

Inspecting Distortion in the Power Amplifiers with the aid of Neural Networks

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Abstract—This paper aims to classify the distortion behavior of a power amplifier (PA) with the aid of a neural network. Power amplifiers have quite extensive usage in communication systems especially with the current developments on 5G and more. However, distortion in the power amplifiers needs attention to be pre-distorted with the help of a feedback mechanism using direct or indirect methods in the digital domain. In the literature, there are several efforts to understand and reduce distortion in amplifier devices. Therefore, in this paper, the distortion behavior in the power amplifier is inspected using the neural networks. In this work, we have obtained a software-defined network using the strength of the neural network to inspect the distorted and non-distorted data as a binary classification on the actual design of the power amplifier in [1]. For this purpose, a neural network system is trained. In the tests, more than 96% accuracy can easily be obtained in an early epoch with the cleverly chosen learning rate (η) which is optimally outperforming thereabouts after $\eta=0.05$ till 0.1. Thus, the linearity and non-linearity response of the PA is considered with the help of the trained network.

Index Terms—digital pre-distortion; neural networks; power amplifier; software-defined radio.

I. INTRODUCTION

Recently, there is a significant interest for the radio frequency (RF) transmitters and RF designers are benefiting from the material of semiconductors due to the well-established Gallium Nitride (GaN) high-electron-mobility transistor (HEMT) [2]. In the past twenty years, many different techniques have been proposed for increasing the efficiency and linear range of the power amplifier (PA) response. From different techniques [3]–[7], digital pre-distortion (DPD) has become the most popular linearization technique in cellular base stations [8] and fifth-generation (5G) wireless technologies [9]–[11].

Digital pre-distorter in RF systems increases the linearity on the PA and recently there are efforts to create an efficient hardware model of DPD that can use direct or indirect learning [12]–[15]. This study aims to inspect the power amplifier discrete data behavior using an early version of the neural network (NN). Especially with increasing research on deep learning systems in the literature, there also becomes the joint between interdisciplinary efforts, i.e. machine learning and radio frequency device modeling. However, NN can sometimes be a black box and in this study, a quick review of the simple NN performance on the PA data is presented. For further consideration, the DPD is to be replaced with a suitable NN system with pre-trained hyperparameters learned well in a wide range of band frequencies.

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In the next generation communication systems, DPD can meet the telecommunication standards and face with new challenges thanks to its excellent linearization performance. Due to this reason, PAs are mostly accompanied by DPD to fulfill an amplification process and compensate the nonlinear behavior of PA. A two dimensional DPD is essential, as there is a delay mismatch between the amplitude and the phase path in polar modulation, also the digital cartesian transmitters suffer from excessive non-linearity. In [16], an adaptive, hardware-efficient feedback polynomial topology for DPD linearization has been proposed. In this topology, non-linearity and memory effects are built separately which affects the reduction on coefficient extractor size considerably. Both the coefficients of nonlinear and linear approaches adaptively can be estimated by using this method, and they can be predicted with the design in the field-programmable gate array (FPGA). A real-valued focused time-delay neural network (RVFTDNN) model has been proposed in [17]. In this model, the compensation process that includes a one-step mitigation procedure is simplifying significantly and as RVFRDD is like a neural network model, it can perform well when there are various distortions.

Recently, for identifying DPD coefficients, a direct learning algorithm is also proposed [18]. Any PAs can be linearized by using sub-Nyquist sampled intermediate frequency (IF) output of a heterodyne transmitter observation receiver (TOR). This method involves a joint time and phase alignment step without affecting DPD performance as a very low IF value can be chosen. In [19], for a wideband direct-conversion transmitter, an augmented real-valued time-delay neural network (ARVTDNN) has been proposed. The input signal of this neural network consists of cartesian elements as I/Q in-phase and quadrature-phase. The performance of this NN is improved by generating both even and odd-order intermodulation products.

