PREDISTORTION SYSTEM IMPLEMENTATION BASED ON ANALOG NEURAL NETWORKS FOR LINEARIZING HIGH POWER AMPLIFIERS TRANSFER CHARACTERISTICS

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Abstract- In order to correct non-linearities due to High Power Amplifiers (HPA) operating near saturation in telecommunication transceivers, a new adaptive predistortion system based on analog Neural Networks (NNs) was developed. Based on size, consumption and bandwidth considerations, Multi-Layer Perceptron (MLP) type NNs were implemented in a 0.6 µm CMOS ASIC. The NNs parameters are digitally updated with a computer, depending on simulation conditions (temperature drifts, ageing variations). The interface between the analog part and the software updating system is integrated in an analog-digital PCB including a FPGA, 6 analog-to-digital converters and 62 digital-to-analog converters. This paper describes the realization of each part of the breadboard system and presents experimental validation results of the whole predistortion module.

Index terms: High Power Amplifiers, Neural Network Hardware, Predistortion, Spatial Telecommunications
I. INTRODUCTION

In satellite telecommunications, power efficiency and spectral efficiency are prominent concerns. For power efficiency purposes, High Power Amplifiers (HPA), such as Travelling Wave Tubes Amplifiers (TWTA) or Solid State Power Amplifiers (SSPA), are operating close to saturation, so as to get the maximum power efficiency onboard the satellite. Nevertheless, this leads to amplitude and phase non-linearities and the link transmission quality is deteriorated [1]. The combination of spectrally efficient modulations with non-constant envelope together with non-linearities leads to strong distortions of the transmitted signals.

There are several solutions to operate the HPA close to its saturation point without generating non-linearities [2]-[6]. One is to implement a module directly on-board the payload, just before the HPA, in order to obtain a linear transfer characteristic at the HPA output [4]-[6]. This solution, called the predistortion method, has the advantage to correct the HPA non-linearities directly onboard the satellite. It is also highly interesting because new satellite generations will have regenerative payloads. Therefore, the signals will be available in baseband, before modulation. Supposing that the frequency transposition does not distort the signal envelope, it is possible to apply a predistortion on the baseband signal before frequency transposition and HPA amplification. Thus, the predistortion system may operate in lower frequency bands, which opens new technological solutions never explored before.

Another point to have in mind is that the HPAs integrated on-board satellites undergo small amplitude and phase variations due to temperature drifts, ageing, and so on. Thus, if the predistortion module is integrated in the satellite payload, it must be adaptive and modify the predistortion transfer characteristic as a function of the drifts.

This paper presents a predistortion module developed in order to take into account all the concerns presented above. The different choices made from the module definition up to the breadboard integration are summed up and justified in the next parts: the way to model the HPA and the linearizer transfer function are developed in part 2. Then, parts 3, 4 and 5 detail respectively the integration of the analog predistortion system, the instrumentation of the analog to digital interface between the analog part and the updating software, and the experimental tests.
achieved to confirm the NN-based predistortion system ability to linearize the different HPA transfer characteristics.

II. MODELING AND LINEARIZATION OF POWER AMPLIFIERS

a. Modeling of HPA transfer characteristic

Since the HPA transfer characteristic has to be linearized directly onboard the satellite, the HPA experimental behavior has to be modeled. For this, it is necessary to collect experimental signal data in relation with its functioning mode at regular time intervals and to analyze these data in order to operate the adequate processing.

Among the existing method to model HPA (Saleh [7], polynomial [8], Volterra [9]), a trade-off between precision and complexity of the model has to be determined. As a matter of fact, the better the precision of the model is, the heavier the computational workload is. Table I presents the different types of models found in the literature with their advantages and drawbacks. The memory effects modeling shown in the second column maybe defined as the dependence of the distortion on the input signal frequency variation. These effects, hard to model, have not been taken into account in this study, so the HPA is considered as memoryless.

