

Slew-Rate Limited Envelopes for Driving Envelope Tracking Amplifiers

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Abstract — This paper presents a practical application of a method for generating slew-rate limited envelopes in order to drive the dynamic supply of envelope tracking (ET) power amplifiers (PAs). The proposed method results useful to generate slower versions of the transmitted signal's envelope to cope with the slew-rate and bandwidth limitations of envelope amplifiers. Moreover, this paper shows experimental results comparing the performance of ET when exciting the drain of a PA (based in a GaN transistor) with both the envelope of the signal and the slew-rate limited version of the envelope.

Index Terms — Amplifier distortion, digital predistortion, efficiency, envelope tracking, envelope amplifier.

I. INTRODUCTION

One of the main common objectives in all Electrical Engineering research areas consists in reducing energy consumption by enhancing power efficiency [1]. Since the power amplifier (PA) is one of the most power hungry devices in radiocommunications, several efforts have been dedicated to find power efficiency solutions to cope with the inherent trade-off between linearity and efficiency. In a classical Cartesian I-Q transmitter with static supply, the PA has to linearly amplify a carrier signal which is both phase and amplitude modulated and usually presenting significant peak-to-average power ratios (PAPRs), which implies that for having linear amplification it is necessary to use extremely inefficient class-A or class-AB PAs. The amplification of non-constant envelope modulated signals using highly linear PAs operating at significant power back-off levels results in unacceptable power efficiency figures.

Some linearization techniques such as digital predistortion (DPD), extend the linear range of power amplifiers which, properly combined with crest factor reduction (CFR) techniques, enable PAs to be driven harder into compression (thus more efficiently). However, typical Class AB PAs show efficiencies ranging from 5 to 10 percent when operated with significant back-off levels. By introducing CFR and adaptive DPD techniques, the efficiency can be improved by a factor of 3 to 5. Finally by applying more efficient topologies such as Doherty amplifiers, or even Class AB amplifiers with supply modulation in combination with DPD, the efficiency can be improved up to 50 per cent [2].

PA drain supply modulation can be carried out using dynamic supply techniques such as envelope elimination and restoration (EER), envelope tracking (ET), and polar transmitter (PT) architectures in conjunction with digital predistortion (DPD) [3]. From the implementation point of view, ET amplification systems (see Fig. 1) are very attractive techniques because can be applied in conventional transmitters based on RF linear amplification topologies by only substituting the conventional static supply for a dynamic one.

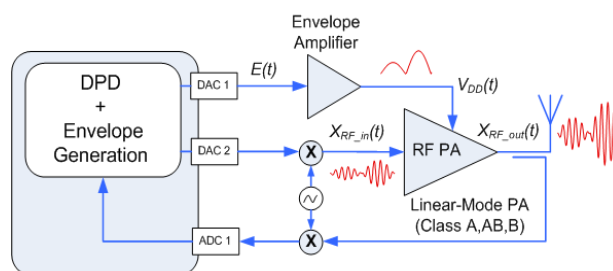


Fig. 1. Block diagram of an envelope tracking PA architecture.

This dynamic supply is carried out by means of an envelope power amplifier. Its role is to efficiently supply the required voltages and currents to the RF transistor drain at the speed imposed by the changes of the RF envelope [3].

The scope of this paper is to apply a new method for generating suitable signals (in terms of speed and bandwidth of the envelope) for exciting the envelope amplifier that drives the transistor drain, critically limited by its slew-rate. In OFDM-based modulations the envelope bandwidth is several times the bandwidth of the baseband complex modulated signal. Then, one of the main challenges in ET envelope drivers is to supply the power required by the transistor at the same speed of the signal's envelope. Recent works present some solutions based in iteratively reducing the envelope bandwidth [4] or reducing the PAPR [5]. Moreover, a new real-time implementable method was recently published in [6]. The scope of this work is therefore, to analyze and compare the effects of driving a GaN transistor drain with the real or with the slew-rate limited version of the envelope. Moreover, in both cases DPD is considered to compensate for both in-band and out-of-band distortion.

