A balancing act: Envelope Tracking and Digital Pre-Distortion in Handset Transmitters

Abstract

Envelope tracking requires the addition of another connector to the RF power amplifier. Providing this supply modulation input leads to many possibilities for improving the performance of the device, such as substantial improvements in linearity and a reduction in the heat dissipated in the RF PA. If the modulating power supply if efficient, you can reduce energy consumption from the battery. However, it's not a journey into a land of completely unalloyed pleasures for the designer. Having recovered from the shock of being told all the decoupling capacitors worth being called such are to be removed, the RF engineer comes back to his design to find while it doesn't burn his fingers, nasty things can happen to the spectrum. This paper takes a practical look at measuring what happens when you apply ET and DPD, using kit you already have, or can easily get.

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Introduction

The design of a handset transmitter has been getting progressively more difficult ever since the industry moved away from a few bands at 900 MHz and the constant envelope of GMSK. To cope with the increase in PAPR of EDGE, polar modulators were introduced. This means phase modulation is applied to the RF signal, and the amplitude modulation component is applied via the power supply. Envelope tracking is a related idea, except the IQ signal is fully modulated and the AM component is given some help by modulated the supply. This paper describes some of the subtleties of ET operation and related measurements

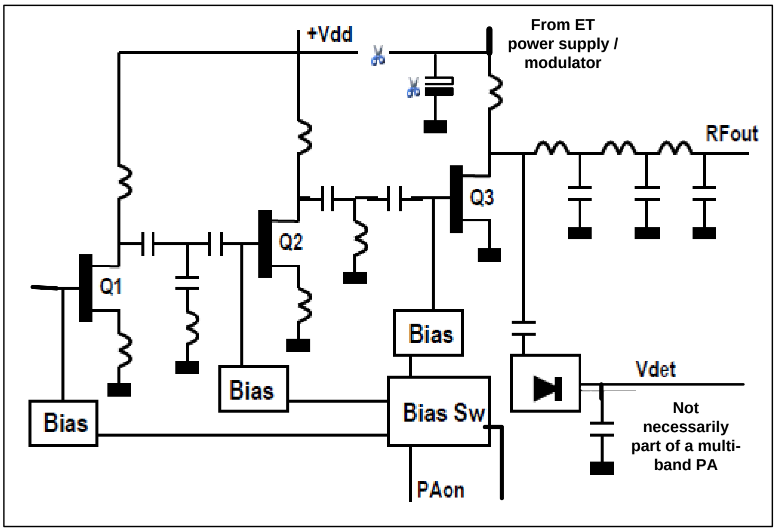


Figure 1 Simplified circuit of a typical handset RF PA

The objectives

The most common picture of the benefit of an ET system is shown in the top section of figure 2. The red shaded area is the *saving in battery energy.* The diagram is, of course, wrong. Voltage never did anyone any harm.

The central traces show the relationship between the voltage "saved" and current, giving a more interesting view of the power saving versus time trace at the bottom of the figure.

Even then, power saving is only one of a several improvements that can be made to the PA. In the context of a power amplifier with harmonic filtering, dramatic improvements in amplitude linearity are possible, without resorting to DPD.

The third aspect of using ET is to increase the supply voltage beyond what would be possible for a fixed supply. Some PA technologies, such as GaN are particularly suited to this. Implementing the switch mode element of the ETPS as a boost supply allows this.