<table>
<thead>
<tr>
<th>Model</th>
<th>Memory effect</th>
<th>Precision</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saleh</td>
<td>No</td>
<td>Not precise</td>
<td>Very simple</td>
</tr>
<tr>
<td>Memoryless polynomial</td>
<td>No</td>
<td>Not precise</td>
<td>Simple</td>
</tr>
<tr>
<td>Volterra</td>
<td>Yes</td>
<td>Very precise</td>
<td>Very complex</td>
</tr>
<tr>
<td>Polynomial with memory</td>
<td>Yes</td>
<td>Precise</td>
<td>Complex</td>
</tr>
<tr>
<td>Hammerstein</td>
<td>Yes</td>
<td>Precise</td>
<td>Complex</td>
</tr>
<tr>
<td>Wiener</td>
<td>Yes</td>
<td>Precise</td>
<td>Complex</td>
</tr>
<tr>
<td>Hammerstein-Wiener</td>
<td>Yes</td>
<td>Precise</td>
<td>Very complex</td>
</tr>
<tr>
<td>Wiener parallel</td>
<td>Yes</td>
<td>Precise</td>
<td>Complex</td>
</tr>
<tr>
<td>Neural network</td>
<td>Yes</td>
<td>Very precise</td>
<td>Complex</td>
</tr>
</tbody>
</table>

The memoryless Saleh model was chosen to describe a 80W Ka-Band TWTA developed during a French Space Agency (CNES) research program. This model has the advantage to be quite simple to use since it describes the non-linearities of the amplifier with only two equations. One represents the AM/AM non-linearities (or amplitude non-linearities) (1) and the other the
AM/PM ones (or phase non-linearities) (2). The gain amplification $A_{HPA}(\rho)$, called AM/AM conversion, and the phase-shift $\phi_{HPA}(\rho)$, called AM/PM conversion, are given by the following expressions:

$$A_{HPA}(\rho) = \frac{\alpha_1}{1+\beta_1 \cdot \rho^2} \quad (1)$$

$$\phi_{HPA}(\rho) = \frac{\alpha_2}{1+\beta_2 \cdot \rho^2} \quad (2)$$

with $\rho$ the signal input amplitude, and $\alpha_1$, $\alpha_2$, $\beta_1$, and $\beta_2$ the scalar parameters of the model. This model fits well the HPA characteristic at first order. Furthermore, by varying the scalar parameters of the model, it is possible to model variations of the amplifier characteristics. The scalar parameters’ values of this model were provided by CNES and allow modeling with satisfying precision the transfer characteristic of the HPA. Figure 1 shows a representation of the normalized output amplitude and of the output phase shift as a function of the input amplitude up to the saturation point. Figure 2 represents different HPA transfer characteristics issued from the model in amplitude and phase.

Figure 1. Representation of normalized AM/AM conversion and AM/PM conversion as a function of the normalized input amplitude
Figure 2. Normalized HPA transfer characteristics in amplitude (V) in blue, and phase-shift (radians) in red, as a function of the normalized input amplitude (V) for different Saleh scalar values.

b. Linearization of power amplifiers

The linearization of a HPA consists in reducing its non-linearities to optimize the efficiency, the amplifier output power and the signal integrity. Several techniques are referenced in the literature in order to proceed with predistortion [4-6], [10], [11]. The technique described in [4] is particularly interesting since the output signal is used to monitor the predistortion module but does not directly participate in the linearization scheme (Figure 3).

Figure 3. Architecture of the predistortion feedback technique
The AM/AM and the AM/PM transfer characteristics of the predistortion functions are deduced from the HPA ones. By comparison with others non-linear modeling systems, the predistortion with Neural Networks (NNs) has the advantage of a high inherent parallelism with a simple repetitive scheme, which makes them attractive for integrated circuit technologies implementation purposes [12-14]. Moreover, NNs have the ability to be adaptive in that their parameters may be updated. In order to predistort continuously baseband input signals, the predistortion system of this study was developed and achieved with Multi-Layer Perceptrons (MLP) NNs [15-16], whose structure is developed in part 3. The architecture of the predistortion system was developed in [17] and is presented in Figure 4.

III. ANALOG PREDISTORTION SYSTEM

An analog-digital implementation was chosen for the NN rather than a digital one, so as to optimize the circuit bandwidth, the input signals' dynamics and the power consumption [12]. The digital updating system was implemented in a FPGA, in order to be more efficient and easily reconfigurable.

