Design and Digital Predistortion Linearization of a Wideband Outphasing Amplifier Supporting 200 MHz Bandwidth

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***Abstract* — This paper presents a holistic approach to design and linearize a wideband outphasing power amplifier (PA) to efficiently amplify a 200 MHz bandwidth (BW) signal compliant with the Data Over Cable Service Interface Specification (DOCSIS) standard. The proposed outphasing PA, based on a load insensitive GaN HEMT class-E topology, was designed to face the trade-off between the output power control range to be covered with high efficiency and the desired BW. Operated following an isogain approach, the linearity performance is ensured by applying digital predistortion linearization, which combined with crest factor reduction (CFR) techniques can enhance the overall power efficiency. An 18.7% average efficiency has been measured when fitting the standard in-band and out-of-band linearity requirements for a 26.3 dBm 64 QAM DOCSIS signal with 12.2 dB of PAPR.**

***Index Terms* — digital signal processing, linearization, outphasing, power amplifier, power efficiency.**

I. Introduction

The power amplifier (PA) is a nonlinear critical building block in a data transmission link. In cable distribution systems (following the Data Over Cable Service Interface Specification (DOCSIS) standard), the signal goes from a few tens or hundreds MHz to about 1.2 GHz. In contrast to narrow band systems where the critical intermodulation distortion products are the 3rd and the 5th (the rest may be filtered out), in cable applications the fractional bandwidth (FBW) is much higher and the even order products may fall in-band. To deal with both out-of-band and in-band distortion one straightforward strategy consists in operating with certain back-off. Nevertheless, when considering orthogonal frequency division multiplexing (OFDM)-like waveforms with high peak-to-average power ratios (PAPR), back-off operation leads to very low system efficiencies, typically below 2%.

This work presents a dual-input power amplifying solution based on the outphasing principle. The selection of both, the wideband PA topology and the compensating reactances, is detailed. Aimed to provide the desired frequency coverage, the mutual load modulating (LM) trajectories need to be properly dimensioned. A novel isogain phase-coding strategy, incorporating digital predistortion (DPD) linearization combined with crest factor reduction (CFR) techniques, is described and validated through experimental results. An improved average efficiency is demonstrated, whilst satisfying the linearity specifications, when handling a demanding signal with a strongly varying envelope and 22% FBW.

II. Outphasing Power Amplifier Design

The performance of an outphasing architecture, which employs a non-isolated combiner to deliberately force load modulation, is, by nature, highly sensitive to frequency variations. There exists a trade-off between the achievable bandwidth and highly efficient power control range.

A. Load-invariant Class-E PA

A 6 W GaN HEMT transistor from Cree Inc. CGH40006P was selected according to the desired output power and the signal PAPR. Using its nonlinear model, load-pull simulations were initially completed at the fundamental frequency, from 800 MHz to 1 GHz (Fig. 1), when the device was biased at V_{DS} = 15 V, V_{GS} = -3.5 V. The higher order harmonics were all terminated in open circuit condition, as typical for class-E operation [1].

The drain terminating network, derived from [2], is composed of a parallel LC circuit, aimed to provide high impedance values at the second and third order harmonics, a series capacitor and an inductance to ground (see Fig. 2). Intentionally, a low-valued coil L_{p1} was selected for the tank, resonating at around 2 GHz, to provide the lowest possible quality factor at the fundamental. The frequency selectivity in load-modulating condition was alleviated, as observed from the evolution of the drain impedance at the fundamental under variable resistive loading in Fig. 1. Although the desired terminations at the harmonics have to be sacrificed in some extent, their global impact on power losses may be kept under control.

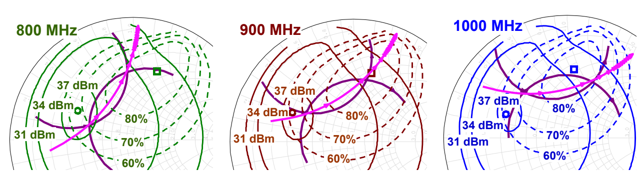

Fig. 1. Load-pull contours, PA (—) and mutual (—) load modulating trajectories at 800 MHz, 900 MHz and 1 GHz.

B. Wideband Chireix Scheme

The value for the combiner's compensating reactance, defining L_{cmb} and C_{cmb}, was determined by the need to confine the amplifiers' LM trajectories to a moderate power control range (around 4-5 dB) in the highest efficiency region. In this way, the Foster rotation of the trajectories may be minimized. Restricting the power coverage of this active load-pulling mechanism, an improved efficiency profile may be possible along the whole band when moving to an operation with fixed outphasing angle and input power variation [3].

The circuit schematic and photograph of the implemented outphasing PA are shown in Fig. 2. It was first characterized as a function of the phase difference between the CW driving signals (pure outphasing mode). The measured efficiency versus output power profiles are presented in Fig. 3. A couple of remarks can be extracted from these results: first, the peak output power is nearly constant along the band, and second, high efficiency may be assured for a moderate output power interval of around 5 dB.