The possibility of using a NN for increasing the power transmission efficiency is demonstrated in [20]. The proposed architecture can be implemented in the low-cost digital signal processor (DSP) and the predistortion process can be divided into various subtasks by choosing the artificial neural network (ANN) parameters. In compensation system, keeping the linearity against frequency, temperature, and voltage variations is significant. This paper reports and modelizes the distortion behavior of PA by using NN. Distortion and basics of PA are elaborated in Section II. In Section III, the distortion inspection and tests are presented for the practical PA by getting use of trained network. Conclusion is followed in Section IV.

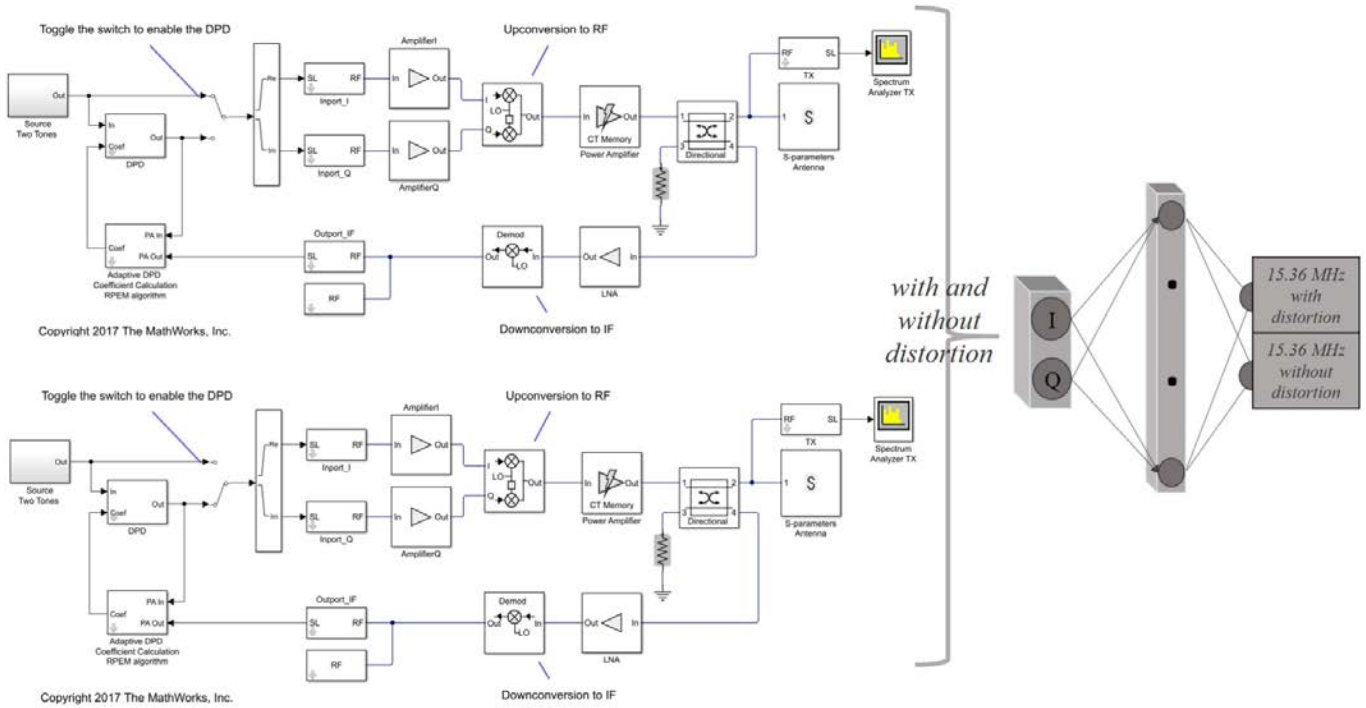


Fig. 1. Scheme for the capturing data from software-defined set-up [21], later to be trained and tested on a 1-hidden layer NN.

II. BASICS OF A POWER AMPLIFIER AND DISTORTION

A. DPD Baseline Specifications

Ultra-wideband and dual-band power amplifiers are important components in the upcoming generation of (e.g. 5G) communication systems requiring high throughput. However, they are suffering from non-linearity of the PAs that generate spectral re-growth and the linearity which causes distortion in-band and spoils the bit-error-rate (BER). Between linearity and efficiency, there is an essential trade-off that must be made considered at the transmitter side.

