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Simplify an Envelope Tracking Measurement with Compact System

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ABSTRACT

This paper presents a compact measurement system to simplify the complexity measurement for envelope tracking PA (ET-PA). The requirements for such system are discussed. Then, the measurement set-up is used to validate these requirements with a 10 MHz LTE signals at 1.8 GHz. The devices which are used in the measurement are a GaAs FET PA, a linear amplifier and a current sensor. The measurement shows how the alignment between the RF signal and tracking signal achieved practically and the average DE of the test PA with fixed bias increases from 22.6 % to 43.9 % with 48.5 % under ET mode. The instantaneous efficiency measurement shows potential improvement when ET used. Also, the AM-AM and AM-PM distortions were reduced using generalised memory polynomial (GMP).

KEYWORDS: *Envelope Tracking, GaAs FET, 10 MHz LTE signals, Instantaneous Efficiency, AM-AM, AM-PM, Generalised Memory Polynomial*

I. INTRODUCTION

Envelope tracking (ET) is a strong contender architecture for enhancing the power efficiency performance of power amplifiers (PAs) in emerging communication systems. However, the design and characterisation of envelope tracking power amplifiers (ET-PAs) introduces a number of significant technical challenges related to the optimisation and interaction of the numerous subsystems involved, namely the PA itself, envelope detection/generation, the supply modulator and linearisation elements. Traditional, PA measurements requires a number of key instruments that can simply include a signal generator and some form of signal analyser. However, a complex measurement set up is required to fully characterise ET-PAs for dern communications systems. In an ET system, the PA can be considered as a three-port device, with a dynamically controlled drain bias voltage. Practically, the ET measurement system consists of an Envelope Tracking Control Host, which is the digital domain of the system, an RF signal generator, an Arbitrary Waveform Generator, and a Vector Signal Analyser. Also, synchronization between these different instruments is required which is a major challenge from a test and a characterisation perspective. Essentially, the synchronization between the RF signal generator and the baseband arbitrary waveform generator (AWG) in an envelope tracking system. Therefore, a measurement system for the envelope requires more complex measurement than fixed bias PAs.

This letter presents, fully implementing a new ET measurement system and includes the characterisation and validation of the requirements for such a system. The paper starts by discussing the essential requirements for an ET measurement system. Then, it demonstrates the NI ET system which will be used to realise the ET measurements. After this the paper demonstrates an experimental validation of the ET characterisation system using 10 MHz LTE modulation.

II. Envelope Tracking Measurement System Requirements

It has been discussed that deploying a full ET system faces several challenges, not only in ET-PA design itself, but also the requirement for more complex stimulus, bias and measurement techniques. Thus, an ET measurement system is needed to satisfy certain criteria, which will be discussed in detail in the following subsections.

A. Modulated Signal and Baseband Generation

The ET measurement system is needed to generate a modulated RF signal based on current and future communication and wireless waveform standards, together with associated baseband ET (dynamic bias) signals. The modulated RF waveforms can be generated using commercial software tools such as MATLAB, in the form of I & Q data. The necessary baseband signals can be obtained from I & Q data directly or by detecting the envelope of the RF signal using a simple RF envelope detector [1].

B. Shaping Functions

The inherent tradeoff between efficiency and linearity in traditional fixed bias PAs is no longer present in the ET [2]. In addition, there is flexibility in achieving the desired performance of an ET-PA, as efficiency and linearity can be optimised using different shaping functions. The mapping between the instantaneous input power and dynamic supply voltage plays a vital role in the ET approach due to the impact on PA design specifications, which include output power, efficiency, and linearity, particularly AM-AM and AM-PM distortion. Unlike the fixed supply PAs, a lower-level of AM-AM distortion can be obtained in ET despite the nonlinear behavior of the device when operated in compression, if the tracking signal is shaped in a specific manner [3]. Furthermore, the bandwidth requirements of the tracking signal, and hence the requirements of an eventual ET modulator, can also be reduced when using the appropriate envelope shaping function. This results in a modest requirement of bandwidth with only a small degradation in efficiency and linearity [4] – very important design information. Hence, the ability to precisely adjust the shaping of the baseband tracking signals is needed to optimise the efficiency and linearity of the ET-PA and to explore the design space that results. Thus, the measurement system should support different types of shaping function with a high degree of flexibility.

