

# Adaptive LINC structure applied to power amplifier with memory effects for wideband signal transmission

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**Abstract**—Power amplifiers (PAs) are inherently nonlinear devices and they are present in all transmitters of a communication equipment. As a result of transmitter nonlinearities, the transmitted signal spectrum expands into adjacent channels. Several linearizing techniques for power amplifiers have been proposed, but the most existing architectures assume that the PA has a memoryless nonlinearity. For wideband signal transmission, such as CDMA or OFDM, the PA memory effects can no longer be ignored. In this work, authors propose and analyze an adaptive digital LINC (Linear amplification with Nonlinear Components) transmitter structure including PA memory effects, applied to a OFDM signal transmission. The major drawback of a LINC structure is the inherent sensitivity to gain and phase imbalances between both amplifying branches. In this work a full-digital base band method is described which corrects any gain and phase imbalances in LINC transmitters mainly due to the un-matching of the two amplifier paths. The method uses adaptive signal processing techniques, includes memory effects and its main advantage is the ability to track the input signal variations and adapt to the changes of amplifier nonlinear characteristics.

**Keywords**— adaptive digital method, PA memory effects, imbalances correction, LINC transmitter.

## I. INTRODUCTION

The new transmission systems, such as code-division multiple access (CDMA) and orthogonal frequency-division multiplexing (OFDM), are very sensitive to nonlinear distortions due to its greatly variable envelope and high peak to mean envelope power ratio values [1-3]. The power amplifier is the most nonlinear component in a transmitter of a communication equipment. The PA presents non-linearities generating amplitude and phase distortions on the power amplifier output signal. As a result of transmitter nonlinearities, the transmitted signal spectrum expands into adjacent channels. One way to achieve linear amplification is by using class A power amplifier working with a high backoff, which corresponds to moving the operating point of the amplifier to the linear region. However, it implies low power efficiency. High power efficiency can be obtained with class

AB or B power amplifiers, but they show more non-linear characteristics. In order to achieve both spectrum and power efficiency, several classical linearizing techniques for power amplifiers have been proposed in the technical literature. These techniques are usually categorized as Feed-forward, Feedback, Predistortion and LINC transmitter. According to the recent literature [3-5], the predistortion technique has been the more useful scheme in order to reduce the effects of nonlinear distortion on the performance of wide-band systems. If the PA is considered as a memoryless system, it can be modeled by the AM/AM and AM/PM characteristics. However, PA memory effects can no longer be ignored for wider bandwidth applications such as W-CDMA or OFDM. In this work authors propose and analyze an adaptive digital LINC transmitter structure based on the results obtained in a previous work [6] but including PA memory effects. Its major drawback is the inherited sensitivity to gain and phase imbalances between the two amplifier branches [7-8]. Several authors have considered different methods to correct the imbalances in LINC transmitters [9-12], but the method presented here includes memory effects. Some advantages of the proposed method with regard to others are: it can operate continuously in background during regular data transmission because it uses the transmitted data as a kind of calibrating signal and its application is not limited by the communication standard, also it can be able to correct any phase and gain imbalance produced between both amplifying branches, and due to its fast convergence rate this method is suitable to be implemented in a real system. The proposed method is carried out in base-band and is full-digital and its functionality has been verified by means of simulation.

## II. LINC TRANSMITTERS

One of the reasons that the LINC transmitter has not been widely used is the difficulty to achieve the accurate gain and phase matching required between the two paths. Errors in gain and/or phase matching will cause incomplete cancellation of unwanted elements in wideband phase modulated signals. As a result, a large number of unwanted spurious products appear in the output spectrum.

The effect of gain and phase imbalances between the two paths may be analyzed as follows. The source signal may be written in complex general format as [14]

$$s(t) = c(t)e^{j\phi(t)} \quad 0 < c(t) \leq c_{\max} \quad (1)$$

The source signal is separated into two constant-envelope signals by a Signal Component Separator (SCS) as shown in Fig.1. These signals are calculated as

$$\begin{aligned} s_1(t) &= \frac{1}{2} [s(t) - e_s(t)] \\ s_2(t) &= \frac{1}{2} [s(t) + e_s(t)] \end{aligned} \quad (2)$$

Where  $e_s(t)$  is a complex signal that is in quadrature to the source signal  $s(t)$ .

