The Effects of Supply Modulator Voltage Ripple on Efficiency and Linearity in Envelope Tracking Power Amplifiers

Sattam Alsahali, Alexander Alt, Peng Chen, Jonathan Lees
Centre for High Frequency Engineering
Cardiff University, Cardiff, UK
AlsahaliSF@cardiff.ac.uk

Abstract — **Envelope Tracking (ET) is emerging as one of the key solutions in radio frequency power amplifier (RFPA) design for 5G communications systems due to its ability to efficiently amplify signals with high peak to average power ratio (PAPR) and high instantaneous bandwidths. This paper presents an experimental investigation into the interaction between the PA and a supply modulator in the presence of typical output voltage fluctuation, or 'voltage ripple'. By synthesising appropriately modulated drain bias voltage and introducing varying amounts of external ripple, the effects on the efficiency and linearity of the RFPA can be observed and analysed. Experimental results show that the efficiency and linearity both degrade as the ripple amplitude increases. By using appropriate *shaping functions* to synthesise specific drain bias voltage however, the effects of ripple can be minimized to improve the overall linearity of RFPA, albeit at the expense of RFPA efficiency. However, although digital pre-distortion (DPD) can be used to address overall linearity, it is shown that the presence of non-coherent supply modulator ripple can severely limit the extent of the improvement.**

Keywords — **Envelope Tracking, ripple, supply modulator, power amplifier, linearity, efficiency, DPD.**

I. INTRODUCTION

Future generation communication systems will need to transfer data at much higher rates than is currently possible to accommodate the dramatic increase in mobile-cellular connectivity and wireless information exchange [1]. To improve spectral efficiency, modulation schemes use signals with high peak-to-average power ratio (PAPR), leading to the substantial variation of the magnitude of the envelope of the modulated signal. This dynamic variation in power distribution requires the classical RFPA to operate under power back-off conditions, avoiding compression which presents technical challenges in terms of achieving high linearity and back-off efficiency simultaneously. To satisfy these requirements, several PA architectures have been proposed to improve the RFPA efficiency, such as envelope elimination and restoration(EER)[2] , envelope tracking (ET) [3-5]and the Doherty PA (DPA) [6]. ET is a strong contender for both base transceiver station and user equipment RFPAs due to its flexibility for multimode-multiband operations [3]. The basic principle of ET architecture is to track the magnitude of the modulation envelope and in response, deliver a dynamic or modulated supply voltage to the active devices comprising the RFPA. This dynamic drain bias voltage keeps the RFPA in or near a compressed state for most of the time, leading to a higher average efficiency. However, ET presents a number of technical challenges, and one of the most significant ones is achieving a sufficient slew rate and bandwidth to accurately track the modulation envelope to achieve good PA performance[7].

The difficulty in ET design and measurement is a consequence of the fact that an ET system comprises several subsystems; as well as the RFPA itself, there is envelope generation, the supply modulator and the linearisation system, as depicted in Fig. 1.

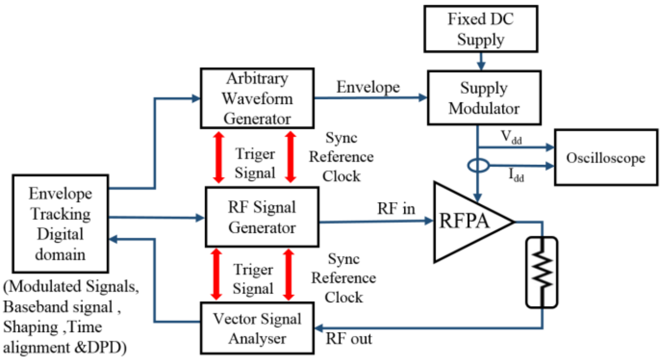

Figure 1 Block diagram of an envelope tracking characterisation system

In an ET system, the PA can be considered as a three-port device, with a dynamically controlled drain bias voltage. The supply modulator is s a critical component as it plays a vital role, in determining the overall performance of the ETPA in terms of bandwidth, linearity, efficiency.