C. Synchronization and Time Alignment

Synchronization between different instruments is a major challenge from a test and a characterisation perspective. Essentially, the synchronization between the RF signal generator and the baseband arbitrary waveform generator (AWG) in an envelope tracking system should be achieved with maximum timing accuracy and minimal jitter. Additionally, due to the frequencies of interest, the delay of the RF modulated waveform and the tracking signal must be adjustable with sub-nanosecond accuracy. This is because the modulated RF signal and the tracking signal travel in two different paths, and will both be affected by the delay, which needs to be compensated. However, the required alignment in ET is not as stringent as it is in EER because in ET, the amplitude information is always maintained in the RF signal path. Misalignment could be a source of nonlinearity however, as the time deviation between these signals can lead to a significant increase in the EVM and ACPR [5]. The misalignment between the RF signal and the tracking signal leads to other unintended interactions, resulting in for example asymmetry in ACPR which is symptomatic of an electrical memory effect, as shown in [6]. Generally, the maximum value of efficiency can be expected when an optimum supply voltage amplitude is applied to the PA, which aligns with the RF modulated signal. Otherwise, the tracking voltage will be either higher or lower than this desired value. So in summary, the system must provide for the precise alignment between the modulated RF signal and the tracking signal to an accuracy in order to minimise any degradation in the efficiency or distortion introduced to the PA [1].

D. Efficiency Measurement

The efficiency measurement is a vital parameter to evaluate the performance of the ET-PA. The efficiency can be defined in several ways, drain efficiency (DE) and power added efficiency (PAE). The drain efficiency is defined as the ratio between the output power of the PA (dissipated at the fundamental load) and the DC power from the DC power supply. Realising a dynamic efficiency measurement is one of the challenges in realising the ET measurement system. This is because the measurement of the instantaneous current and voltage supplied to the PA should be taken between the supply modulator and the ET-PA, which can potentially affect the combined performance of the ET-PA. Nevertheless, the practical measurement of the instantaneous current and voltage in an ET-PA can be achieved where dedicated probes are used to measure the instantaneous current and voltage supplied and displayed and captured directly using the oscilloscope.

E. Digital Pre-Distortion

As an ET-PA is maintained for most of the time near its compression point, the non-linearity that results, generally, must be corrected and usually through using digital pre-distortion (DPD) linearization. In the pre-distortion method, the cancellation of distortion is introduced in the input rather than in the output stage by distorting the input signal in a specific manner which is inverse to the PA distortion produced, in order to cancel it [7].The input signal is passed through a virtual digital pre-distorter circuit, which adds the necessary pre-distortion before amplification. Then, the introduced nonlinear behaviour is corrected through the non-linearity of the output stage. Thus, the measurement system should include customisable DPD, as mentioned previously, in order to linearise the ET using a memoryless lookup table (LUT) and different memory pre-distortion models.

III. Envelope Tracking Measurement System Arrangement

A modulated microwave measurement system from National Instrument (NI) is used as the basis for the advanced ET measurement system, as shown in Fig. 2 . This measurement system is implemented within a NI PXIe chassis equipped with a Vector Signal Transceiver (VST) which is able to support up to 1 GHz signal bandwidth and up to a maximum operating frequency of 6 GHz, itself comprising a vector signal generator (VSG) and a vector signal analyser (VSA). In addition, a dual- channel Arbitrary Wave Generator (AWG) with a bandwidth of 400 MHz, is used to generate the envelope of the RF signal. A two-channel fast oscilloscope with 400 MHz bandwidth is used to monitor the drain current and voltage signals to measure the efficiency. All these modules are interconnected via the backplane of chassis that is capable of carrying numerous clock and trigger distribution lines. Also, a tight synchronization is achieving using NI's 'T-Clock' capability, which accurately aligns sample clocks and trigger events to allow all devices to start generating simultaneously.

The software which is mainly used to control the measurement system is a National Instruments (NI) software package called RFIC [8]. This software application, which runs on the PC controller in the NI chassis, uses a graphical interface to configure all key hardware. It is also used to fully exploit the hardware capabilities and perform the essential digital signal processing and other tasks needed for ET measurements, including downloading commercial waveforms to the VST, shaping the RF envelope and digital pre-distortion (DPD). Furthermore, the software is utilised to measure and display the average efficiency, ACPR, AM-AM, AM-PM, with/without DPD measurements. Importantly, the software has the ability to align the RF signal and the tracking signal by applying a digital delay to the RF signal. However, this software application has some limitations and cannot for example be easily customized to do other required measurements. Hence, LabView applications needed to be developed to enable additional measurement capabilities, including instantaneous efficiency, implementing new shaping functions, customising waveforms and time-alignment characterisation.