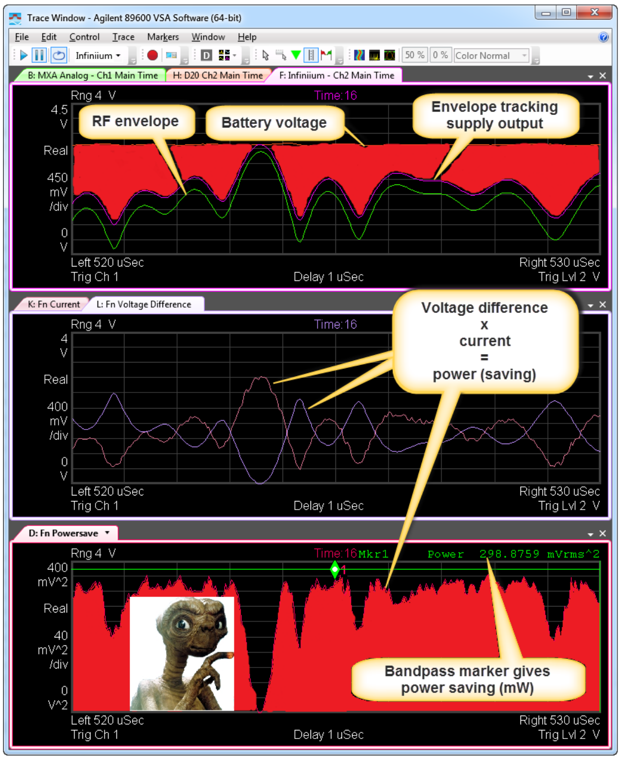


Figure2: ET: Modulating the supply based on the RF envelope

Envelope tracking operation

Figure 3 shows an ET system to consist of three parts; the ET power supply (a.k.a. modulator), a modified RF PA and the shaping table. Actually there are four parts, because a time delay has to be added to the IQ path to balance the difference in delay of the envelope signal thought the ETPS and the RF signal through the PA.

Envelope tracking shares the idea of a power supply modulator with polar modulation, but the similarities ends there. With a basic ET system, the RF signal is fully IQ modulated. Power supply modulation does not supply the amplitude modulation in the troughs of the envelope. Although the W-CDMA or LTE envelope bandwidth is considerable wider than EDGE, it is quite possible to deliver a modulated supply current of large fractions of an amp from devices with a footprint suitable for use in a smartphone.

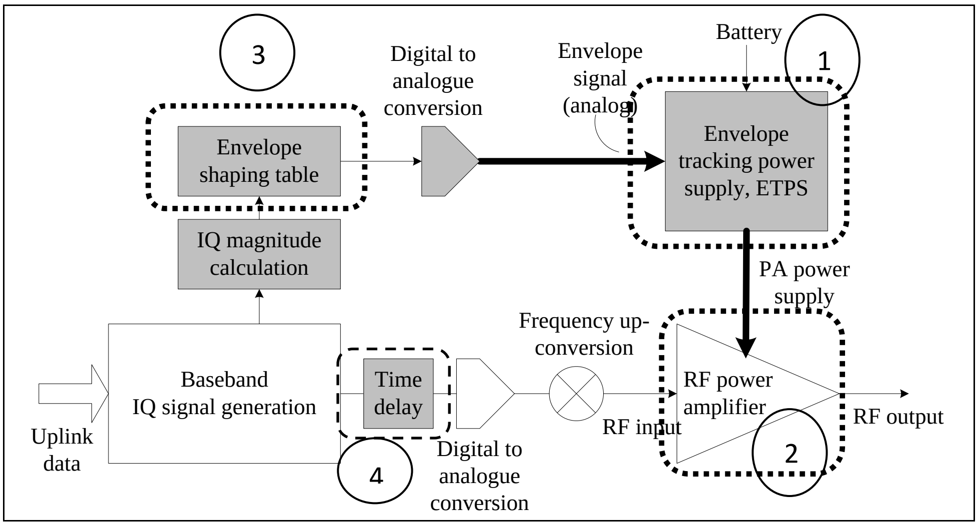


Figure 3 Components in an envelope tracking system

The shaping table

The relationship between the RF envelope and the power supply is “shaped”, rather than simply linear. It doesn’t appear in any dictionaries yet, but the supply signal undergoes “de-toughing”. Figure 4a shows how the term comes about. Using a shaping function such as one of those in figure 4b, the supply voltage to the PA shown in the darker trace, never reaches 0V.The inset highlights the difference between the shaped envelope and the modulated RF envelope.