Figure 4: Global predistortion system architecture

The inner structures of the analog predistortion module and of the MLP-type NNs were described in [17] and are shown respectively in Figure 5 and Figure 6.
Figure 5. Schematic of the analog predistortion module

Figure 6. Multi-Layer Perceptron Neural Network structure
Computer simulations confirmed the chosen structure ability to linearize HPA gain distortion, for varying simulation conditions and by taking into account variations due to technology non-homogeneities and voltage offsets together with corruption of the NN signals by white noises [15-16]. The feedforward NNs were integrated in CMOS 0.6 µm technology (Figure 7). The NN circuits are detailed in [18], [19].

Figure 7. a. Layout of a neuron (dimensions: 330µmx300µm – Multiplier sizes: 70µmx70µm); b. Layout of the neural network;

In order to correct both non-linearities represented in Figure 1, the predistortion output signals and have to follow:

\[ I_e = I \cdot g(\rho^2) \cos(\theta(\rho^2)) - Q \cdot g(\rho^2) \sin(\theta(\rho^2)) \] (3)

\[ Q_e = Q \cdot g(\rho^2) \cos(\theta(\rho^2)) - I \cdot g(\rho^2) \sin(\theta(\rho^2)) \] (4)

with \( \rho^2 \) the square modulus of signals \( I \) and \( Q \), and \( g(\rho^2) \) and \( \theta(\rho^2) \) the respective outputs of NNg and NNθ [3]. The functions \( g \) and \( \theta \) may be modified as parameters of each NN after their calculation by the algorithmic part. As the AM/PM distortion amplitude is lower than 0.4 radian, (1) and (2) may be approximated by:

\[ I_e = I \cdot g(\rho^2)(1 - \frac{\theta(\rho^2)}{2}) - Q \cdot g(\rho^2)\theta(\rho^2) \] (5)

\[ Q_e = Q \cdot g(\rho^2)(1 - \frac{\theta(\rho^2)}{2}) - I \cdot g(\rho^2)\theta(\rho^2) \] (6)
$\rho^2$ is obtained thanks to the Analog Device component AD835, which includes a 4-quadrants multiplier and an adder. This circuit was fully qualified and its static and dynamic behavior validated for the purpose of this study.

The processing module is implemented as shown in Figure 8.

![Figure 8. Inner structure of the processing module](image)

Figure 9 represents the waited and the experimental predistorted signals as a function of the square modulus of the signals and . Signals and are defined as if each NN performs its approximation task ideally. Both test curves are very close to ideality. The maximum error observed with regard to the desired predistorted characteristic is equal to 10mV for a signal amplitude of 1V. Thus, if it is assumed that both NNs will approach the desired transfer characteristics, the complete analog predistortion system achieves its task correctly.

Besides, to ensure that the linearizer does not inject signals above the input saturation voltage of the HPA, a limiter may be used between the predistortion module and the amplifier.
Figure 9. Processing $I_e$ and $Q_e$ as a function of $\rho^2$ (dashed lines: modeled functions, solid lines: measured values)

IV. UPDATING SYSTEM

a. Structure

It is important to perfectly control the variations of the predistorted signals ($I_e, Q_e$) as a function of the input signals ($I, Q$) and the parameters of each NN.

Figure 10 represents the structure of the analog-digital interface between the analog predistortion system and the computer developed in [17] and [19]. The signals $I, Q, I_e, Q_e, I_r$ and $Q_r$ are digitally converted through 6 ADC whose resolution is 12 bits, in order to obtain a resolution lower than $500\mu$V. As the bandwidth of the signals ($I, Q$) is equal to $25\text{MHz}$, the sample frequency was set to $100\text{MHz}$ in order to have at least 4 points per period. The number of data stored from each sampled signal during $100\mu\text{s}$ is equal to 1024.
Figure 10. Analog-digital interface

Once the 1024 data issued from each sampled signal have been transmitted to the computer via a RS232 link, the delays due to the different analog operations between the input and the output signals are taken into account. Indeed, the predistortion system and the amplifier introduce a phase-shift between their inputs and outputs. An intercorrelation step allows finding out the value of this phase-shift (in number of samples) in order to synchronize the signals and realize the predistortion calculation over the same sample. The intercorrelation is calculated between the modulus of \((I, Q)\) and \((I_e, Q_e)\) and the modulus of \((I, Q)\) and \((I_r, Q_r)\).