Supply modulators, in literature, are generally categorised as linear or switching modulators, or combinations of these. Linear modulators have a low noise and high bandwidth but suffer from low efficiency. Switching modulators offer high efficiency but are only suitable for operation in systems with small modulation bandwidths. The advantages of both linear and switching modulators can be obtained with a hybrid modulator, which consists of an efficient switching amplifier and a high efficiency linear amplifier. The former deals with low frequency, high current components and the lower power, high frequency components are processed with the latter [3]. Despite the wide range of literature available [8-11] in supply modulator design methodologies, there are still significant challenges in achieving the required supply modulator performance in terms of modulation bandwidth, output voltage ripple, efficiency and switching frequency, which limit the application of ET in commercial systems. This paper investigates experimentally the interaction between the PA and a supply modulator, and specifically output voltage ripple, by adding external ripple-like signals to the RFPA's modulated drain bias voltage. Section II describes the ET measurement and characterisation system that is used to measure the effects that ripple has on PA performance. Section III investigates the impact of different magnitudes of ripple on the PA performance, and Section IV considers the idea of using shaping functions to minimize the effect of the ripple, and the impact of ripple on linearity and specifically the usefulness of DPD in the presence of increasing amounts of ripple.

II. ET SYSTEM

An ET measurement and characterisation system must be able to generate a modulated RF or microwave signal based on relevant communication standard waveforms, and a corresponding representation of the envelope magnitude which can either be detected/AM-demodulated from the modulated RF, or preferably calculated from the baseband input signal which is expressed in terms of its in-phase (I) and quadrature (Q) components as shown in equation (1) which provides the magnitude of the envelope signal (a).

$$a = \sqrt{I^2 + Q^2} \tag{1}$$

In ET , the drain bias voltage can be shaped using specific functions (*shaping functions*) that relate the instantaneous magnitude of the input signal to the dynamic drain bias voltage, in order to optimise the PA performance in terms of efficiency, gain, power and linearity [12, 13]. Moreover, a specific shaping function can used to maintain the drain bias voltage above zero to avoid a collapse the gain [14].

In the measurement system presented, a supply modulator is driven with a shaping function generated signal to produce the variable drain bias voltage required for the PA. At the same time, the modulated input signal is used to drive the PA, and as this signal and the generated drain bias voltage follow two different paths, they will be subjected to different delays, which need to be compensated for to ensure correct ET operation. Incorrect time alignment between these signals will lead to a significant increase in EVM and ACPR [15]. Generally, to keep efficiency high, the ET RFPA must be kept near the compression, and ideally any non-linearity that results from this mode of operation can be linearised using DPD functionality. The measurement system must be able to characterize the performance of the RF PA by analysing the dynamic power added efficiency (PAE), as well as performing linearity measurements, such as AM/AM, AM/PM, gain compression, output power, adjacent channel Power ratio (ACPR) and error vector magnitude (EVM).

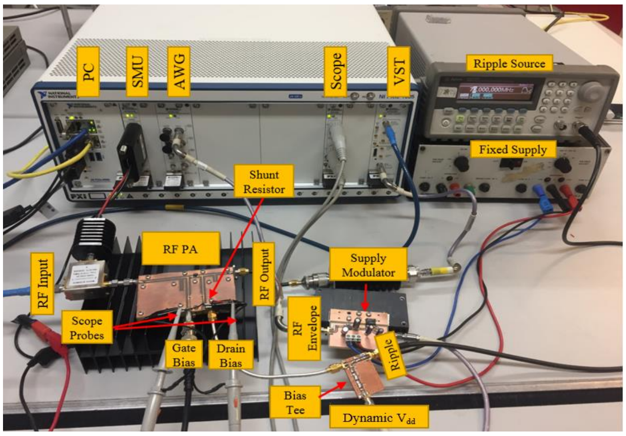

Figure 2 Measurement setup for the entire ET system.

For signal generation and measurement, a National Instrument (NI) PXIe chassis is equipped with a Vector Signal Transceiver (VST) which comprises of a vector signal generator (VSG) and a vector signal analyser (VSA) used to produce the modulated input signal and to measure the output signal respectively. An arbitrary waveform generator (AWG) is used to generate the input for the supply modulator based on the envelope of the input signal. Within the same chassis, a two-channel oscilloscope is used to measure the drain voltage and drain current that are required to calculate the dynamic efficiency. These modules are all synchronized internally to an accuracy of 100ps. LabVIEW application code, developed by NI was customised to control the hardware capabilities and perform the essential digital signal processing tasks needed for ET such as implementing the shaping functions, generating the envelope of the input signal or performing DPD. Furthermore, the LabVIEW code was used to measure the performance of the ET PA in terms of instantaneous PAE, EVM and ACPR.

