmatrix} F_{2.4\,GHz} & \cdots & F_{2.496\,GHz} \\ V_{2.6\,V} & & V_{2.6\,V} \end{bmatrix}\right] \tag{15}$$

The size of the matrix in (15) is 2*225. Each column represents the input. The total number for the S-parameter in the testing set is 225 as shown in 16 and 17 for each of (magnitude and phase).

$$\left[\begin{bmatrix} F_{2.4\,GHz} & & F_{2.496\,GHz} \\ V_{1\,V} & \cdots & V_{1\,V} \\ |\,S_{11}\,| & & |\,S_{11}\,| \end{bmatrix} \cdots \begin{bmatrix} F_{2.4\,GHz} & & F_{2.496\,GHz} \\ V_{2.6\,V} & \cdots & V_{2.6\,V} \\ |\,S_{11}\,| & & |\,S_{11}\,| \end{bmatrix}\right] \tag{16}$$

$$\left[\begin{bmatrix} F_{2.4\,GHz} & & F_{2.496\,GHz} \\ V_{1\,V} & \cdots & V_{1\,V} \\ \angle S_{11} & & \angle S_{11} \end{bmatrix} \cdots \begin{bmatrix} F_{2.4\,GHz} & & F_{2.496\,GHz} \\ V_{2.6\,V} & \cdots & V_{2.6\,V} \\ \angle S_{11} & & \angle S_{11} \end{bmatrix}\right] \tag{17}$$

After prepare the training input set, and applying it to the network the error average and Standard dev. results will be shown in Table 9 for each of (magnitude and phase).

Table 9. Average Error and Standard dev. For S_{11} and S_{22} (Magnitude and Phase)

S-parameter	$\mid S_{11} \mid$	$\angle S_{11}$	$\mid S_{22} \mid$	$\angle S_{22}$
Training test				
Average error	0.0538	1.54E-01	2.97E-02	9.302
Standard dev.	0.103	0.415	0.073	29.237
Testing test				
Average error	1.278	0.677	0.906	46.982
Standard dev.	3.972	2.514	0.743	76.189

Table 10 Average Error and Standard dev. For S12 and S21 (Magnitude and Phase)

S-parameter	$\mid S_{12} \mid$	$\angle S_{12}$	$\mid S_{21} \mid$	$\angle S_{21}$
Training test				
Average error	0.0533	2.219	0.286	8.798
Standard dev.	0.0933	7.334	0.761	21.874
Testing test				
Average error	0.516	57.994	6.852	75.675
Standard dev.	0.323	88.992	8.843	113.5

CHAPTER 6

CONCLUSIONS

Neural modeling of nonlinear circuits and their dynamic behaviors is one of the most important areas of microwave CAD. This thesis has presented a neural network method for modeling nonlinear microwave circuits and its applications for simulation. The proposed method is based on the feed forward neural networks, which is one of the well-known neural networks. The model has several advantages. Firstly, the model is based on single tone measurement of harmonics which required post process for obtaining IIP3. Single-tone measurements are simpler than multi-tone measurements. Moreover, the model includes small-signal S-parameters in order to achieve macromodel of RF PA. After being trained, the proposed model can be conveniently incorporated into existing simulators.

Simulation results have shown that the feed forward neural networks can provide an accurate macromodel for nonlinear radio frequency power amplifiers. The proposed method provides simplicity, fast and accurate representation of the harmonic behavior of the RF PA. It has been also expected that the proposed method is applicable to modelling, simulation and optimization of the other microwave circuits.

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