In order to control the whole system linearity, the demodulated HPA output signals are then compared to the input signals in order to observe if both couples of signals are proportional and phased. If so, the NNs' parameters are not updated. If not, a software training phase begins with the stored raw data, in order to calculate the new NNs' parameters, and then better linearize the distorted HPA transfer characteristic. Once the 62 NNs' parameters updated, they are converted and injected into the analog integrated NNs via two ICs of 32 DACs. The training procedure of the NNs is described in part IV.a.

b. Realization
Figure 11 and Figure 12 present photographs of the analog predistortion system and of the analog-digital interface respectively. In Figure 12, the 6 analog signals to sample are injected at (1). After the analog-to-digital conversions, the data are stored in the FPGA (2) before being transmitted to the computer via the RS232 link (3).

After calculation, the updated NNs' parameters are sent to the FPGA via the RS232 link. If necessary, the 62 digital parameters are converted by 62 DACs distributed in two ICs of 32 DACs (4) in order to be injected at the same time in the analog predistortion system.

Each Neural Network dissipates continuously 500mW, for a total power consumption of 3W for the whole analog predistortion system, including the adder, the multipliers and the processing module. The analog-digital interface dissipates 4.5W continuously, with 600mW for each ADC and 200mW for the FPGA.

Figure 11. Analog predistorsion system photograph
V. EXPERIMENTAL TESTS ACHIEVED ON THE GLOBAL PREDISTORTION SYSTEM

a. Preliminary setup
Every elementary function of the NN (adder, multiplier) may present an undesired offset or multiplying factor at its output. Before determining the linearization ability of the system, these errors have to be characterized. Therefore, a preliminary setup algorithm was performed in order to determine these errors. For each NN and for each of the 31 elementary functions, the imprecision was accurately modeled and memorized. The training software was then adapted with the adequate constants.

b. Test procedure
An interface was developed using the NI LabWindows/CVI environment to control this analog-digital circuit and process the input and output data. The test procedure applied to determine the linearization ability of the whole predistortion system is detailed in Figure 13.
Figure 13. Test procedure to validate the linearization ability of the predistortion system

First, the user has to specify the Saleh model which fits better to the HPA characteristics to linearize. Then, the user defines the amplitude and phase error criterions for which NNs' parameters have to be updated. Then, a sequence of I and Q voltages is performed and injected into the linearizer. The waveforms' frequency relative to and signals may vary arbitrary between 0.1MHz and 25MHz.

A first acquisition of $I$, $Q$, $le$ and $Qe$ is achieved for null weights and biases. After that, $lr$ and $qr$ voltages are determined as a function of $le$ and $Qe$ sampled values and Saleh's scalars. Then, $(I, Q)$, $(le, Qe)$ and $(lr, qr)$ are compared in order to achieve the intercorrelation and synchronize the signals on the same sample.

After the intercorrelation step, $(I, Q)$, and $(lr, qr)$ are compared in amplitude and in phase. If the errors are lower than the criterions defined by the users, the NNs' parameters are not modified. If
not, both NNs are trained in order to respect both criterions. The backpropagation method, associated with the simple gradient algorithm [20], is used on relevant data. As soon as the convergence is observed and the user's criterions respected, the algorithm stops, and the updated NNs' parameters are validated with all the acquisition data. After the validation phase, the NNs' parameters are transmitted to the analog predistortion system. Then, a new acquisition is automatically achieved to confirm that the new parameters' values experimentally correct both AM/AM and AM/PM non-linearities.

c. NN convergence
The developed NI LabWindows/CVI code allows the user to choose between three linearization criterions: the user may specify the maximum tolerable error between \((l, Q)\) and \((l_r, Q_r)\), or the maximum average tolerable error, or a fixed number of iterations of the backpropagation algorithm. In any case, an absolute maximum number of iterations was fixed to 100000 in order to avoid linearization system divergence. Nonetheless, even with 100000 iterations, the processing time remains under 1 second.