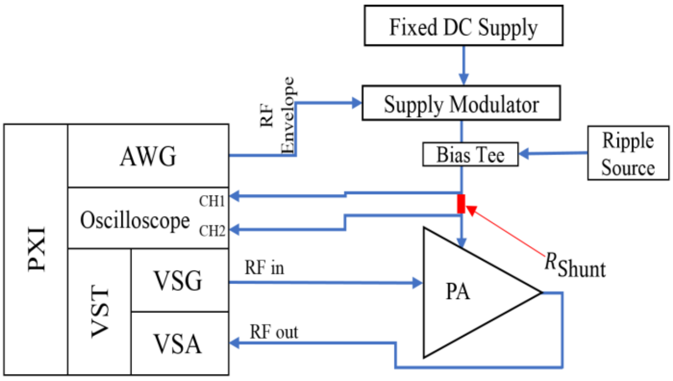

Figure 3 ET measurement system schematic including additional ripple voltage source

Fig. 2 shows the ET system used for the measurements in this paper. The test RFPA is designed around an ATF-53189 GaAs pHEMT device, and has a bandwidth of 100 MHz centred at 2 GHz, biased in class AB ($V_{ds} = 4V$). The PA is driven to its 1dB compression point at PEP. The supply modulator used consists of two operational amplifiers; an inverting voltage amplifier based on a THS4001device and an inverting current amplifier using an LT1210 device. The injected 30MHz ripple is generated using an Agilent 33250A AWG and combined with the modulated supply voltage using a suitable bias-tee. The combined modulated drain voltage is supplied to the drain of the PA as shown in figure 2.

A 10-MHz LTE signal with 8.6 dB PAPR is used for excitation. The envelope of the signal was extracted and shaped with the de-troughing shaping function [3] given in (2) to form the required drain bias voltage:

$$f(a) = V_{max}\left(1 - {}^{V_{min}}/_{V_{max}}\right)\cos(a * {}^{\pi}/_{2}) \qquad (2)$$

where $f(a)$ is the modulated drain bias voltage, a is the magnitude of the envelope of the input signal, V_{min} and V_{max} are the minimum and the maximum values for the drain bias voltage respectively. This shaping function is used to keep the drain bias signal above the knee voltage, avoiding gain collapse and significant phase distortion [3]. As shown in Fig. 4, the minimum magnitude for drain bias voltage is kept above a knee voltage of 1 V, while the maximum magnitude of the drain bias voltage is limited to 4 V. Then, an external ripple is added to the drain bias voltage with a peak-to-peak voltage increasing from 0 to 2V. The peak-to-peak voltage ripple is normalized to 2V.

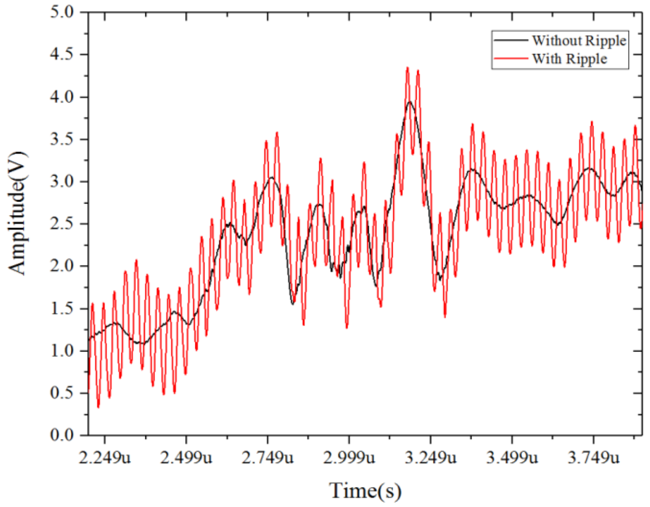

Figure 4 Modulated drain bias voltage using 10MHz LTE signal without (black) and with 30MHz ripple (red)

To compensate for the delay introduced into the modulated drain bias voltage due to the bias-tee, the time delay between the RF signal and modulated drain bias voltage was readjusted to optimise the performance of the RFPA in terms of efficiency and linearity. Thus, the time delay was swept, and the optimum delay in this case was found to be 90ns.