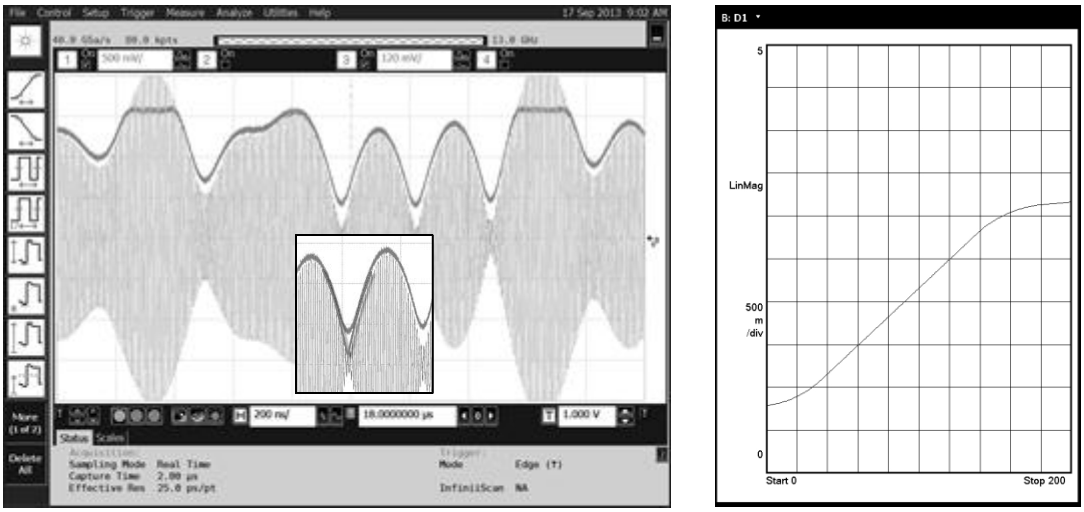


Figure 4a: Modulated RF and envelope signals   4b The associated shaping table

Along with an RF power amplifier, with biasing modified to work with a supply modulated final stage, and the tracking power supply, the shaping table is the most easily modified component in an ET system. It is where the designer gets to define what they want to achieve. Trade-offs include the practicality of calibration in manufacturing, power added efficiency of the ET system as a whole, RF linearity and spectral performance. As we shall see later, the apparently modest differences between the two trajectories in figure 5b can have a significant impact on the PA's performance.

The tracking power supply design itself takes considerable care and attention. Simply displacing some of the heat dissipated in the PA with a fixed supply can have some advantages, but the goal is to make the PA system more efficient. A subject in its own right, the ETPS is typically designed as a multi-phase switching supply with a high performance, very low output impedance linear amplifier.

As shown in figure 5a, the shaping table affects the spectrum of the envelope signal the ETPS has to deliver. The bandwidth of the main signal component is the same as the RF signal it is derived from. The envelope's harmonic content, caused by the magnitude conversion of the original I+jQ signal, can be reduced by the choice of the appropriate shaping function.

