Hybrid Envelope Amplifier for Envelope Tracking Power Amplifier Transmitters

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***Abstract*—This paper presents an envelope tracking (ET) Power Amplifier (PA) whose architecture includes an efficient Envelope Amplifier (EA) and a bandwidth reduction algorithm suitable for real time applications. The EA consists of a hybrid amplifier combining switched and linear amplification. A bandwidth ans slew-rate reduction algorithm has been incorporated in order to allow wide-band envelope amplifications. Non-linearities introduced by the Hybrid EA (HEA) and the dynamic supply are compensated with Digital Pre-Distortion (DPD). The ET PA has been tested using 64-QAM signals and commercial devices. Results show that non-linearities produced by the HEA are compensable and that the architecture provides efficiency improvements compared to the conventional linear EA.**

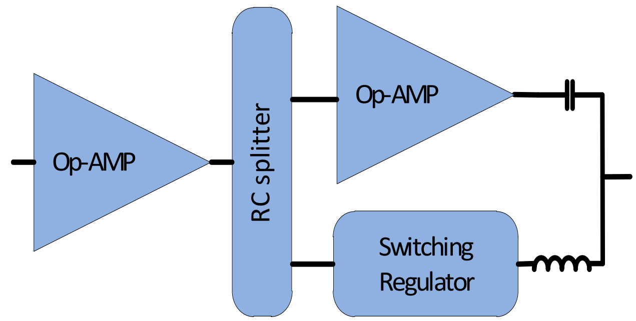

Fig. 1. Hybrid envelope amplifier for EER proposed in [1] .

I. Introduction

The necessity for high speed data rates and high spectral efficiency in communications technologies is pushing new communications standards to transmit signals based on linear modulations schemes and exhibiting rapid envelope variations. These type of signals force the operation of the Power Amplifier (PA) at high back-off levels to avoid distortions on the linear modulations, degrading PA's efficiency.

Architectures based on dynamic power supply, such as Envelope Tracking (ET) and Envelope Elimination and Restoration (EER), have been actively investigated as possible solutions to achieve linear and high efficient amplification. In these architectures the efficiencies of both the Radio Frequency Power Amplifier (RFPA) and the Envelope Amplifier (EA) influence the overall performance. Therefore, it is necessary to count on a linear and high efficient EA.

Fig. 1 shows the Hybrid EA (HEA) for EER PA presented in [1]. The low frequencies are amplified using a Switched Envelope Amplifier (SEA) while the high frequencies are amplified by the Linear Envelope Amplifier (LEA). Although the most efficient strategy is to supply the RFPA with the envelope of the RF signal, it is not always possible due to the large Bandwidth (BW) exhibited by this signal. In such cases, it is possible to use techniques based on Slew Rate (SR) reduction [2] and BW [3] reduction to relax the EA's requirements at the expense of efficiency degradation.

This paper presents an ET architecture incorporating an EA similar to the one proposed in [1]. An algorithm for real-time envelope's BW reduction has been included aimed to maintain the envelope spectrum within the limits of the LEA's frequency response. The frequency splitting of the BW reduced envelope is performed digitally as well as the compensation of its nonlinear distortions. Slow Envelope Dependent Digital Pre-Distorsion (SED-DPD) is used to compensate separately the distortions introduced by the dynamic power supply. The rest of this paper is organized as follows. In section II, the proposed ET architecture is briefly described as well as the behavioral model and DPD structure of both the RFPA and the EA. Section III describes the BW reduction algorithm whereas Section IV describes the experimental setup and results. Finally, conclusions are given in Section V.

II. ET Proposed Architecture

Fig. 2 shows the proposed ET architecture. The envelope of the generated signal is reduced in BW to ensure that the spectral characteristics of the envelope are within the LEA's capabilities. Afterwards, a digital split-band is performed accordingly with the available hardware features. The high frequency components go through the LEA while the low frequencies are first modulated, using pulse codification strategies such as Pulse Width Modulation (PWM) or Delta-Sigma (Δ-Σ), then amplified by the SEA and then low pass filtered. Both high and low frequencies are proportionally amplified and later combined using a bias-tee, whose L and C are chosen according to the cutoff frequency.