Considering the limitation in the power control range (no more than 10 dB at 1 GHz) and the efficiency degradation for high values in the outphasing angle [3], a combined mode or mixed-mode of operation seemed to be mandatory. This is the reason why the gate voltage was slightly increased above pinch-off, to force a sort of class-J operation with a softly compressed gain profile. The implemented topology was then characterized versus both the power and phase difference between the CW input signals (Fig. 4).

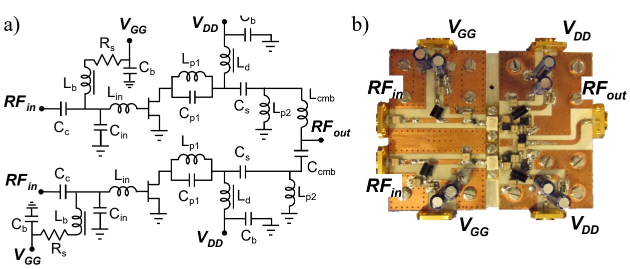

Fig. 2. a) Schematic and b) photograph of the outphasing PA.

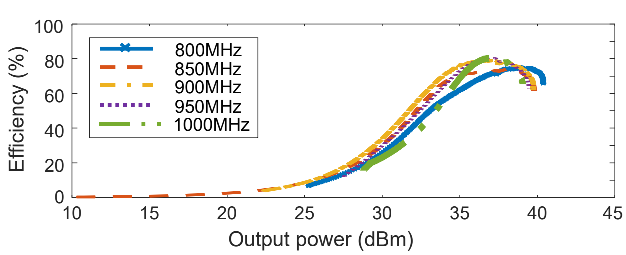

Fig. 3. Efficiency vs. output power profiles in pure outphasing mode.

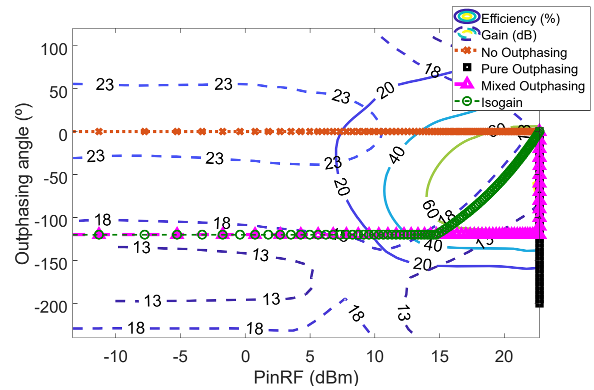

Fig. 4. 2D contours (gain and efficiency) with possible operating modes.

The trajectories for different operating modes have been included over the obtained 2D contours. Note that the isogain operating strategy [4] could be a good trade-off choice to provide an enhanced efficiency profile whilst being amenable for linearization. A nearly constant 17 dB gain could be possible maintaining a 120º phase difference up to an input power level of 14.8 dBm and properly reducing the outphasing angle above this value.

III. Generation of the Outphasing Signal

The block diagram of the wideband outphasing system with DPD is shown in Fig. 5. The baseband complex outphasing signal components can be defined as

$$x_{outph}^{r}[n] = A[n]e^{j(\varphi_x[n]+\alpha[n])} = x_{outph}^{r,I}[n] + jx_{outph}^{r,Q}[n] \tag{1}$$

with r=1,2, being each of the branches of the outphasing PA. Moreover, $\varphi_x[n]$ is the original phase of the signal $x[n]$, while $A[n]$ is the amplitude of the outphasing components. Unlike the pure outphasing components, some amplitude variation is allowed to be able to meet the linearity requirements,

$$A[n] = \beta\,|x[n]| \tag{2}$$

with $0 < \beta < 1$ being a gain factor.

The outphasing angle is $2\alpha[n]$, where $\alpha[n]$ is defined as

$$\alpha[n] = f(E[n]) = \left(1 - \frac{E[n]}{\max\{E[n]\}}\right)\cdot\varphi_0 \tag{3}$$

with φ_0 being the maximum $\alpha[n]$ (i.e., half the maximum outphasing angle), $\varphi_0 = \pi/3 = 60^{\circ}$ according to the results in Fig. 4. The envelope $E[n] = T\{|x[n]|\}$, is a shaped version of the original input signal's instantaneous envelope $|x[n]|$. In general, the shaping function $T\{\cdot\}$ can be used to generate a reduced slew-rate version of the original instantaneous envelope [5]. In our particular case, we have only considered some dethroughting to prevent the envelope to drop below a certain threshold. Following the proposed isogain outphasing mode, the outphasing angle swing is limited. Thus, below a certain threshold value, the outphasing angle is kept constant to 120º.

For DPD linearization we used a modification of the composite memory polynomial (CMP) behavioral model described in [6]. As depicted in Fig. 5, the coefficients of the DPD were estimated iteratively following a direct learning approach.