II. GENERATION OF THE SLEW-RATE LIMITED ENVELOPE

The generation method is described in [6], and it basically consists of processing the real signal's envelope $E(n)$ for obtaining (in real-time) an slew-rate limited version $E_s(n)$ of the signal's envelope. $E_s(n)$ is calculated using the present and future values of the envelope ($E(n+1)$, $E(n+2)$, etc.). Therefore, the resulting slower envelope will suffer a delay with respect to the original modulated signal. This delay has to be compensated synchronizing the modulated signal and the calculated slower envelope. In fact, in all ET and PT amplification structures is necessary to consider some mechanisms to align the signals involved in the transmission. To understand the functioning of the algorithm, first it is necessary to define the following parameters: $\pm\Delta_M$ is the maximum allowed increment/decrement, $N = (\Delta_M)^{-1}$ is the minimum number of steps for going from 0 to 1 in an envelope with normalized dynamic range of 1, $E(n)$ is the envelope and $E_s(n)$ is the generated 'slow envelope' or 'envelope of the envelope'. Moreover, the resulting 'envelope of the envelope' must accomplish the following conditions:

- i) At time n the generated envelope $E_s(n)$ must be at least $E(n+1) - \Delta_M$ in order to accomplish $E_s(n+1) > E(n+1)$. Similarly, $E_s(n)$ must be at least $E(n+2) - 2\Delta_M$ in order to accomplish $E_s(n+2) > E(n+2)$, at least $E(n+3) - 3\Delta_M$, and so on.
- ii) The following slew rate restriction must be accomplished:

$$E_s(n-1) - \Delta_M < E_s(n) < E_s(n-1) + \Delta_M \quad (1)$$

By using the intermediate variable $y(n)$ that represents an upper bound of $E(n)$ and a lower bound of $E_s(n)$, the algorithm (in its causal version) can be formulated as:

$$y(n-N) = \max_{i=0,1,\dots,N} \{E(n-N+i) - i \cdot \Delta_M\} \quad (2)$$

$$E_s(n-N) = \max \{y(n-N), E_s(n-N-1) - \Delta_M\} \quad (3)$$

This algorithm is designed to be implemented in a FPGA device. Further details on the FPGA implementation and its real-time functioning can be found in [6].

III. EXPERIMENTAL TEST-BED

For testing purposes we used a Cree Inc. Eval. Board CGH40006P-TB (GaN transistor) at 2 GHz and a 5 MHz bandwidth OFDM modulated test signal. The signal generation and measurement equipment consist in: an Agilent MXG N5182A RF vector generator, a Tabor WW2572A arbitrary wave generator, an Agilent Infinium

DSO90404A oscilloscope for capturing the signals and an Agilent N2783A probe for measuring the transistor drain current. The overall system is controlled (all this equipment is connected to a PC by through USB and GPIB buses) by a PC running Matlab. We have used the high-speed (35 MHz bandwidth and 900V/ μ s slew-rate at $A_v=2$ and 10 Ω load) high-current (1.1 A) Linear Technology IC LT1210 as the envelope amplifier.

The objective of this work is to test the performance of the ET when the PA is driven with the slew-rate limited version of the envelope. Therefore, for the sake of simplicity we have considered the slightly efficient IC LT1210 as the envelope driver. Future developments will be aimed at applying this method of reduction of the slew-rate requirements to high bandwidth applications and thus, extending the applicability bandwidth of some efficient envelope amplifiers [7].

IV. EXPERIMENTAL RESULTS

In order to evaluate the performance of the ET with the slow envelope, different scenarios have been considered. Results were obtained exciting the PA drain with both the real envelope and the slew-rate limited envelope. DPD compensation was also considered in both cases.