$$e_s(t) = js(t) \cdot \sqrt{\frac{c_{\max}^2}{|s(t)|^2} - 1} \quad (3)$$

Thus

$$s(t) = s_1(t) + s_2(t) \quad \text{and} \quad |s_1(t)| = |s_2(t)| \quad (4)$$

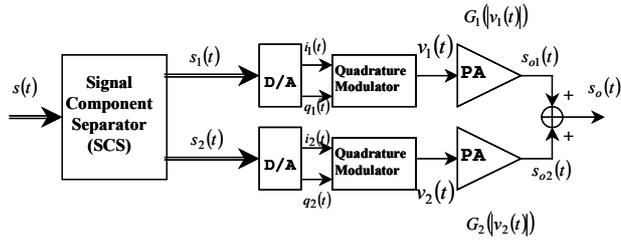


Figure 1. Schematic diagram of the LINC transmitter

The amplifier of each path is characterized by a level-dependent complex gain, with an output complex signal in each path given by

$$\begin{aligned} s_{o1}(t) &= v_1(t) \cdot G_1(|v_1(t)|) \\ s_{o2}(t) &= v_2(t) \cdot G_2(|v_2(t)|) \end{aligned} \quad (5)$$

Where  $v_1(t)$  and  $v_2(t)$  are the baseband representation of the instantaneous complex envelope amplifier input signal in each path.

Therefore, if ideal D-to-A converters (DACs) and quadrature modulators are supposed, that is,  $s_1(t) = v_1(t)$  and  $s_2(t) = v_2(t)$ , the output signal in complex format then becomes

$$\begin{aligned} s_o(t) &= s_{o1}(t) + s_{o2}(t) = s_1(t) \cdot G_1(|v_1(t)|) + s_2(t) \cdot G_2(|v_2(t)|) \\ &= s(t) \cdot \frac{G_1(|v_1(t)|) + G_2(|v_2(t)|)}{2} - e_s(t) \cdot \frac{G_1(|v_1(t)|) - G_2(|v_2(t)|)}{2} \end{aligned} \quad (6)$$

The second term in (6) implies that there is an unwanted residual signal due to imperfect cancellation (it tends to zero as the gain and phase matching are perfected). The term introduces interfering power in the adjacent channel limiting the spectrum efficiency of the system.

The aim of this method is to reduce the factor  $[G_1(|v_1(t)|) - G_2(|v_2(t)|)]$  as much as possible. The method is based on adaptive signal processing techniques and its main advantage is to track input signal variations and possible changes due to temperature variations, amplifier bias and component aging, among others.

### III. CORRECTION METHOD

#### A. Power Amplifier Model

To take into account the memory effects of the PA, a polynomial model with memory has been used. This model is based on the results obtained in [13] with the Motorola GaAs MESFET power amplifier working at 1.455GHz.

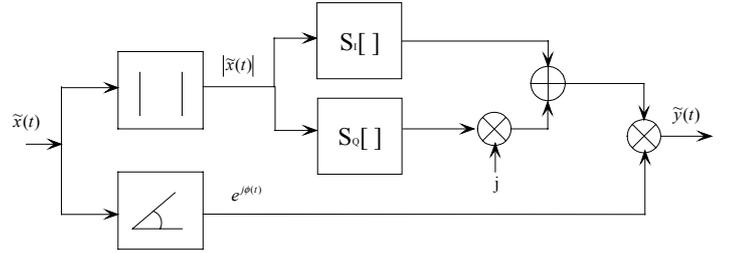


Figure 2. Power Amplifier Model

Considering a discrete-time model, sampling at  $t=mT$ , with  $T$  the sampling period, the PA output signal at time  $m$  is given by the following equation

$$\tilde{y}(m) = \sum_{c=0}^{P-1} \sum_{l=0}^D b_{c,l} \tilde{x}(m-lm_0) \tilde{x}(m-lm_0)^c \quad (7)$$

$m_0$ : distance between memory taps.

$b_{c,l}$ : Coefficients calculated by least squares for the model MRFC1818.

$\tilde{x}(m)$ : PA input signal.

The PA model has a memory  $D$  and a highest nonlinearity order  $P$ .

In this work an amplifier model with  $D=1$  and  $P=10$  is used.