IV. Experimental Test Bench and Results

The outphasing PA was experimentally evaluated using a Matlab-controlled test bench that interfaces waveform generation and acquisition instruments. The direct RF generation at 900 MHz of a 200 MHz bandwidth, 64 QAM (OFDM-based) DOCSIS signal with a PAPR of 12.2 dB, was carried out through the AWG M8190A from Keysight at 7.968 GSa/s and 14 bits. A digital storage oscilloscope (Keysight 90404A) was used to acquire the RF output signal at 20 GSa/s with 8-bit resolution.

As listed in Table I, up to 25% of power efficiency can be obtained with moderate linearity levels (ACPR<-35 dBc) while backing-off and properly combining DPD and CFR (see test case 4), the targeted linearity specifications of ACPR<-40 dBc and EVM <-40 dB can be met with power efficiency values greater than 18%.

Table I.
Linearity and Efficiency of the Isogain Outphasing Power Amplifier.

Test cases: DOCSIS signal, 64 QAM, 200 MHz BW and 12.2 dB PAPR	P_{out_avg} (dBm)	EVM (dB)	Worst-ACLR (dBc)	η_{avg} (%)
#1 – No DPD – No CFR	26.7	-31.9	-23.1	12.3
#2 – DPD – No CFR	26.4	-40.6	-35.4	25.0
#3 – DPD – No CFR	26.3	-41.5	-37.0	22.7
#4 – DPD w/ CFR (PAPR=11.5dB)	26.3	-42.3	-40.0	18.7
#5 – DPD – No CFR	25.9	-42.9	-40.0	17.9

Table II.
Comparative of the State-of-the-Art Outphasing Power Amplifiers.

Ref.	*f_0 (GHz)*	*$BW_{6dB, 60\%}$ (%)*	*P_{out_max} (W)*	*Signal/PAPR (dB)*	*Worst ACLR (dBc)*	*η_{avg} (%)*
[7]	0.9	33	>24	3.84 MHz WCDMA / 6.7	-44#	>70#
This work	**0.9**	**19.4**	**10**	**200 MHz CATV 64 QAM /12.2**	**-40**	**18.7**
[8]	1.9	6.3	25.1	10 MHz LTE /9.6	-45.33	59.4
[9]†	1.95	-	18	40 MHz 16 QAM OFDM / 6.5	-33	41.4
[10]	1.95	12.8	19	3.84 MHz WCDMA / 9.6	-47	54.5
[11]*	2.14	-	50	3.84 MHz WCDMA / 9.6	N.R.	38
[12]	2.3	4.3	70.6	3.84 MHz WCDMA / 9.6	-49	53.5

#*simulated* †*Multi-level Supply Modulated* **4-way*

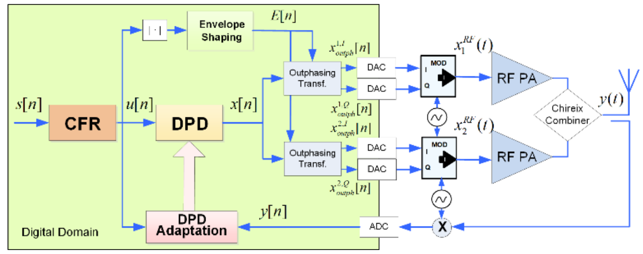

Fig. 5. Block diagram of a wideband outphasing system w. DPD.

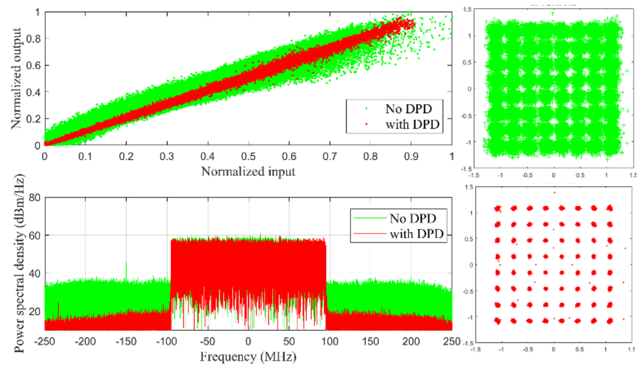

Fig. 6. AM-AM, Output Spectra and 64-QAM constellations before (green) and after (red) DPD linearization.

Fig. 6 shows the AM-AM, Output Spectra and 64-QAM constellations of the DOCSIS signal before and after DPD linearization. Finally, Table II highlights the relevance of this work by showing a comparative to some state-of-the art outphasing PAs available in literature.

V. Conclusion

The designed outphasing PA faces the power efficient reproduction of a signal with one of the most challenging combined requirements in terms of fractional bandwidth, PAPR and associated linearity among those reported in the literature. A novel approach is proposed for iteratively coding the outphasing angle while ensuring both in-band and out-of-band linearity requirements. Following an isogain load-modulating strategy, an average efficiency of 18.7% was measured when fitting the standard ACPR and EVM specifications for a 26.3 dBm 64 QAM DOCSIS signal with 12.2 dB of PAPR and 200 MHz BW.

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