The RF output signal and the RFPA's supply voltage are monitored to estimate the RPFA and EA distortion respectively. The DPD is performed in both cases following the indirect learning method, a postdistortion function is estimated from the input and output and then it is copied to be used as predistortion function. In the case of the RFPA DPD, a SED-DPD compensates the distortion caused when the RFPA is fed with a voltage different to the RF-input's envelope.

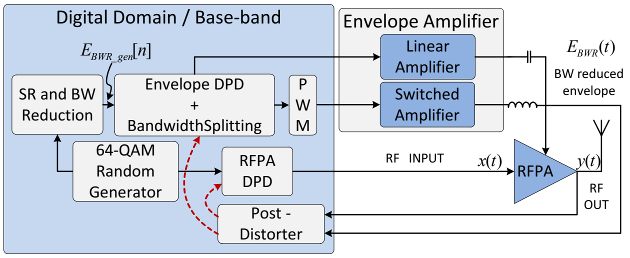

Fig. 2. Block diagram of the proposed ET architecture.

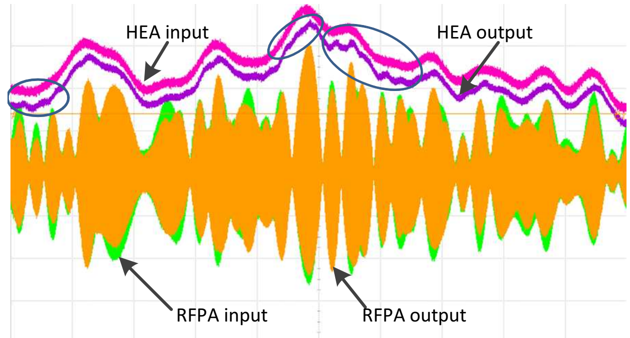

Fig. 3. RFPA and EA inputs and outputs.

Although the efficiency achieved by switched amplifiers is high, there exist hardware limitations on the maximum power and bandwidth achievable. Moreover, its efficiency decreases as the switching frequency increases. Therefore, in the proposed architecture, the cutoff frequency should be chosen according to the available hardware characteristics.

A. *RFPA model and DPD*

When a signal different to the envelope is used to supply the RFPA in ET architectures, the nonlinear distortion that appears at the RFPA's output cannot be compensated uniquely using dynamic behavioral models, such as the memory polynomial. Instead, the model needs to take into account the RFPA's supply signal to compensate this type of nonlinear distortion [4]. Moreover, when the RF-signal exhibits significant bandwidth and rapid envelope variations the memory effects of the PA have to be taken into account as well. Therefore, taking into account the notation described in Fig. 2, and according to [4], in the digital domain the PA input-output relationship can be described as follows:

$$y[n] = \sum_{i=0}^{M}\sum_{j=0}^{N}\sum_{p=0}^{P}\sum_{q=0}^{Q}\gamma_{ijpq}x[n-\tau_j] |x[n-\tau_j]|^i(E_{BWR}[n-\tau_q])^p \quad (1)$$

where $E_{BWR}[n]$ is a BW-reduced version of the original envelope, which is assumed to be equal to the generated signal, $E_{BWR\_gen}[n]$. $E_{BWR}[n]$ provides the power supply to the RFPA while $x[n]$ and $y[n]$ are its input and output signals respectively. On the other hand, τ_j and τ_q (with $\tau_0 = 0$) are the most significant tap delays of the reduced envelope and input signal, which contribute to the characterization of memory effects. The total number of coefficients (γ_{ijpq}) to be found in (1) is giving by $(M+1).(N+1).(P+1).(Q+1)$.

The mathematical model described in (1) is also used to perform the SED-DPD following the indirect learning method. Least squares fitting approach is used to estimate the postdistorter function from the input and output RFPA measured data.