## B. Structure of the Correction Method

A schematic diagram of the simulation model is depicted in Fig.3. The source signal is separated into the two constant-envelope signals by an SCS. These signals are multiplied by different complex vectors, one for each branch ( $K_1$  and  $K_2$ ). These vectors are computed and continuously updated to reduce the out-of-band spurious emission by means of an adaptive algorithm. This algorithm needs a reference of the output signal to update the complex coefficients. A feedback signal,  $r(t)$  is obtained by means of a downconversion process of the output power amplifier signal  $s_o(t)$ , where  $1/G_L$  is the downconversion gain, including the output coupler gain. This downconversion gain allows to adjust the range of signal values to the quadrature demodulator input and it is defined as the mean of the amplifying branches gain.

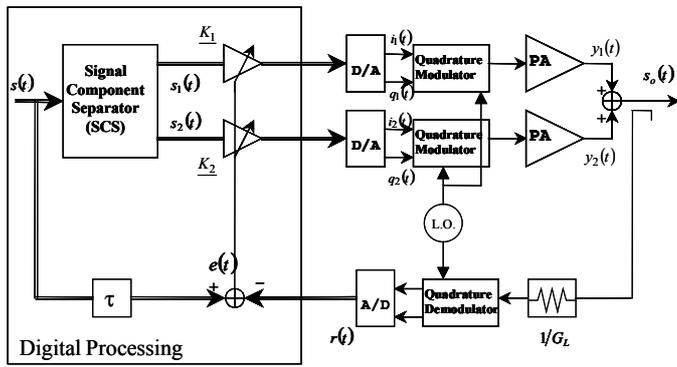


Figure 3. Simulation model

The complex vector of each path consists of  $D+1=2$  terms to take into account the memory effects of the power amplifier.

$$\underline{K}_n = (K_{n,0} \quad K_{n,1}) \quad n=1,2 \quad (8)$$

The adaptation criterion of the algorithm is to minimize the mean-squared-error. The error signal to update terms  $K_{1,l}$  and  $K_{2,l}$  is the difference between the source signal,  $s(t)$ , and the feedback signal,  $r(t)$ .

$$e(t) = s(t) - r(t) \quad (9)$$

and to calculate the terms with memory,  $K_{1,0}$  and  $K_{2,0}$  the error signal is defined as

$$e_0(t) = s(t-t_0) - r(t-t_0) = e(t-t_0) \quad (10)$$

it coincides with the error signal  $e(t)$ , defined in (9), at time  $t-t_0$ .

The cost functions to minimize are defined as

$$J = E \left[ |e(t)|^2 \right] \quad J_0 = E \left[ |e_0(t)|^2 \right] \quad (11)$$

Where  $E[\cdot]$  denotes the statistical expectation operator.

Applying some approximations, we finally get the result

$$\nabla_{K_{n,1}} J \approx -2 \cdot E \left[ e(t) \cdot s_n^*(t) \right] \quad n=1,2 \quad (12)$$

$$\nabla_{K_{n,0}} J_0 \approx -2 \cdot E \left[ e_0(t) \cdot s_n^*(t-t_0) \right] \quad n=1,2 \quad (13)$$

Therefore, using the instantaneous estimate of the gradient, the updated value of the adaptive coefficient at time  $m+1$  is computed by using the simple recursive relation

$$K_{n,1}(m+1) = K_{n,1}(m) + \mu_1 \cdot e(m) \cdot s_n^*(m) \quad n=1,2 \quad (14)$$

$$K_{n,0}(m+1) = K_{n,0}(m) + \mu_0 \cdot e_0(m) \cdot s_n^*(m-m_0) \quad n=1,2 \quad (15)$$

Where the positive real-valued constants,  $\mu_0$  and  $\mu_1$  (step-size), control the speed of convergence and the misadjustment (final excess error) of the algorithm.

## IV. SIMULATIONS

The source signal for simulations is an OFDM signal of 1MHz bandwidth and 0dBm input signal power. The power amplifier in path 1 is simulated using the presented model and the amplifier in path 2 is simulated introducing several imbalances in complex coefficients  $b_{c,l}$  of the equation (7).

Figure 4 compares the normalized input power spectral density,  $S(f)$ , and the normalized output power spectral density,  $S_o(f)$ , in two cases: using a classical LINC structure, and using the proposed adaptive LINC structure, in both cases with a 1.5dB gain imbalance and a  $5^\circ$  phase imbalance between amplifying branches. As seen, an improvement around 20 dB in the out-of-band spurious reduction is obtained when the imbalances correction method, proposed in fig. 3, is applied.