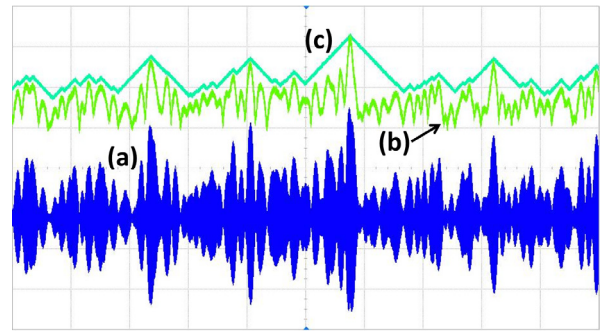


Fig. 2. Oscilloscope capture of: a) OFDM 16-QAM RF signal @2 GHz, b) real envelope and (c) slew-rate limited envelope.

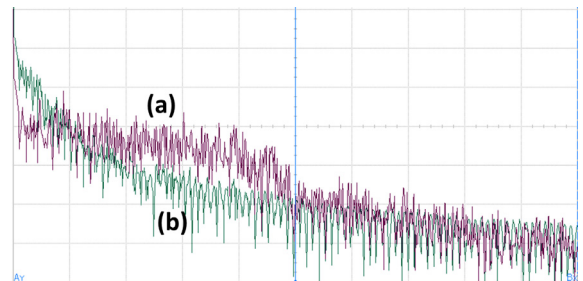


Fig. 3. Power spectra (center 10 MHz and span 20 MHz) of: a) an OFDM envelope and b) its slew-rate limited ($N=100$) version.

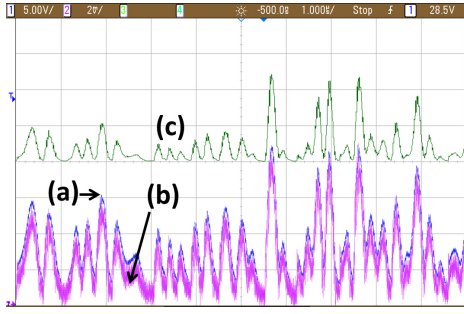


Fig. 4. a) Drain transistor voltage and b) current, and the product of both (plot c).

Fig. 2 and Fig. 3 show the time-domain waveforms and power spectra of the envelope $E(t)$ of the OFDM 16-QAM modulated test signal and its slew-rate limited version $E_s(t)$, respectively. Fig. 4 shows the drain voltage and current applied to the GaN power transistor. The product between the voltage and current drain is used to calculate the transistor power consumption. As it can be observed in the AM-AM characteristic and output power spectra in Fig. 5 and Fig. 6 respectively, ET with the real envelope but without DPD shows significant spectral regrowth. The in-band and out-of-band distortion without DPD, expressed in terms of adjacent channel power ratio (ACPR) and error vector magnitude (EVM) in Table I, results unacceptable. Due to the dynamic supply, the gain of the transistor is being modified and the resulting nonlinear characteristic has to be compensated with DPD. As it can be observed in Table I, applying DPD to compensate for nonlinear distortion implies a slight loss of efficiency.

On the contrary, when applying ET with the slow envelope and without DPD, the out-of-band distortion is kept into reasonable values, as it can be appreciated in Table I, Fig. 7 and Fig. 8. However, the in-band distortion has to be compensated with DPD. Fig. 9 shows the OFDM 16-QAM constellation of the ET with slow envelope and DPD compensation. In this case, as it is shown in Table I, the power efficiency after applying DPD is slightly better.

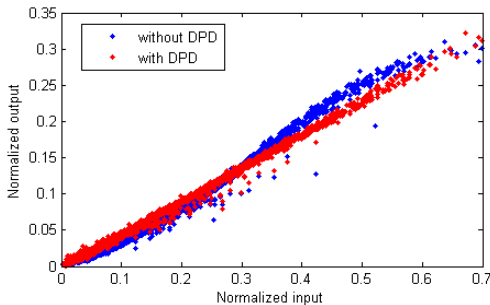


Fig. 5. AM-AM characteristic for ET with real envelope ($E(t)$).

