# Phase-Only Digital Predistortion Technique for Class-E Outphasing Power Amplifiers

Pavel Afanasyev#1, Prasidh Ramabadran#2, Somayeh Mohammady#3, Ronan Farrell#4, John Dooley#5,
#National University of Ireland Maynooth, Ireland
1pavel.afanasyev.2017@mumail.ie, 2Prasidh.Ramabadran@mu.ie, 3Somayeh.Mohammady@mu.ie,
4Ronan.Farrell@mu.ie, 5John.Dooley@mu.ie

*Abstract* — **Efficient and linear power amplifiers (PA) are an essential part of forthcoming 5G wireless systems. Outphasing class-E PAs offer high power efficiency and an option for higher efficiency cellular networks. However, they employ signal component separators, which split the signal into two paths. In order to efficiently recombine the signal, nonlinear power combiners are used. This paper proposes a novel phase-only predistortion technique for outphasing class-E PAs. The predistortion coefficients can be extracted based on AMAM characteristics of the output signal and an analytical model of an outphasing Class E PA. The suggested technique has been validated by simulation of an outphasing power amplifier in ADS Ptolemy software. It is shown that applying this technique to a 16QAM OFDM modulated signal with 20 MHz bandwidth improves error vector magnitude (EVM) from** $10.39\%$ **to** $2.43\%$ **compared to the signal without predistortion.**

*Keywords* — **outphasing amplifier, class-E, power amplifiers, nonlinearity, predistortion.**

## I. Introduction

In order to fulfil the increasing requirements for channel capacity future communication systems should use high-order modulation schemes which in turn requires high linearity of the transmitter. There are several power amplifier (PA) structures that provide high linearity and high efficiency at the same time: Doherty PA [1], envelope tracking [2], envelope elimination and restoration [3], outphasing PA [4]. Since all these amplifier structures introduce some distortion various predistortion techniques have been proposed to improve linearity of the transmitted signal [5].

The idea of outphasing PA was initially introduced in [4]. This concept was reintroduced in [6] where the term linear amplification with nonlinear components (LINC) was used. In an outphasing PA a transmitted signal $S_{in}(t)$ is transformed into two phase modulated parts according to expressions:

$$S_1(t) = \frac{S_{inmax}}{2} \cdot e^{+j\theta(t)} \tag{1}$$

$$S_2(t) = \frac{S_{inmax}}{2} \cdot e^{-j\theta(t)} \tag{2}$$

$$\theta(t) = \arccos\left(\frac{S_{in}(t)}{S_{inmax}}\right) \tag{3}$$

where $S_{inmax}$ is the maximum magnitude of the transmitted signal, $\theta(t)$ - outphasing angle.

The separation is performed in the digital domain by a signal component separator (SCS). The signals after the SCS ($S_1$ and $S_2$ in Fig. 1) have constant envelopes and therefore can be amplified with high efficiency non-linear power amplifiers without suffering from nonlinear distortion. The amplified signals ($S_{1a}$ and $S_{2a}$ in Fig. 1) are recombined to achieve an amplified replica of the input signal. Hence, the key advantage of the outphasing PA is its capability of amplifying the input signal with high efficiency. However, all practical outphasing PA structures introduce some non-linearity due to amplitude and phase imbalance between branches [7].

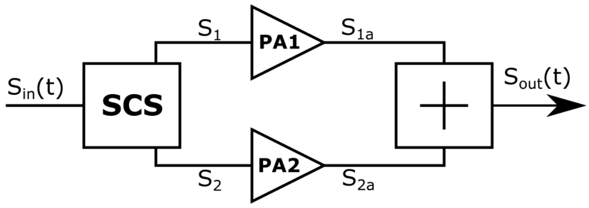


Fig. 1. Block-diagram of a LINC transmitter.

In order to address these issue various predistortion techniques have been proposed in literature. In [8] a phase correction technique was applied for a single class-E PA. However, it requires measurement of phase at the output ot the PA and therefore cannot be directly applied to LINC transmitters. In [9] the authors use an iterative procedure in order to estimate magnitude and phase compensation coefficients. The technique presented in [10] is based on representation of branch amplifiers as power sources with constant output impedance. However, since the behaviour of most power amplifiers is different from an ideal power source, it is difficult to apply this technique to real outphasing PAs. In [11] the authors find phase predistortion coefficients for a class-D outphasing power amplifier solving non-convex optimisation problem.