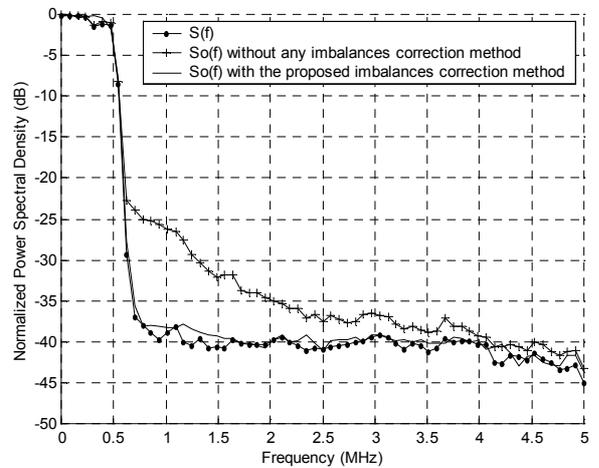


Figure 4. Normalized Power Spectral Density of simulated input  $S(f)$  and output  $S_o(f)$  signal with and without the imbalances correction method.

The proposed method compensates the existing imbalances between both amplifying branches when the PA is characterized as a memory model. This method consists of two complex adaptive vectors, one in each path, with two terms ( $K_{n,1}$  and  $K_{n,0}$ ). They are calculated by means of the equations (14) and (15). This correction method is based on the scheme proposed in [6], where the PA was characterized as a memoryless model, and therefore, only one term in each complex vector ( $K_{n,1}$ ) was used, and it was computed by using the equation (14).

Figure 5 compares the normalized output power spectral density,  $S_o(f)$ , in three situations where a LINC transmitter structure is used: without applying any imbalances correction method, using the imbalances correction method proposed in figure 3 (called “correction method with memory”), and using the method proposed in [6] (called “correction method without memory”). As seen in Figure 5, the best solution in order to reduce spurious emission outside the channel bandwidth is to use an imbalances correction method, which takes into account the memory effects introduced by the power amplifier.

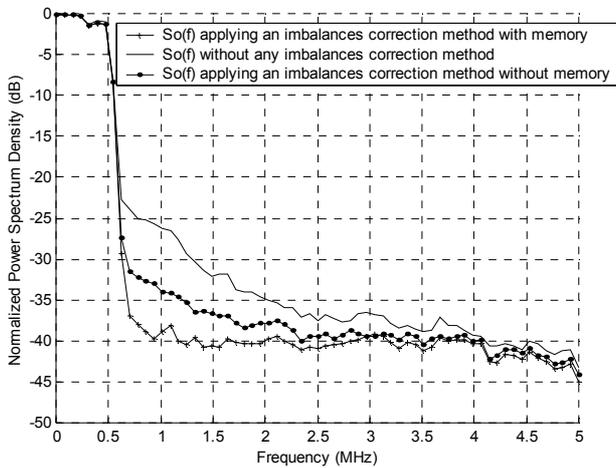


Figure 5. Normalized Power Spectral Density of output  $S_o(f)$  signal with a LINC transmitter structure and: without any correction imbalances method, applying the proposed “correction method with memory” and applying the “correction method without memory”.

### A. Coverage

The convergence speed can be measured by analyzing the time evolution of the error signal  $e(t)$ . The step size parameters,  $\mu_l$  and  $\mu_o$ , are chosen to reduce the out-of-band spurious as quickly as possible. According to the simulation (Fig.6), the adaptive coefficients reach its optimal value rapidly ( $< 2 \mu s$ ); therefore this method is suitable in order to be implemented in a real system.

We have also analyzed whether the value range of adaptive coefficients is suitable for its implementation in a digital processor. Figure 7 and 8 show the value range of the real and imaginary part of the coefficients,  $K_{1,1}$ ,  $K_{2,1}$ ,  $K_{1,0}$  and  $K_{2,0}$ . It demonstrates that the value range of adaptive coefficients along time is delimited and it is appropriate in order to be implemented in any digital processor device.