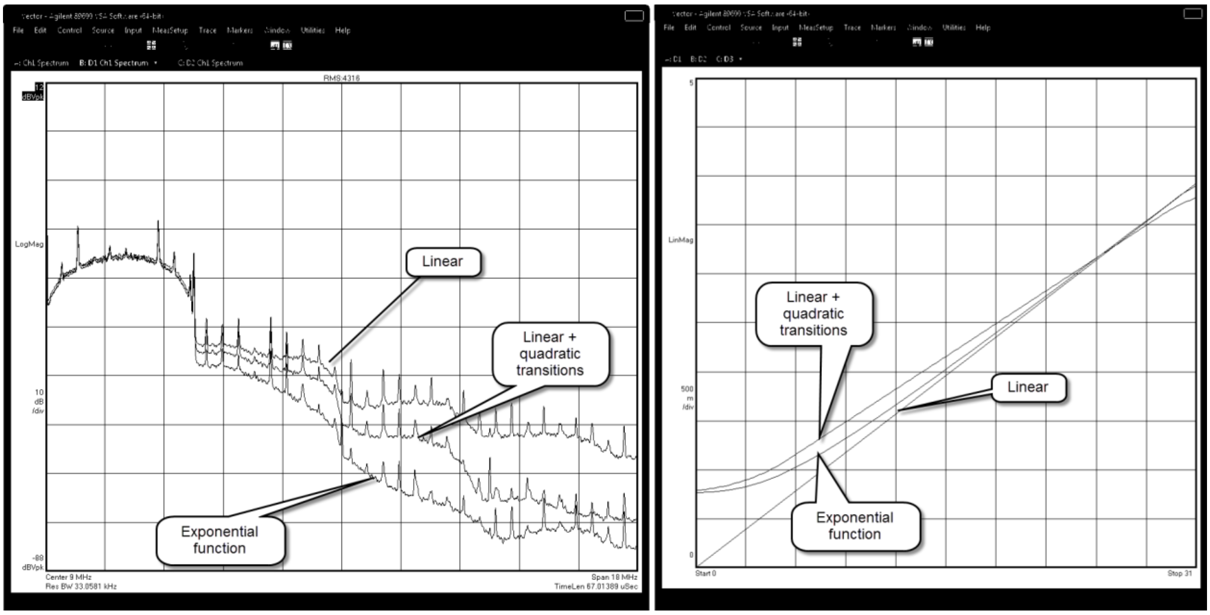


Figure 5a The variation in baseband spectrum caused by…. Fig 5b different choices in shaping table

The choice of shaping table, or de-troughing coefficients, is not immediately obvious. The relationship between RF and envelope directly affects linearity and instantaneous efficiency, as well as the spectrum of the signal fed to the supply modulator. Whatever shape is adopted has be reasonably insensitive to errors in the amplitude of the PA input signal.

The RF spectrum, both adjacent to and some distance from the carrier, is affected by unwanted signals from the ETPS, such as switching spurious and noise, and errors in the modulation waveform. Trade-offs may be required in the system design of an FDD receiver.

Measurement configuration

Figure 6 shows a measurement configuration that allows comprehensive analysis of the signals and their relationship in an ET system. The supply voltage and current signals may also be measured using the baseband input of an Agilent X series signal analyser.