B. *Envelope Amplifier model and DPD*

In order maintain the efficiency of the whole ET architecture, the EA should operate at its maximum efficiency. That is, in the case of the LEA, close to the saturation point where nonlinearities become notable. Moreover, nonlinearities are introduced by the interaction of inductors and capacitors directly with the RF signal. Those distortions are notable on the EA's output. They appear as clipping on maximums of the BW reduced envelope and ripple resembling the envelope of the RF input signal as Figure 3 shows. The signals displayed in green and orange are the RFPA's input and output respectively, while the magenta and purple are the input and output of the EA.

The EA input-output relationship can be described using a polynomial structure. Following the notation described in Fig. 2 the input-output relationship could be written, in the digital domain, as follows:

$$E_{BWR}[n] = \sum_{i=0}^{M}\sum_{j=0}^{N}\sum_{p=0}^{P}\sum_{q=0}^{Q}\gamma_{ijpq}|x[n-\tau_j]|^i (E_{BWR\_gen}[n-\tau_q])^p \quad (2)$$

Following a similar procedure to the described on the RFPA's DPD, the mathematical model presented in (2) is used to perform the DPD of the envelope.

III. Bandwidth Reduction Algorithm

Recently, two different approaches based on SR [2] and BW [3] reduction of the envelope showed that these strategies are suitable to adapt the envelope characteristics to the EA limitations at the expense of efficiency degradation. However, it is possible to find a good compromise between the EA efficiency and the RFPA efficiency degradation.

On the one hand, the method proposed in [3] limits the BW of the envelope iteratively, which may represent an issue in real time applications. On the other hand, the method proposed in [2] consists on a real time algorithm where the resulting signal is limited in SR but not in BW, making challenging its amplification if only SEA are considered and requiring a wide band LEA if only LEA is considered. Therefore, the algorithm for envelope reduction used in this paper is based on the one proposed in [2] and includes modifications over its original version, restricting the BW of the resulting signal.

Fig. 4 shows the envelope of a 64-QAM signal in blue, the SR Reduced Envelope (SRRE) in red and the BW Reduced Envelope (BWRE) in green. From the waveform of the SR

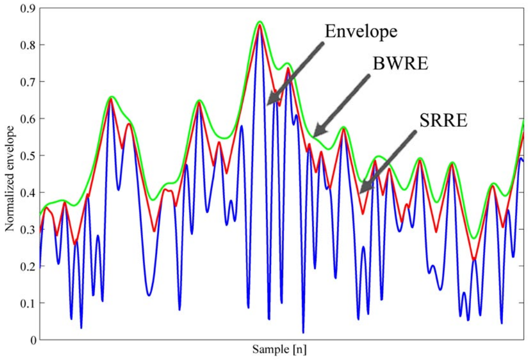

Fig. 4. Time representation of the envelope and its SR and BW limited versions.

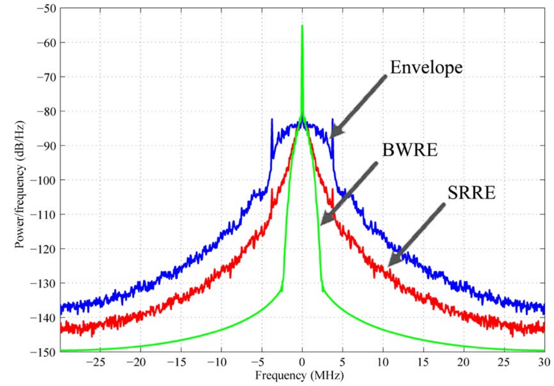

Fig. 5. Frequency representation of the envelope and its SR and BW limited versions.

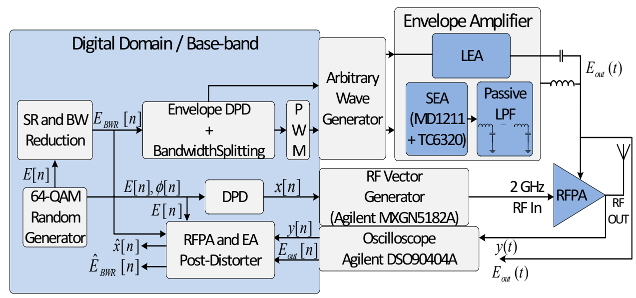

Fig. 6. Block-diagram of the experimental ET set-up.