In this work we propose a phase-only predistortion technique which can be applied to class-E outphasing amplifiers with a nonisolated Chireix combiner. Phase predistortion coefficients are directly extracted from AMAM characteristics of the output signal. The calculation of predistortion coefficients is based on an analytical model of the Chireix combiner and therefore is more computationally efficient compared to the techniques presented previously in the literature. The presented method is proved using simulation of outphasing class-E PA with 16QAM OFDM modulated signal in ADS software.

## II. NONLINEARITY OF CLASS-E OUTPHASING POWER AMPLIFIER

Due to their high efficiency switch mode PAs, and class-E amplifiers in particular, have been effectively applied as branch amplifiers for outphasing PAs [12]. Indeed, since two outphasing signals have constant envelope, they can theoretically, be amplified with a high level of linearity with switch mode amplifiers.

In the general case, both the amplitude and phase of an amplified signal will depend on the load presented to the amplifier. Due to load modulation effects this dependence causes amplitude and phase imbalance between outphasing amplifier branches which in turn causes nonlinear distortion of the transmitted signal.

In a particular case of load-independent class-E PA efficiency does not depend on presented load [13]. The load network of such amplifier consists of DC-feed inductance $L$, parallel capacitance $C$, series reactance $X$ that can be both inductive and capacitive, and load $Z_L$ as shown in Fig. 2.

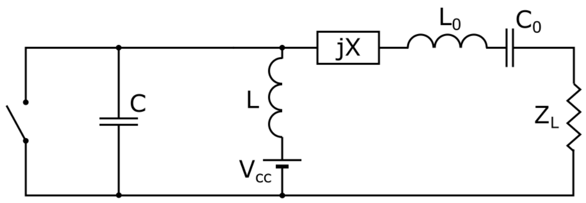


Fig. 2. General equivalent circuit of Class-E power amplifier with finite DC feed inductance.

The input parameters for synthesis of such an amplifier are: output power level $P_{out}$, supply voltage $V_{cc}$, carrier frequency $f_c$ and mistuning factor of the $LC$ resonator $q = \frac{1}{2\pi f_c \sqrt{LC}}$. It has been shown in [13] that if the mistuning factor is chosen as $q = 1.3$ then efficiency of such a class-E PA will not depend on the output load. It also should be noted that voltage across the output load will not depend on the output load. Therefore, the only source of nonlinearity is phase distortion between outphasing amplifier branches.

In order to recombine the signal after amplification stage isolated and nonisolated combiners are widely used. Isolated combiners provide very high linearity of the output signal. However, since a lot of power is dissipated in the resistor these combiners have very low efficiency. Nonisolated combiners, such as Chireix combiners, were initially introduced in [4]. It has been shown that these combiners can significantly improve efficiency of LINC systems at the cost of linearity [14]. In the general case a Chireix combiner consists of two quarter-wavelength transmission lines and reactive components as shown in Fig. 3. The value of reactive components are chosen to achieve zero input reactance at certain outphasing angles.

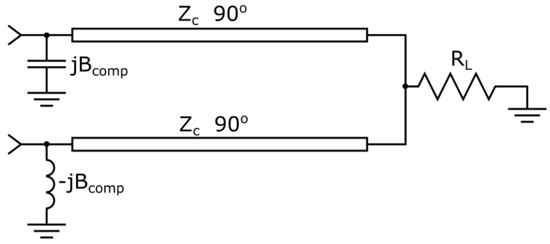


Fig. 3. Structure of nonisolated Chireix combiner.

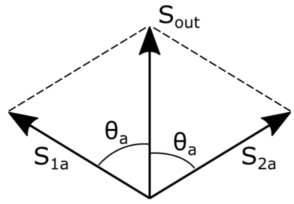


Fig. 4. Recombination of amplified signals in outphasing PA.

Input impedance of Chireix combiner branches can be defined by expressions:

$$\frac{1}{Z_{in1,2}} = \frac{2R_L}{Z_c^2}\cos^2\theta \mp j\left(\frac{R_L}{Z_c^2}\sin 2\theta - B_{comp}\right) \tag{4}$$

where $Z_{in}$ is the input impedance of combiner, $\theta$ is the outphasing angle at the input of combiner, $Z_c$ is the characteristic impedance of transmission lines, $B_{comp}$ is the compensating susceptance, and $R_L$ is the load impedance.