RF designers attempt to design PAs which are supporting the multi-band. However, for the dual-band, PAs produce distortion on in-band and cross-band because of the non-linearity that results in unwanted signals. Additionally, distortion increases in multi-band operation because of the cross-modulation with intermodulation distortion (IMD) of PA. For having the linear portion, the PA can be operated at *backed off* (a lower power). Besides, for wideband code division multiple access (WCDMA) and orthogonal frequency division multiplexing (OFDM), having high peak-to-average power ratios (PAPR) result in distortion. For increasing the power efficiency, it is concluded that the PA is caused to be operated closer to the compression region.

For compensating the nonlinear behavior of PA, the DPD technique as a software-defined solution in this research used effectively. With the help of a pre-distorter, the PA can be operated up to its saturation point, results in acceptable linearity and efficiency. Two significant reasons for choosing the DPD technique are the ability to keep the entire efficiency and to get usage of digital signal processors such as digital-to-analog converters (DACs) and analog-to-digital converters (ADCs). For ADCs and DACs, it is so critical to utilize

high-speed converters with high resolution in wideband DPD systems.

In [21], a methodology for reducing the output signal distortion for RF transmitters is described by using an example. The output signal of the feedback path ADC has a sampling rate lower than the input signal of the DPD's static nonlinear function. For simulation purposes, related set-up [21] for getting a suitable set of experimental data to be used in this work is shown in Fig. 1.

Distortion classification is handled using NN and the proposed non-linearity inspection steps with the aid of a neural network are given in Fig. 2. NN details are explained in the next sub-section.

B. Neural Network Consideration

A neural network is based on a collection of connected units, i.e. neurons. As utilized in this paper, a multi-layer perceptron (MLP) in which each neuron in each layer is connected to the all in the next layer requires several parameters on the implementation phase. In this paper, the MLP is obtained from scratch on software that works in conjunction with the Simulink model referenced from [21]. Thus, the fundamental parameters such as the learning rate (η), number of epoch in training, hidden layer counts and the number of neurons per layer, etc. can be decided in a software-defined simulation. The basic requirements for implementing a neural network can be given as follows:

- 1) Configuring neural network in terms of the hidden layer, training functions, and the parameterized learning rate
- 2) Suitable error function
- 3) Training and testing the dataset

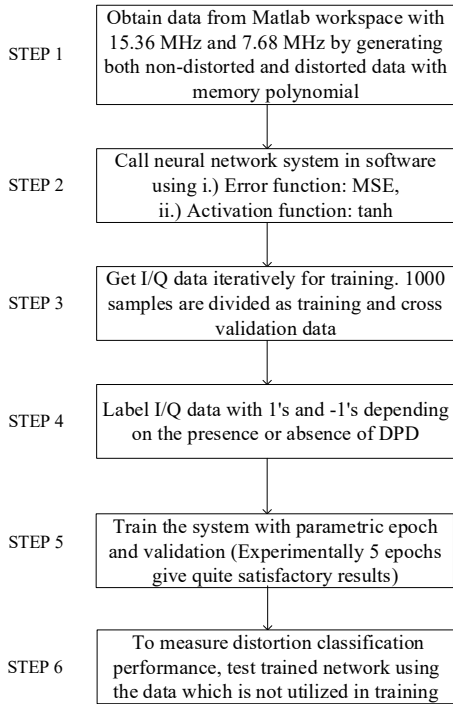


Fig. 2. Flowchart of the proposed non-linearity inspection steps on a power amplifier by utilizing the multi-layer perceptron.