III. MEASUREMENT RESULT

A. *Measurement of efficiency*

To calculate power added efficiency, both the drain current and drain voltage need to be measured. To achieve this, a 510 mΩ shunt resistor is placed in series between the supply modulator and the PA. The voltage drop across this precision resistor then allows measurement of the dynamic drain current, as shown in Fig. 3. While the drain voltage is detected using a single-ended voltage probe. These two measurement steps enable the software to calculate the instantaneous efficiency. Figure 5, shows the average efficiency measurement when systematically increasing the amplitude of the ripple. Fig. 5 shows that, the average efficiency drops from 42% to 31% as normalized ripple amplitude increases from 0 to 1.

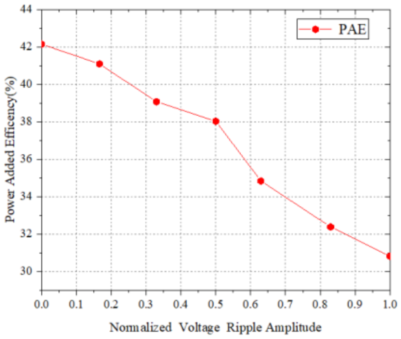

Figure 5 Measurement of the PAE for different normalized ripple amplitudes

B. *Linearity Measurement*

The linearity performance of the PA is investigated by measuring the in-band and the out-of-band distortion in terms of EVM and ACPR respectively, when the output ripple amplitude is increased as depicted in Fig. 6. The figure shows that the EVM without ripple is around 6%, while errors increase to 15.8% when normalized ripple amplitude is increased to 1. The ACPR also suffers from increased ripple, increasing from -32.7 dBc without injected ripple to -28.6 dBc when normalized ripple amplitude reaches 1. This degradation of the linearity can be explained by the interaction between the modulated supply voltage and the knee region. After adding the ripple, the supply voltage drops below value necessary to keep it out of the knee region.

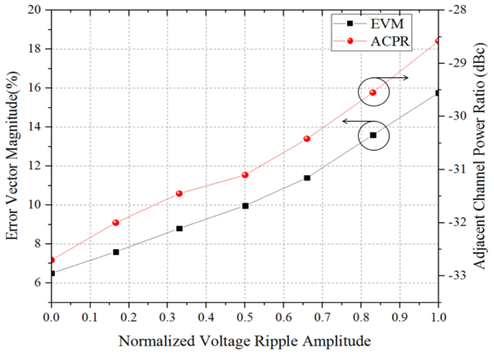

Fig. 6 Measured EVM (in-band distortion) and ACPR (out-band distortion) for increasing output ripple amplitude

IV. MINIMIZING THE IMPACT OF VOLTAGE RIPPLE

In this section, the shaping function and DPD algorithms are used to minimize the nonlinear behavior of the PA. As shaping functions provide the flexibility to trade-off efficiency and linearity of a PA, the degradation in linearity due to ripple is another factor that can be considered when designing the shaping function itself. Here, the modulated drain bias voltage was shifted by +0.5 V to keep the modulated drain bias voltage, including the additional output ripple amplitude, above the device's knee region. After increasing this minimum voltage, the linearity performance of the RFPA shows a recovery in terms of EVM from 8.1% to 7.3% and the ACPR is improved from- 31.6dB to -32.7dB. However, there is a reduction in the efficiency from 39.1% to 37.5%, which is expected as the DC power can be expected to increase.

Moreover, the DPD functionality provided in the ET system is used to further improve the linearity. A generalized memory polynomial (GMP) with up to 5th harmonic order and 7th order memory length is applied to enhance the linearity. The linearity performance was re-measured after DPD is applied, the results are shown in table 1. They show the drain bias voltage with added ripple results in EVM of 8.29% while the no-ripple case results in only 3.3%. In addition, the magnitude of both lower and upper ACPR for the pre-distorted output signal with added ripple is approximately 1dB less than for the case without ripple, after DPD has been applied as shown in Table 1.

Table 1: The linearity performance of the RF PA after the DPD

Normalized Ripple voltage	EVM	Lower_ACPR	Upper_ACPR
0	3.3%	-39.19dBc	-40.26 dBc
0.5	8.29%	-37.8dBc	-39.11 dBc

V. CONCLUSION

In this paper, a measurement-based investigation of the effect of supply voltage ripple on the ETPA is presented. The measured results show that both efficiency and linearity degrade as the output ripple amplitude increases and allow for the first time a realistic evaluation of the acceptable ripple voltage from a PA perspective. Reshaping the drain bias voltage with an appropriate shaping function can reduce the interaction between the drain voltage and the knee region, and enhances the linearity performance, albeit at the cost of lower efficiency. Importantly, it is shown that the usefulness of digital pre-distortion (DPD) linearisation is limited when significant non-coherent output ripple is present, due to the un-predictable nature of the interaction between the load-line and knee region.