d. Experimental results
The first test was achieved with null NN parameters and with Saleh's scalars parameters provided by the French Space Agency (CNES). These parameters correspond to the transfer characteristic of a specific HPA in well-defined experimental conditions. Figure 14 presents respectively the experimental AM/AM and AM/PM transfer characteristics, observed after transposition of the HPA output, respectively without predistortion (solid curve), with an ideal predistortion system (solid straight) and with the implemented predistortion system (dots). The grey dots are actually scatterplots of several measurements and are spread due to the sampling frequency. Besides, the ideal phase value after predistortion is surrounded by the maximal and minimal tolerated phase deviation, adjusted by the user. The predistortion system, with null parameters is able to correct the non-linearities of the HPA model, but the linearization is not accurate and a training phase of the NN is required.
Once the training was achieved and the NNs’ parameters updated, in less than one second, the predistortion system was able to correct both non-linearities with a SER higher than 30dB [21]. Figure 15 presents respectively the experimental AM/AM and AM/PM transfer characteristics, observed after transposition of the HPA output after the training and the parameters’ update. The difference between the ideal AM/AM curve and the dots and the hysteresis that seems to occur was caused by a 20 ns phase shift between the signals and , lower than the sampling period and that therefore could not be corrected by the intercorrelation step (Figure 16). Moreover, the resolution of the acquisition system was not high enough, and the AM/PM characteristic seems to deviate from the ideal phase value for the small input amplitudes. Higher sampling frequency and resolution would therefore have provided more accurate curves.
Figure 16. Focus on two samples of the same input amplitude with a phase-shift lower than the sampling period as a function of time (left) and consequences on the AM/AM characteristic (right).

Then, the Saleh's scalars were modified (Figure 17) to investigate if the predistortion system is able to correct HPA transfer characteristic drifts due to temperature variation, ageing, and so on, or to linearize others HPAs whose transfer characteristics fit with these Saleh model scalar values. Since the new HPA modeled characteristics are not correctly linearized with the first NN weights’ and bias’ values (Figure 18), the neural networks must both be trained in order to fit this new model. Once the training is achieved and the NNs’ parameters updated, the predistortion system is once again able to correct both non-linearities in less than one second with a SER higher than 30dB (Figure 19).

Figure 17. Modification of the Saleh parameters. Solid curve: new values; dots : former values
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Figure 18. Representation of the normalized experimental AM/AM (left) and AM/PM (right) curves without predistortion (solid curve) and with predistortion (solid straight: ideal; dots: experimental points) as a function of the normalized input amplitude for the new Saleh’s scalars and the old NN weights’ and bias’ values.

Figure 19. Representation of the normalized experimental AM/AM (left) and AM/PM (right) curves without predistortion (solid curve) and with predistortion (solid straight: ideal; dots: experimental points) as a function of the normalized input amplitude for the new Saleh model and the updated NN weights’ and bias’ values.

VI. CONCLUSIONS

The developed analog predistortion system was validated by correcting many well-defined distortion characteristics in laboratory conditions. Therefore, the analog predistortion system is able to linearize different HPAs whose transfer function fits with the Saleh model. Moreover, the satisfactory operation of the NNs' parameters' update instrumentation was checked by continuously changing the Saleh's coefficients. Thus, this project shows that it is possible to linearize HPAs with an integrated predistortion system based on analog neural networks. The next step is the test of the whole structure with different HPAs, in varying experimental conditions. The test procedure will be more complex, since it requires expensive test benches and
to properly adapt the linearizer breadboard in these environmental conditions. If these tests are relevant, the feasibility of adaptive HPA linearization with analog neural networks will be proved. A new optimized version of the complete analog part will be integrated in an ASIC with a more recent technology in order to optimize bandwidth and power consumption, and to transform this laboratory breadboard into an engineering model. As for the digital part of the system, the processing part will be integrated in a microprocessor or a FPGA [22], and the interface between the analog and the digital parts will be updated with regard to the new available components. Eventually, the processing part of the future optimized version will have to take into account the memory effects of the power amplifier, in order to allow linearization over larger bandwidths.

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