In order to construct a model describing the nonlinearity of class-E outphasing PA we make the following assumptions:

1) Magnitudes of the gains of the branch amplifiers are identical, constant and equal to $G$.
2) Phases of the gains of the branch amplifiers depend only on the load presented to branch amplifiers.

These assumptions mean that if after the SCS both signals have the same magnitude $V_1$ and can be expressed as

$$\begin{cases} S_1 = V_1 e^{j\theta(t)} & \text{(5a)} \\ S_2 = V_1 e^{-j\theta(t)} & \text{(5b)} \end{cases}$$

then after amplification the signals will be:

$$\begin{cases} S_{1a} = GV_1 e^{j(\theta(t)+\Delta\theta_1(t))} & \text{(6a)} \\ S_{2a} = GV_1 e^{-j(\theta(t)-\Delta\theta_2(t))} & \text{(6b)} \end{cases}$$

Two amplified signals are combined together with a Chireix combiner as shown in Fig. 4. Therefore, the outphasing angle at the inputs of the Chireix combiner $\theta_a$ can be expressed as:

$$2\theta_a = 2\theta + \Delta\theta_1 - \Delta\theta_2 = 2\theta + \Delta\theta_{12} \tag{7}$$

where $\Delta\theta_{12} = \Delta\theta_1 - \Delta\theta_2$ is the phase distortion introduced by branch amplifiers.

Since both $\Delta\theta_1$ and $\Delta\theta_2$ depend on the load presented to branch amplifiers they depend on the outphasing angle

$\theta_a$. Hence, $\Delta\theta_{12}$ is also a function of $\theta_a$. This function can be found with load-pull simulation of the amplifier and approximation of the analytical function $\Delta\theta_{12}(\theta_a)$.

Once the values $\theta_a$ have been found, magnitude of the voltage across the output load can be expressed as:

$$V_L = \frac{GV_1 R_L}{Z_c}\sqrt{2(1+\cos 2\theta_a)} \tag{8}$$

where $R_L$ is the output load resistance (e.g. input impedance of transmitter antenna), $Z_c$ is the characteristic impedance of the Chireix combiner transformers. From (8) it follows that if $\theta_a \neq \theta$ then the input amplitude to output amplitude (AMAM) response of outphasing PA will be nonlinear.

## III. Phase-only predistortion technique

In the previous section it has been shown that the AMAM characteristic of an outphasing power amplifier can be defined from a known function $\Delta\theta_{12}(\theta_a)$. However, in order to linearize the PA, the initial signal should be predistorted based on an AMAM curve. The output signal of the PA can be captured using an analogue-to-digital converter. Having both input and output signals, the AMAM curve can be plotted. For a narrowband signal it is assumed the memory effect can be neglected, and AMAM curve can be approximated by the polynomial:

$$\frac{V_L Z_c}{2GV_1 R_L} = a(v) = \sum_{i=0}^{N} a_i v^i \tag{9}$$

where $v = V_{in}/V_{inmax}$ is the normalised input voltage. Having found the expression for the AMAM curve one can find the outphasing angle at the input of the Chireix combiner:

$$2\theta_a = \arccos\left(2a^2(v) - 1\right) \tag{10}$$

Having found the outphasing angle $\theta_a$ for each value $v \in [0,1]$, the outphasing angle distortion $\Delta\theta_{12}$ can be found using expressions (9) and (10):

$$\Delta\theta_{12} = 2\theta_a - 2\theta \tag{11}$$

It should be noted that in order to find the predistortion coefficients $\Delta\theta_{12}$ should be expressed as a function of $\theta_a$. For this reason, $\theta_{12}$ can be numerically approximated with a polynomial function.

In order to predistort the signal, the initial outphasing angle values between $S_1$ and $S_2$, $\theta$ need to be modified so that $\theta_a = \theta$. From (11) it follows that new values $\theta'$ can be found as:

$$\theta' = -0.5(\Delta\theta_{12} - 2\theta) \tag{12}$$

The proposed predistortion technique can be outlined in the following steps:

1) Capture the output signal and plot the AMAM curve.
2) Approximate the curve with a suitable order polynomial.
3) For each value of output voltage find the distortion of the outphasing angle according to (10) and (11).
4) Find predistorted outphasing angle values using (12).