reduced envelope, it is evident that the lack of BW limitation is mainly due to the presence of peaks. Those peaks are introduced by the algorithm when it is necessary to change drastically from a positive to a negative slope (convex peak), or vice-versa (concave peak). Therefore, the modifications were focused on their elimination. When the envelope is being processed by the algorithm described in [2], if a convex peak is generated, its maximum value is replicated N-times. This replication process only takes place if that value is above its neighbor values. Afterwards, to remove the introduced discontinuities, the signal is averaged using N/2 samples before the peak location and N/2 samples after the peak location. The replication of the local maximums ensures that all the maximums are preserved even after the averaging process. The number of samples, N, is chosen according with the desired bandwidth of the output signal. For example, if the samples are generated at time-intervals T_s, then N is giving by $N = 1/BW/T_s$. This process lead to a free-peaks and BW limited signal, as shown in Fig. 4 and Fig. 5. However, after the averaging process, high-frequency components could still be present and can be removed by low-pass filtering. Special attention should be paid on the final filtering process, since the passing band should be wider or equal to the equivalent low-pass filter performed by the averaging process. As counterpart, the modifications over the original algorithm reduce even more the efficiency of the ET PA since the BW reduced envelope is always above the SR reduced envelope.

The modified algorithm is suitable to implement in a digital processors due to its simplicity. The results shown in Fig. 4 and Fig. 5 were extracted from its implementation on a Field Programmable Gate Array (FPGA) Virtex-4 whose clock speed was set to 60 MHZ.

IV. Experimental Set-Up and Results

Fig. 6 shows the complete experimental set-up. The SEA is realized using the Supertex Integrated Circuits (IC) MD1211 and TC6320 followed by a 8^{th} order passive Low Pass Filter (LPF). The LEA consists on the high-spped (35MHz BW and 900V/μs SR At Av=2 and 10 Ω load) high-current (1.1 A) Linear Technology IC LT1210

The HEA supplies dynamically the voltage to a Cree Inc. Eval. Board CGH40006P-TB (GaN transistor) to amplify a 64-QAM signal generated by an Agilent MXG N5182A RF vector signal generator. The RF vector signal generator modulates the signal at 2 GHz while the envelopes are generated by a Tabor WW2572A arbitrary wave generator. Measurements were captured by an Agilent Infinium DSO90404A oscilloscope and the overall system was connected to, and controlled by, a PC running MATLAB.

For comparative purposes, measurements were performed using a 64-QAM 4.5 MHz BW. The bandwidth of its envelope was considered to extend up to 30 MHz and therefore suitable to amplify with the LEA included in the set-up. Four cases, based on two main scenarios, are studied to evaluate the performance of the proposed ET architecture. In the first scenario, the RFPA's supply ($V_{DD}(t)$) is the envelope of its input ($E(t)$) which leads to two cases of study: when the EA is the LEA and when the EA is the HEA. In the second scenario, ($V_{DD}(t)$) is the BW Reduced Envelope signal ($E_{BWR}(t)$) which leads also to two cases of study: when the EA is the LEA and when the EA is the HEA.

Fig. 7 shows the AM-AM characteristic of the HEA. The dotes displayed in red and blue show the input-output relationship before and after performing DPD. Notice that the largest the amplitude is the bigger the distortion is. Moreover, there is a notable distortion for the largest amplitudes even when

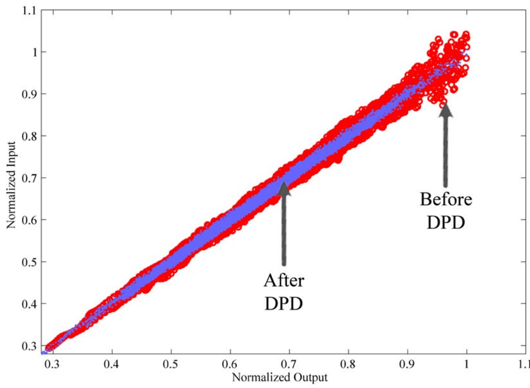

Fig. 7. AM-AM characteristic of the HEA.