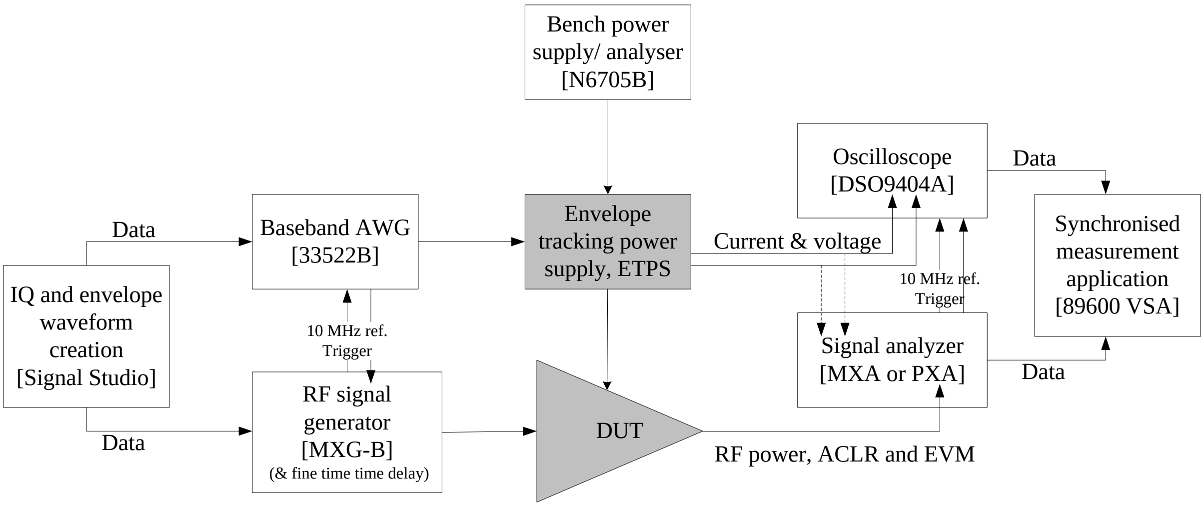


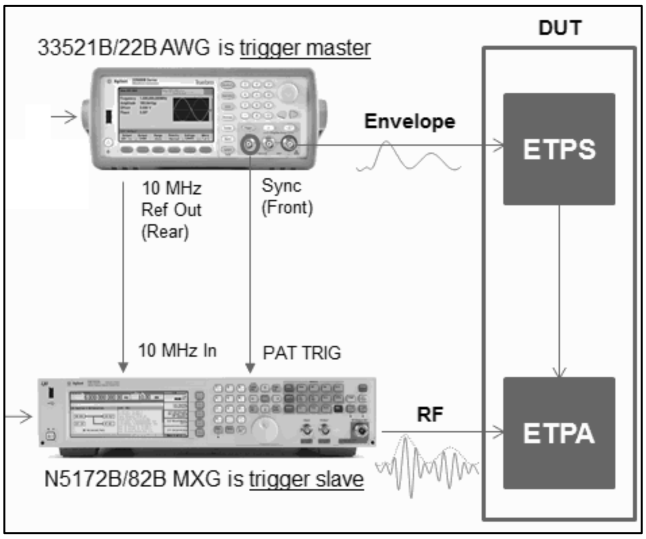
Figure 6 Configuration for testing ET DUT

High resolution timing alignment without a common clock, and time alignment measurement

In situations where existing equipment needs to be used, adding an AWG to an RF signal generator is a natural path to explore.

What makes this particularly challenging is the accuracy of time alignment required.

Whilst the requirement ultimately depends on the distortion level being sought, a rule of thumb is for the timing error (in ns) to be less than 0.2*RF bandwidth (in MHz). In the majority of cases, this is significantly less than the interval of the clocks used to generate the I,Q and envelope waveforms.



Trigger circuits clocked from a high quality 10 MHz reference can provide very repeatable time alignment if care is taken resetting the trigger circuit state machines. Figure 7 shows the use of a new family of AWG, the Agilent 335xx & 336xx, with the MXG signal RF signal generators. Two BNC cables are all that is needed to achieve the required alignment accuracy.

Figure 8 gives an indication of the resolution available by combining stable trigger with a delay introduced to the IQ envelope signal within the RF generator.

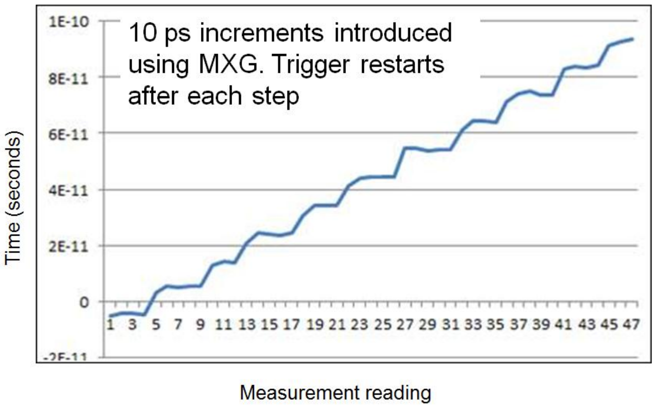


Figure 8: Generation and measurement of 10ps steps with off-the-shelf hardware

A basic time alignment assessment can be made simply by displaying the modulated RF and envelope signals on an oscilloscope. Measuring time alignment with better than 1ns resolution is challenging, even when the modulated signal is 20 MHz wide.

A signal correlation algorithm developed for the PA distortion & graphing analysis in 89600 VSA provides this capability. Figure 9 shows the difference between measurement using the time waveforms on the oscilloscope trace, and using the correlation based algorithm.