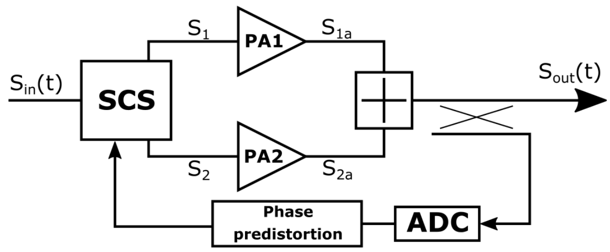


Fig. 5. Block-diagram of the proposed predistortion technique.

A block-diagram of this predistortion system is shown in Fig 5. The modification of outphasing angle can be carried out in the digital domain along with signal component separation.

## IV. Measured results

In order to prove the concept of the proposed phase-only predistortion technique we performed simulation using ADS-Ptolemy co-simulation tool from Keysight. An 16QAM OFDM modulated signal with bandwidth 20 MHz and sample rate 320 Msps was generated and split into two outphasing phase modulated signals. The both phase modulated signals were upconverted to carrier frequency 3.5 GHz and sent to inputs of outphasing PA. The outphasing PA consisted of two identical class-E load-independent amplifiers and a Chireix combiner with compensating reactive elements as shown in Fig. 3. The reactive elements were designed to provide zero susceptance for outphasing angle 73° since the probability density function of outphasing angle for OFDM modulated signal reaches maximum at this value. For the first simulation, input signal was separated into two outphasing paths without any predistortion, and amplified with the outphasing class-E amplifier. As a result, due to the phase imbalance between branches the signal experience strong nonlinear distortion as shown in Fig. 6 and 7.

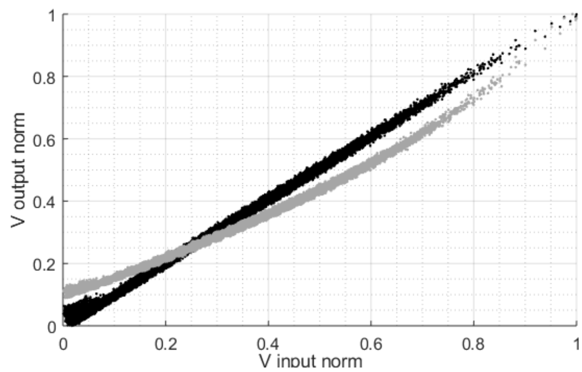


Fig. 6. AMAM plot of 20 MHz 16QAM OFDM modulated signal: grey dots - no predistortion applied; black dots - phase predistortion applied.

In order to perform the predistortion the AMAM characteristic shown in Fig. 6 (the grey curve) was approximated with a fourth-order polynomial function. Phase correction coefficients were calculated according to the

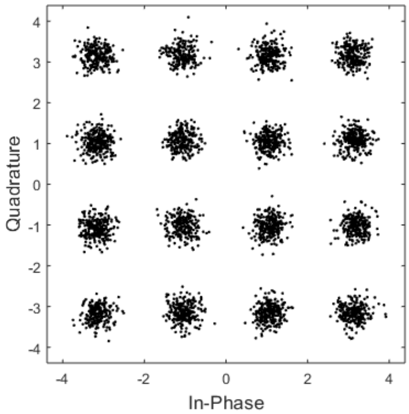


Fig. 7. Constellation of 20 MHz 16QAM OFDM modulated signal (no predistortion applied). EVM = 10.39 %.

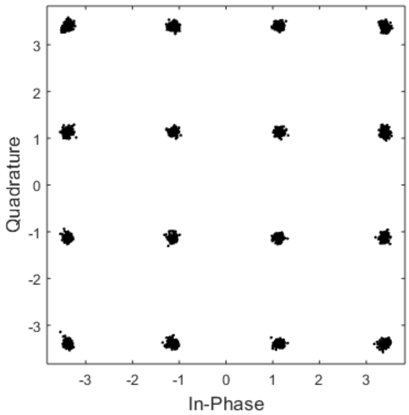


Fig. 8. Constellation of 20 MHz 16QAM OFDM modulated signal (phase predistortion applied). EVM = 2.43 %.

equations (10) - (12). The correction was realised in the simulation setup as an additional block in the signal component separator. The AMAM plot of the output signal and its constellation are shown in Fig. 8 and 6 (the black plot). From the presented plots one can see that using the proposed technique we managed to reduce the EVM of the amplified signal from 10.39% to 2.43%. It should be noted that since the proposed technique does not take into account memory effect, EVM improvement would be less for signals with wider bandwidth.