The neural network (NN) consists of three parts as an input layer, hidden layers, and the output layer. The number of hidden layers and the related neurons is considered depending on the non-linearity of the data. An activation function is used to obtain the desired nonlinear modeling and performance in the hidden layers. Additionally, determining the length of a dataset for modeling the process is an important consideration for saving modeling time. While training the network, the optimal data length can be accessed by an empirical method with the aid of cross-validation data accuracy as also experimented in this paper. Therefore, the most important consideration in implementing any neural networks is providing suitable data for training and test. For this purpose, we gather training and test data in two different ways by either adding or removing the DPD to the PA. These two different classes are obtained as given in Fig. 1. After obtaining suitable data, the training phase starts as the PA outputs are sampled with a class label 1 and -1 for depending on the usage of the activation function. Thereafter, the neural system training is handled using the PA data with distortion and non-distortion. The labels are used in this paper as -1 for direct PA output without DPD and 1 for DPD-PA.

III. TESTS ON THE INSPECTING DISTORTION IN PA

A. Network Training and Test Accuracy

In this main part, the proposed software-defined environment on Matlab is going to be presented. The 1-hidden layer network on the software platform is constructed from the scratched to make any possible hardware design in the future.

TABLE I
TEST RESULTS

Number of Train Samples	Learning Rate	Epoch	Best Accuracy (%)
600	0.01	5	44.8
	0.02		48.1
	0.03		50.2
	0.04		51.7
	0.05		53.2
	0.06		53.5
	0.07		54.2
	0.08		54.7
	0.09		55.8
	0.1		54.3
650	0.01	5	41.9
	0.02		47.7
	0.03		53.9
	0.04		65.3
	0.05		96.9

First, the previously constructed Matlab add-on from MathWorks [21] is set for data collection purposes. In the model, 7.68 MHz data is used in the tests to classify whether the test data from 15.36 MHz is distorted or not. Adaptive DPD coefficient algorithm for the coefficient calculation recursive predictor error method (RPEM) related memory polynomial is applied. On the network training zero weights are initialized first, thus there is no random weight initialization. The loss function is used as a mean square error (MSE). The tanh activation function is used on the neuron triggering as the labels (1 and -1) are chosen suitably concerning the tanh function range. Sampling on the PA data is done using two frequencies as 15.36 MHz and 7.68 MHz in which the latter is obtained as two halves of the 15.36 MHz points by sub-sampling. This is to augment the data in hand and create two classes with and without distortion. The memory polynomial-based pre-distortion is associated with half of the points from 15.36 MHz sampled data with $\varepsilon = \frac{1}{7.68 \cdot 10^6}$ sec shift of the first half. The train is done with sub-sampled data on 7.68 MHz halves. In Fig. 3. and Fig. 4, we present the plots of some data samples and the test environment. Fig. 5. shows the neural network and practical PA details which can be used for the distorted and non-distorted I/Q data in the presence of DPD in simulation. After the training phase on different parameters, the test data is experimented on the network.

Table 1. shows the related test accuracy results with 96.9% highest. On these results, the notable considerations are the decision of learning rate and the number of training samples. In a 1-hidden layer MLP with tanh activations and MSE loss function, the learning rate outperforms for ≥ 0.05 in general. According to multiple tests, the I/Q data input size >600 significantly increases the classification accuracy for ≥ 0.05 learning rate values. This is parallel to the general behavior of the neural network system, as much as training samples increase the test accuracy which results in correct binary classification for distorted and non-distorted data in our case. The best results are obtained at 5th epoch among the first 10 epochs.