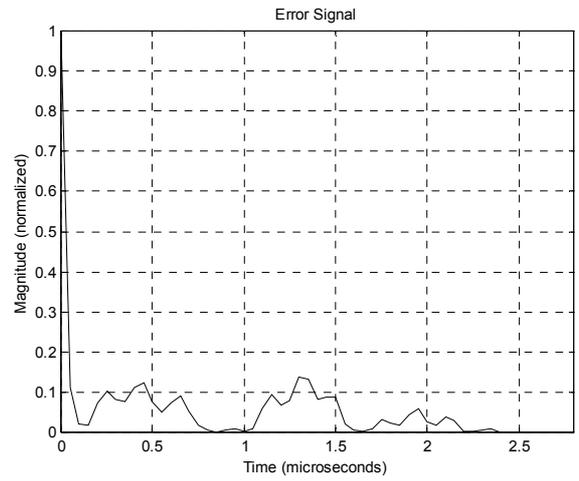


Figure 6. Evolution of the error signal

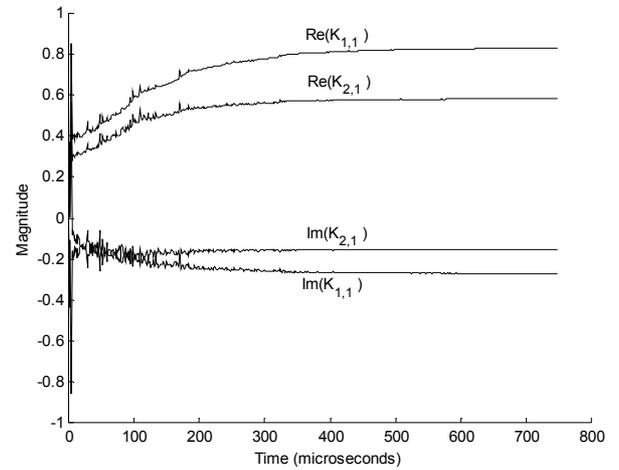


Figure 7. Value range of adaptive coefficients,  $K_{1,1}$  and  $K_{2,1}$

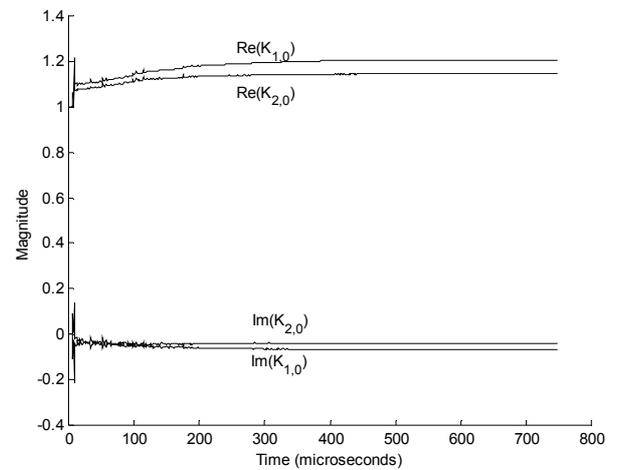


Figure 8. Value range of adaptive coefficients,  $K_{1,0}$  and  $K_{2,0}$

## B. Computational Load

The computational load of the proposed adaptive imbalances correction algorithm is another important issue in the implementation of this method.

According to equation (14) the number of instructions, multiplications (MPY) and additions (ADD), needed to calculate one complex coefficient, for example  $K_{1,1}$ , are 6 MPY and 4 ADD. The total instructions number to obtain the 4 complex coefficients ( $K_{1,1}$ ,  $K_{2,1}$ ,  $K_{1,0}$  and  $K_{2,0}$ ), taking into account the calculation of the error signals, can be seen in Table 1. The multiplication between input signal,  $s_n(m)$ , and calculated complex coefficients (*Signal Transmission Upgrade*) has to be also included in the total computation.

TABLE I. Number of Instructions of the proposed adaptive algorithm and the signal transmission upgrade

	MPY	ADD	TOTAL
<i>Adaptive Algorithm</i>	24	20	44
<i>Signal Transmission Upgrade</i>	16	8	24

The total number of instructions and so the computational load can be reduced approaching the DSP features, such as special instructions for signal processing. For example, the most of the digital processor device possess the MAC instruction, which includes one multiplication and one addition instruction, and it is executed in only one clock cycle. Therefore, the inclusion of the proposed imbalances correction algorithm in a DSP does not imply a very costly neither complex implementation.

## V. CONCLUSION

We have investigated the applicability for OFDM transmission systems of an adaptive digital method of amplifier linearization, based in a LINC transmitter scheme, in order to reduce the nonlinear distortion. The presented method corrects the undesirable gain and phase imbalances, which appear between amplifying branches in LINC transmitters. Using a simulation we have demonstrated that it is possible to reduce the spurious emission outside the channel bandwidth in a system with a multicarrier modulation, taking into account the memory effects of the power amplifier. As a result of its adaptive technique, this method can track the input signal variations and possible changes due to variations in operating conditions.

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