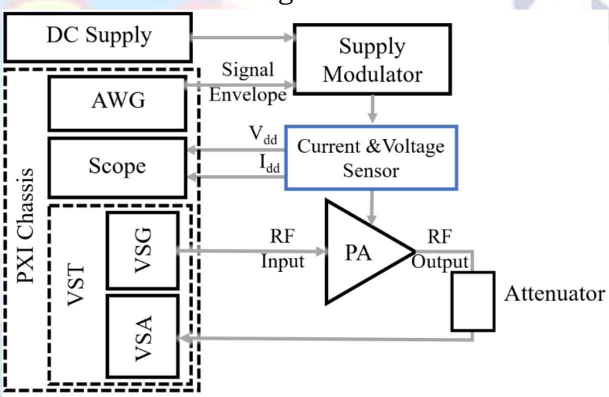

Figure 1 Simple representation for typical ET measurement system

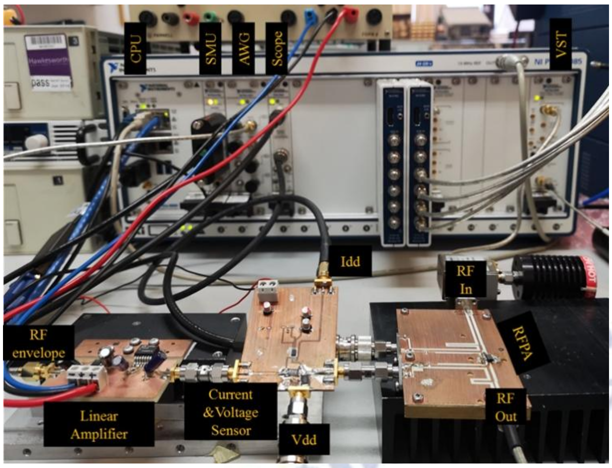

Figure 2 Picture of the complete ET measurement test bench

IV. ET MEASUREMENT

To demonstrate the capability of the system under ET a 0.35 W GaAs FET, a linear amplifier and a current sensor was built using a MAX9643 differential Op-amp were designed. The supply modulator was placed as close as possible to the drain of the PA to minimise parasitics, which might impact the tracking signal and degrade performance and the efficiency measurement. The current sensor board was placed between the supply modulator and the PA. The output signal of the board was connected directly to the fast sampling dual channel oscilloscope as shown in Figure 1 and Figure 2. As the VSG generated sufficient amplitude, no driver was required, which makes the measurement set-up simpler, and the VSG output could be connected directly to the PA. A circulator, however, was added before the ET-PA to absorb any reflections from the PA which could potentially damage the VSG.

A. Shaping Function

For this measurement, the envelope of the 10 MHz LTE signal was extracted and shaped with the de-troughing function as shown in (1):

$$f(V) = V(1-d)\cos(V * \tfrac{\pi}{2}) \qquad (1)$$

$$d = {V_{dd\,(\min)}}/{V_{dd\,(\max)}} \qquad (2)$$

Where f(V) is the modulated drain supply voltage, V is the normalized magnitude of the envelope of the input signal, Vdd(min) and Vdd(max) are the minimum and the maximum values for the drain supply voltage. The sensor board was calibrated by eliminating the time delay differences between the instantaneous current and voltage waveforms which enhances the accuracy of the efficiency measurement.

B. Time Alignment Characterisation

To characterise the alignment between the RF and tracking signals, the centre frequency was temporarily reduced to 400 MHz which is the maximum bandwidth of the oscilloscope. Then, the RF signal and tracking signal (Vdd) were probed with two high-speed voltage probes. As illustrated in Figure 3, the output signal (RF1) did not align with the tracking signal (Vdd) before applying the delay. Therefore, the delay, which was performed in the digital domain, to the RF signal was swept until both RF signal (RF2) and tracking signal (Vdd) align.

C. Efficiency Measurement

After the alignment was achieved, the ET-PA was driven up to its 1 dB compression point, with 10 MHz LTE signal at a centre frequency of 1.8 GHz using both 4.5 V fixed and dynamic bias with a minimum voltage of 1.5 V and a maximum voltage of 4.5 V, using the linear modulator which was designed and measured previously. Table 1 compares PA performance under fixed bias and ET operation, where the ET increases average drain efficiency from 22.6 % to 43.9 %. The linearity performance was also measured. The in-band distortion (EVM) was measured to be 3.6 % for the ET-PA, while for fixed bias, it was measured to be 2.1%. The out-band distortion (ACPR) was measured to be -38.4 dBc and -40.3 dBc for ET and fixed bias PA configurations respectively. The ET-PA has 2 dB lower ACPR than fixed bias and has 1.5 % worse EVM, which was expected as the ET-PA has lower linearity performance due to the fact the ET-PA is compressed for most of the time. However, the linearity of the ET-PA might be improved using other shaping functions to optimise linearity such as the Iso-gain shaping function.