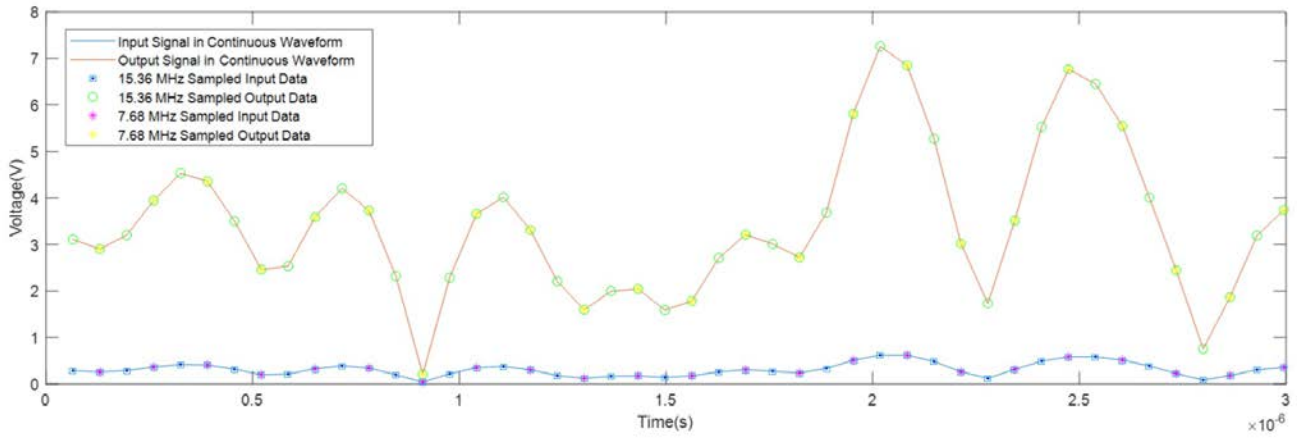


Fig. 3. Sampling with 15.36 MHz and 7.68 MHz for input and output signals (in absolute value) of a PA.

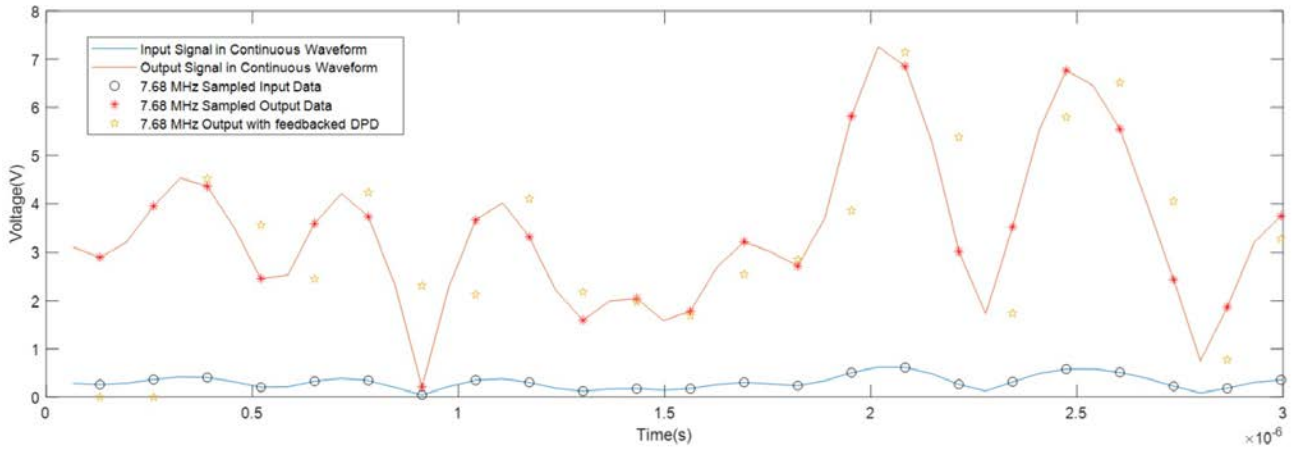


Fig. 4. The DPD feedback effect on 7.68 MHz data points only from the one half of 15.36 MHz.