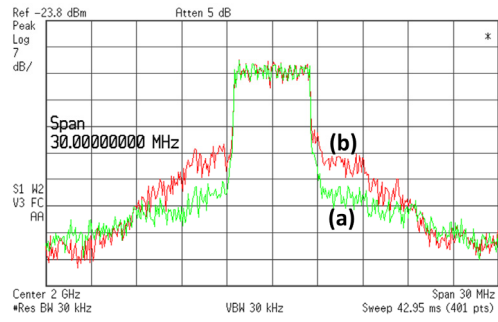


Fig. 6. Output power spectra for ET with real envelope ($E(t)$): a) with DPD and b) without DPD.

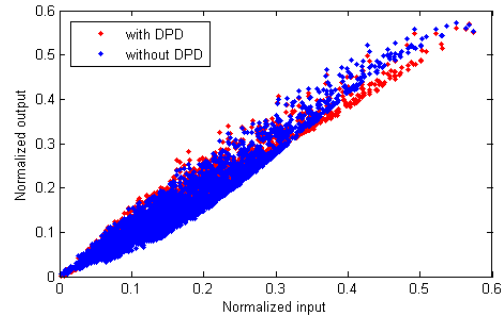


Fig. 7. AM-AM characteristic for ET with slow envelope ($E_s(t)$).

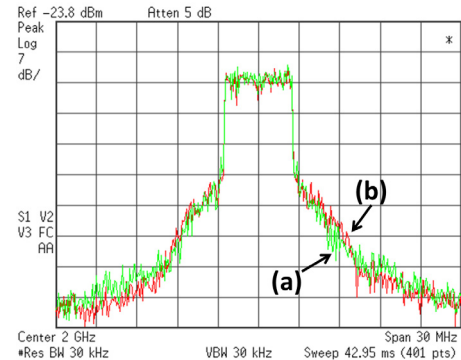


Fig. 8. Output power spectra for ET with slow envelope ($E_s(t)$): a) with DPD and b) without DPD.

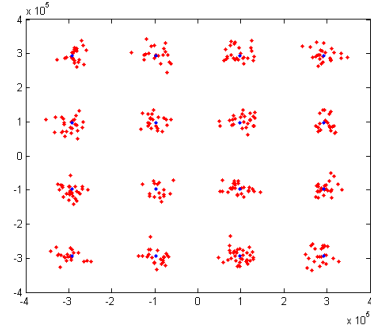


Fig. 9. OFDM 16-QAM constellation after demodulation, for ET with slow envelope ($E_s(t)$) and DPD (EVM=6.68%).

TABLE I
COMPARISON OF DIFFERENT PA SUPPLY STRATEGIES

	ACPR	EVM	DC Power	Mean Output Power	PA Efficiency
1) PA with fixed supply	-29.6 (L) -29.7 (U)	86 %	1.98 W	0.2 W	12.86%
2) ET PA real envelope	-24.2 (L) -24.6 (U)	149.8%	0.73 W	0.25W	34.7%
3) ET PA real envelope + DPD	-32.8 (L) -30.7 (U)	1.95%	0.81W	0.25W	31.23%
4) ET PA slow envelope	-29.3 (L) -29.3 (U)	118.9%	0.93 W	0.25W	27.20%
5) ET PA slow envelope + DPD	-28.4 (L) -28.4 (U)	6.68%	0.89 W	0.25W	28.35 %

V. CONCLUSION

This work has shown the viability of doing envelope tracking when using as a drain signal a slew-rate limited version of the envelope of the signal. By using this slow envelope, good efficiency figures have been obtained. As it was expected, the PA efficiency using ET with the slower version of the envelope was slightly worse than using ET with the real envelope, but significantly better than considering a fixed supply. The out-of-band linearity presented by the ET with slow envelope was acceptable and significantly better than using ET with the real envelope. However, DPD is still required to compensate for the in-band distortion. The AM-AM characteristic showed that by using ET with slow envelope, some kind of memory effects may be appearing and moreover, the DPD compensation achieved out-of-band was very limited compared to the one obtained with the real envelope. Thus, future efforts will be devoted to a better understanding of the nonlinear distortion arising when applying ET with slow envelope and to design new DPD strategies (eventually incorporating memory effects compensation capabilities [8]) to improve the out-of-band compensation.

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