ACKNOWLEDGMENT

The authors would like to thank Saudi Arabia Cultural Bureau in London and Engineering and Physical Science Research Council in the context of the research project EP/N016408/1 for funding this research work.

REFERENCES

[1] J. J. Yan, C.-S. Yoo, E. M. Trask, D. Kim, and P. M. Asbeck, "Effect of signal PAPR on efficiency of envelope tracking power amplifiers," in *2013 Asia-Pacific Microwave Conference Proceedings (APMC)*, 2013, pp. 860-862.

[2] F. Wang, D. F. Kimball, J. D. Popp, A. H. Yang, D. Y. Lie, P. M. Asbeck, *et al.*, "An improved power-added efficiency 19-dBm hybrid envelope elimination and restoration power amplifier for 802.11 g WLAN applications," *IEEE Transactions on Microwave Theory and Techniques,* vol. 54, pp. 4086-4099, 2006.

[3] Z. Wang, *Envelope Tracking Power Amplifiers for Wireless Communications*: Artech House, 2014.

[4] Z. Wang, "Demystifying envelope tracking: use for high-efficiency power amplifiers for 4G and beyond," *IEEE Microwave Magazine,* vol. 16, pp. 106-129, 2015.

[5] P. Asbeck and Z. Popovic, "ET comes of age: Envelope tracking for higher-efficiency power amplifiers," *IEEE Microwave Magazine,* vol. 17, pp. 16-25, 2016.

[6] V. Camarchia, M. Pirola, R. Quaglia, S. Jee, Y. Cho, and B. Kim, "The Doherty power amplifier: Review of recent solutions and trends," *IEEE Transactions on Microwave Theory and Techniques,* vol. 63, pp. 559-571, 2015.

[7] J. Jeong, G. Chaudhary, and Y. Jeong, "Time mismatch effect in linearity of hybrid envelope tracking power amplifier," *IEEE Microwave and Wireless Components Letters,* vol. 25, pp. 550-552, 2015.

[8] J. Kim, D. Kim, Y. Cho, D. Kang, B. Park, and B. Kim, "Envelope-tracking two-stage power amplifier with dual-mode supply modulator for LTE applications," *IEEE Transactions on Microwave Theory and Techniques,* vol. 61, pp. 543-552, 2013.

[9] R. Shrestha, R. van der Zee, A. de Graauw, and B. Nauta, "A wideband supply modulator for 20 MHz RF bandwidth polar PAs in 65 nm CMOS," *IEEE journal of solid-state circuits,* vol. 44, pp. 1272-1280, 2009.

[10] J. Hu, C. Liu, and Y. Hu, "A supply modulator with fast mode transition for RF power amplifier," in *Circuits, Devices and Systems (ICCDS), 2017 International Conference on*, 2017, pp. 49-53.

[11] M. Tan and W.-H. Ki, "An efficiency-enhanced hybrid supply modulator with single-capacitor current-integration control," *IEEE Journal of Solid-State Circuits,* vol. 51, pp. 533-542, 2016.

[12] Z. Mokhti, J. Lees, P. J. Tasker, and C. Cassan, "Investigating the linearity versus efficiency tradeoff of different power amplifier modes in an envelope tracking architecture," in *Microwave Integrated Circuits Conference (EuMIC), 2015 10th European*, 2015, pp. 357-360.

[13] F. L. Ogboi, P. J. Tasker, M. Akmal, J. Lees, J. Benedikt, S. Bensmida, *et al.*, "High bandwidth investigations of a baseband linearization approach formulated in the envelope domain under modulated stimulus," in *European Microwave Integrated Circuit Conference (EuMIC), 2014 9th*, 2014, pp. 361-364.

[14] A. Bräckle, L. Rathgeber, F. Siegert, S. Heck, and M. Berroth, "Power supply modulation for RF applications," in *Power Electronics and Motion Control Conference (EPE/PEMC), 2012 15th International*, 2012, pp. LS8d. 3-1-LS8d. 3-5.

[15] F. Wang, A. H. Yang, D. F. Kimball, L. E. Larson, and P. M. Asbeck, "Design of wide-bandwidth envelope-tracking power amplifiers for OFDM applications," *IEEE Transactions on Microwave theory and techniques,* vol. 53, pp. 1244-1255, 2005.