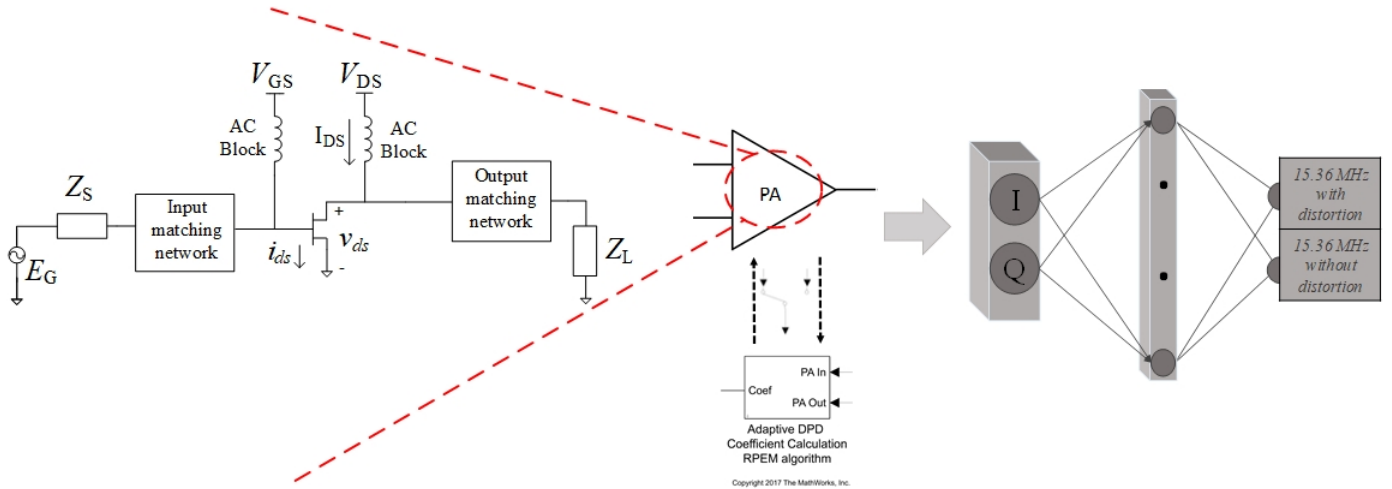


Fig. 5. The PA illustration of the system to be tested practically.

B. Distortion Test on a Practical PA

To demonstrate the validity of the proposed methodology for inspecting non-linearity of power amplifier, we use designed wideband PA in [1]. The related data is extracted by simulating the presented PA in Keysight Advanced Design System (ADS) environment. Fig. 6 shows the amplitude-to-phase modulation

(AM-PM) response of the designed PA. After simulating and obtaining various data, we insert normalized phase data points to construct network like in Section III and consider the linearity or non-linearity condition. The network responses that 97.2% the phase response is regular and this PA can be used in the DPD concept.

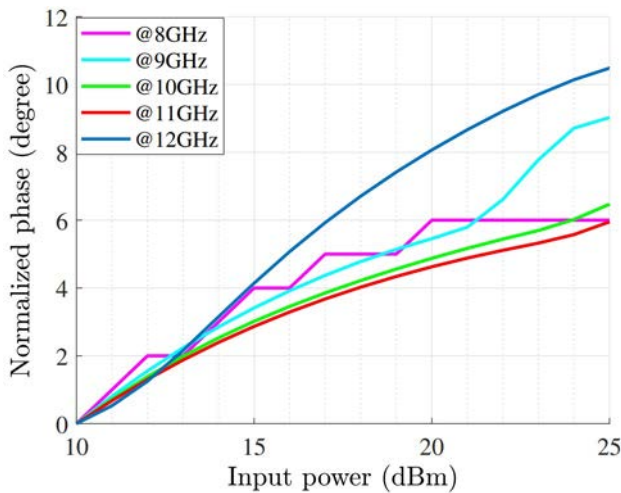


Fig. 6. AM-PM response of designed power amplifier in [1].

IV. CONCLUSION

In this research, we firstly construct and train the neural network with the proposed methodology, then we validate the method by considering linearity or non-linearity response of a power amplifier in [1].

In the first phase, we sub-sample PA data which is supplied by Mathworks and using the memory polynomial DPD, we obtain the linearized PA output. DPD output is feedforward to measure the effect of the DPD on a learning system. Thus, 15.36 MHz related distortion can be inspected using half of the 7.68 MHz points in the inputs. In the second phase, the proposed methodology is demonstrated by inserting the normalized phase response of practically simulated PA. The output accuracy of the network shows that the PA has a linear response. For future work, a light-weight neural network architecture, which is a hardware efficient network in terms of circuit complexity and power consumption, is aimed to work in collaboration with the practical PA of our research group.

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