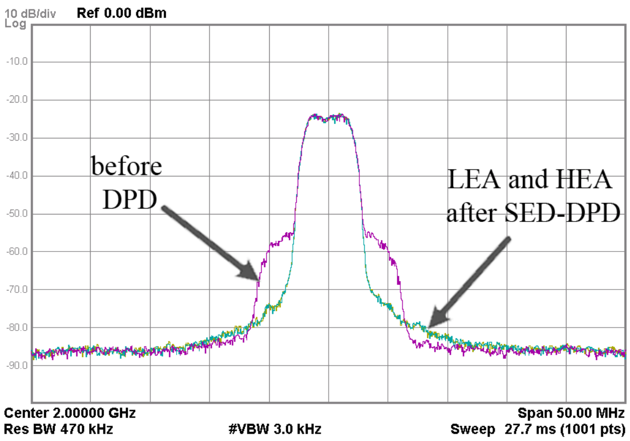

Fig. 8. Spectrum of a 64-QAM signal before and after SED-DPD when the BW reduced envelope is used as dynamic supply.

there is no obvious evidence of the LEA compression point. Fig. 8 shows the spectrum of the 64-QAM signal before and after the SED-DPD. In both cases using the LEA and using the HEA the spectral regrowth associated to the EA and RFPA nonlinear behavior has been corrected.

Performance comparisons of the proposed ET were realized in all the aforementioned cases after compensating the inherent nonlinear distortions. Table I summarizes the measurements results. Because the scope of this paper is to evaluate the efficiency of the proposed architecture, the SEA's efficiency is assumed to be 90%, which is a reasonable figure for a switched DC-DC converter providing the output power range presented in this study. The measurements were performed using a 64-QAM 4.5 MHz BW exhibiting 7.17 dB PAPR.

From Table I it is notable the efficiency enhancement of both the LEA (η_{LEA}) and the EA (η_{EA}) when using the HEA. Moreover, the EA's efficiency is higher when the envelopes' BW reduction is performed (77% for $V_{DD}(t) = E(t)$ and 83% for $V_{DD}(t) = E_{BWR}(t)$). As expected, there is an efficiency reduction on the ET architecture (η_{ET}) when the BWRE is used to supply the RFPA.

Besides the efficiency improvements, the linearity levels are

TABLE 1

Performance comparison of the proposed ET architecture

Measure	$V_{DD}(t) = E(t)$		$V_{DD}(t) = E_{BWR}(t)$	
	LEA	HEA	LEA	HEA
BW_{VDD} [MHz]	30	30	2	2
PAPR_{VDD} [dB]	7.17	7.17	5.03	5.03
P_{out} LEA [W]	1.37	0.55	2.5	0.41
P_{RFout} [W]	0.59	0.58	0.63	0.65
η_{LEA} [%]	37	57	49	59
η_{EA} [%]	37	77	49	83
η_{ET} [%]	15	22	12	20
$ACPR_L$ [dB]	-61	-60.54	-60.65	-60.80
$ACPR_U$ [dB]	-61	-60.45	-60.73	-60.75
EVM [%]	0.89	1.38	0.98	1.01

kept relatively high. Thanks to the DPD, the EVM figures have improved (initially were around 129% in all the cases of study) and the spectral regrowth has been corrected (see Fig. 8 and ACPR values in Table I). However, these figures are slightly worse when using the HEA because nonlinear distortions are bigger and more difficult to compensate. It was fond that, in general, the larger the RF BW's signal is, the more difficult to compensate are the nonlinear distortions associated to the envelope. As counterpart, the LEA might need to compensate high frequency components and therefore need a larger frequency response. Nevertheless, the BW requirements are lower than when only LEA is considered.

V. Conclusion

An efficient ET architecture has been proposed where the BW envelope reduction and the cutoff frequency are the two main parameters to trade the efficiency of the EA. The experimental results have shown that the proposed HEA improves the efficiency of the ET. The best efficiency figures are obtained when using the HEA and when the RF envelope signal supplies the RFPA. However for wide band signals is not always possible to perform the amplification of its envelope, hence it is necessary to use the BWRE which yield competitive efficiency figures.

Acknowledgment

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