Table 1: Measured performance for ET and fixed biased with LTE10 MHz and 6.8 dB PAPR

Biasing Method	Mod.BW (MHz)	PAPR (dB)	Pout (dBm)	PAE (%)	ACPR (dBc)	EVM (%)
4.5 V Fixed	10	6.8	25.1	22.6	-40.3	2.1
ET	10	6.8	25.2	43.9	-38.4	3.6

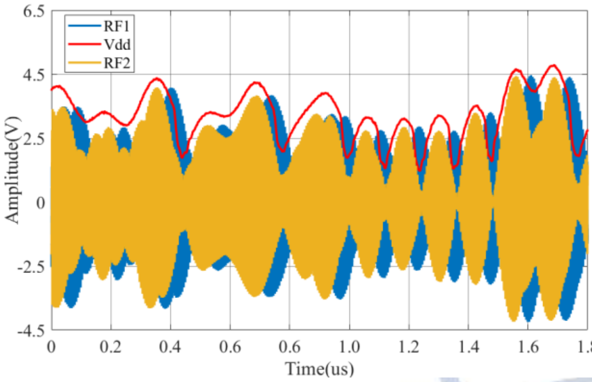

Figure 3The RF signal voltage and the tracking drain voltage (Vdd) for two cases; ne without delay adjustment, and the other with delay applied.

Generally, the measurement of the average efficiency is useful to evaluate the performance of the ET-PA and to compare it to other techniques. However, the instantaneous efficiency is vital to show the fundamental principle of ET to maintain efficiency over a wide range of OBO. This instantaneous efficiency allows a deeper understand to be developed in terms of how efficiency changes at the rate of the envelope for example, when different shaping functions are applied. Figure4 shows the measured instantaneous DE under ET and then for a fixed 4.5 V bias can be plotted against output power, as shown in Fig.5. The DE of the PA maintained in a high plateau region, which is above 50 % over 5 dB OBO from 20.2 dBm to 25.2 dBm.

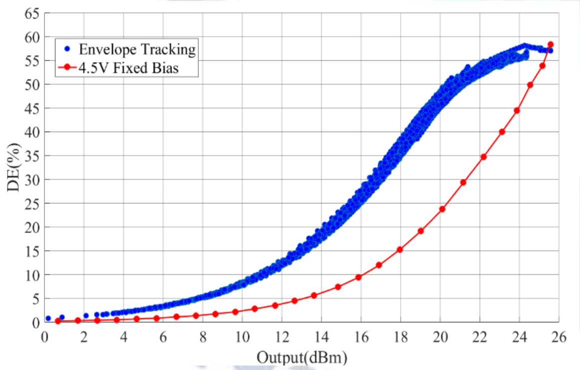

Figure 4 Comparing the instantaneous DE for ET and 4.5 V fixed bias

D. Applying Digital Predistortion (DPD)

The DPD functionality was used to linearise the output signal by applying a generalised memory polynomial (GMP) with (order=3, memory depth=5). Figure 5, shows the measurement of AM-AM distortion using the gain as function the input where GMP DPD flattens the gain which enhances the linearity performance of the PA. However, when the PA is deeply compressed, the DPD struggled to fix the nonlinearity. The AM-PM measurements before and after applying the GMP DPD is shown in Fig.6, where phase variations up to 8° were observed, while after applying DPD, variations dropped to within 1°. The spreading at lower input powers is almost completely down to the envelope delay between input and output modulation envelopes. These AM-AM and AM-PM measurements could potentially be used to define the shaping function for the tracking signal, which could linearise the PA without the need to apply DPD.

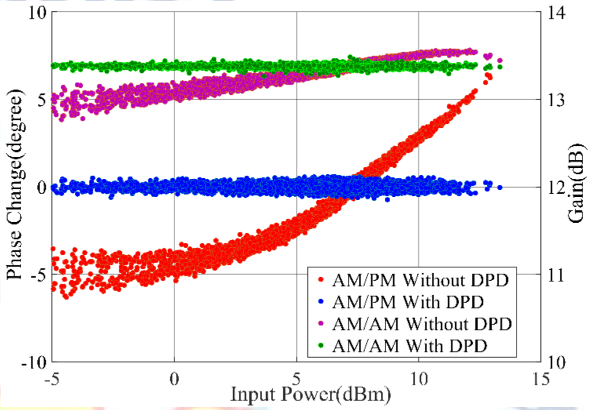

Figure 5 AM-AM & AM-PM distortions before and after DPD applied

V. Conclusion

In this paper, a full ET measurement system is realised and validated. This involves firstly outlining the important requirements for ET measurement system. Then, a commercial NI PXI system is used as the core for the ET measurement system and is described in detail. The ET measurement system was characterised and all the essential requirements for this type of system were validated using 10 MHz LTE signal. The time alignment between the RF signal and the tracking signal is characterised using different methods, including monitoring both RF signal and tracking signal with a high speed oscilloscope and measuring the degradation of the linearity. The average DE of the PA with fixed bias increase from 22.6 % to 43.9 % with 48.5 % improvement. The measurement for the instantaneous efficiency is maintained around 50 % over a 5 dB OBO which shows the essential criteria of ET. The digital pre-distortion (DPD) is used to compensate the degradation in the linearity by reducing both AM-AM and AM-PM distortion.

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