## V. Conclusion

High efficiency outphasing PAs require predistortion in order to ensure linear operation. A phase-only predistortion technique for class-E outphasing power amplifiers has been presented. The technique is based on the analytical relationship between the amplitude of the output signal and the outphasing angle at the input of the Chireix combiner. The proposed technique has been validated by extensive simulation in ADS. It has been shown that the proposed phase-only predistortion applied to an outphasing PA, improves the EVM performance from 10.39% to 2.43% for a 20 MHz 16QAM OFDM modulated signal.


## Acknowledgment

This publication has emanated from research conducted with the financial support of Science Foundation Ireland (SFI) and is co-funded under the European Regional Development Fund under Grant Number 13/RC/2077.


## References


[1] W. H. Doherty, "A new high efficiency power amplifier for modulated waves," *Proceedings of the Institute of Radio Engineers*, vol. 24, no. 9, pp. 1163–1182, Sept 1936.

[2] F. H. Raab, P. Asbeck, S. Cripps, P. B. Kenington, Z. B. Popovic, N. Pothecary, J. F. Sevic, and N. O. Sokal, "Power amplifiers and transmitters for RF and microwave," *IEEE Transactions on Microwave Theory and Techniques*, vol. 50, no. 3, pp. 814–826, March 2002.

[3] L. R. Kahn, "Single-sideband transmission by envelope elimination and restoration," *Proceedings of the IRE*, vol. 40, no. 7, pp. 803–806, July 1952.

[4] H. Chireix, "High power outphasing modulation," *Proceedings of the Institute of Radio Engineers*, vol. 23, no. 11, pp. 1370–1392, Nov 1935.

[5] F. M. Ghannouchi and O. Hammi, "Behavioral modeling and predistortion," *IEEE Microwave Magazine*, vol. 10, no. 7, pp. 52–64, Dec 2009.

[6] D. Cox, "Linear amplification with nonlinear components," *IEEE Transactions on Communications*, vol. 22, no. 12, pp. 1942–1945, December 1974.

[7] A. Birafane and A. B. Kouki, "On the linearity and efficiency of outphasing microwave amplifiers," *IEEE Transactions on Microwave Theory and Techniques*, vol. 52, no. 7, pp. 1702–1708, July 2004.

[8] T. Sowlati, Y. M. Greshishchev, and C. A. T. Salama, "Phase-correcting feedback system for class e power amplifier," *IEEE Journal of Solid-State Circuits*, vol. 32, no. 4, pp. 544–549, April 1997.

[9] T. Hwang, K. Azadet, R. S. Wilson, and J. Lin, "Linearization and imbalance correction techniques for broadband outphasing power amplifiers," *IEEE Transactions on Microwave Theory and Techniques*, vol. 63, no. 7, pp. 2185–2198, July 2015.

[10] A. Birafane and A. B. Kouki, "Phase-only predistortion for linc amplifiers with Chireix-outphasing combiners," *IEEE Transactions on Microwave Theory and Techniques*, vol. 53, no. 6, pp. 2240–2250, June 2005.

[11] Y. Jung, J. Fritzin, M. Enqvist, and A. Alvandpour, "Least-squares phase predistortion of a +30 dBm class-D outphasing RF PA in 65 nm cmos," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 60, no. 7, pp. 1915–1928, July 2013.

[12] A. Ghahremani, A. Annema, and B. Nauta, "Outphasing class-E power amplifiers: From theory to back-off efficiency improvement," *IEEE Journal of Solid-State Circuits*, vol. 53, no. 5, pp. 1374–1386, May 2018.

[13] M. P. van der Heijden, M. Acar, J. S. Vromans, and D. A. Calvillo-Cortes, "A 19W high-efficiency wide-band CMOS-GaN class-E Chireix RF outphasing power amplifier," in *2011 IEEE MTT-S International Microwave Symposium*, June 2011, pp. 1–4.

[14] F. Raab, "Efficiency of outphasing RF power-amplifier systems," *IEEE Transactions on Communications*, vol. 33, no. 10, pp. 1094–1099, October 1985.