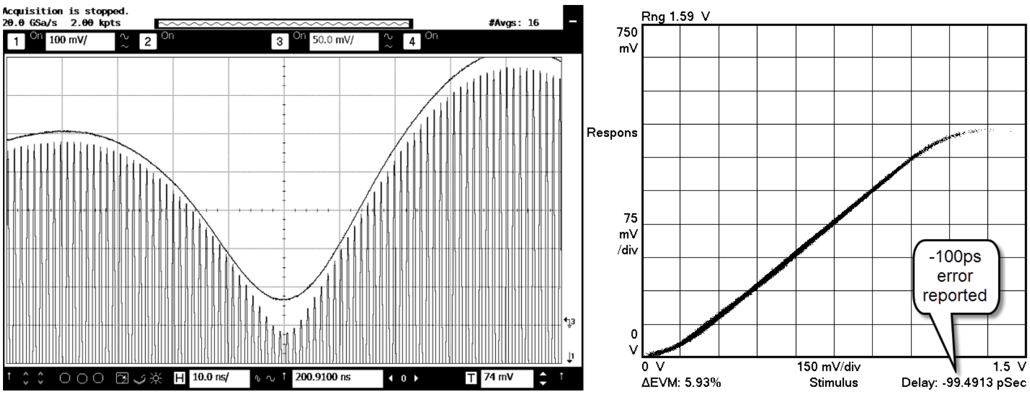


Figure 9: Oscilloscope and correlation measurement of RF & envelope alignment

Single input linearity measurements

A comprehensive analysis of the signals associated with the RF and envelope tracking can be made using an oscilloscope. As has just been described, an oscilloscope is particularly suitable where high resolution timing measurements are needed. High dynamic range spectrum measurements require an RF signal analyzer, and in some situations the only signal available for measurement is the RF.

If a reference version of the test signal is available, "before and after" measurements of the PA can be made, with connection only at the PA output. The same high resolution correlator in 89600 VSA used for alignment measurements now aligns the RF measurements. The reference may come from one of three places. If it the original IQ file, the signal generation must not introduce any significant distortion, which is indeed practicable. If it's taken from the signal generator output, a switch is needed. The third option is to operate the PA at a point where it is substantially linear. This technique does have some limitations, but is of considerable practical value.

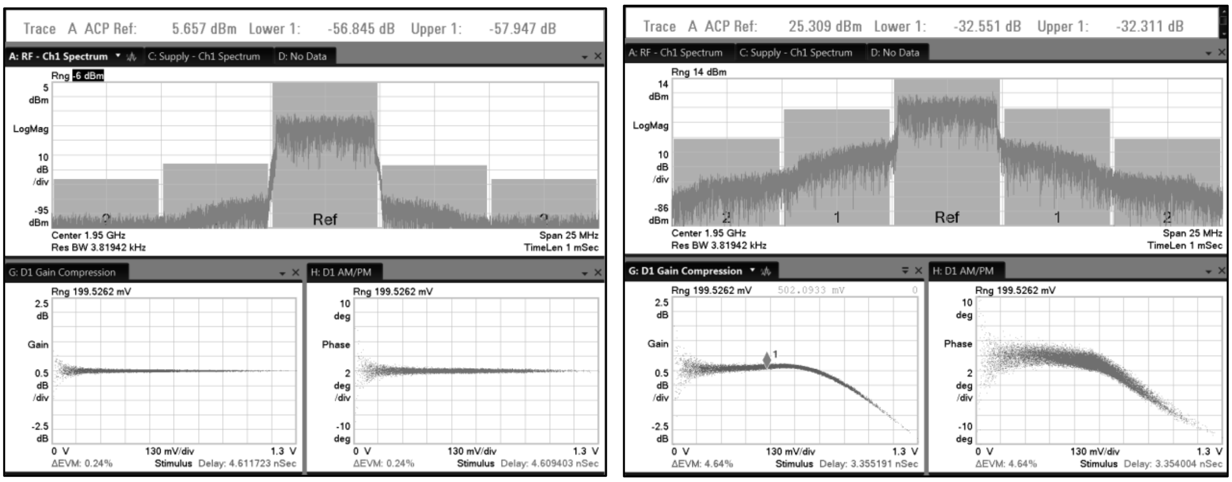


Figure 10: PA output at linearity reference and +25dBm with a fixed power supply

Figure 10 shows an example of the PA output used for the reference measurement, and at the desired test power, with a fixed supply. The gain compression typical of fixed supply operation is clear to see in the bottom right of the figure.

The potential for ET to improve linearity is seen in figure 11. ACP, gain compression and phase linearity all improve.

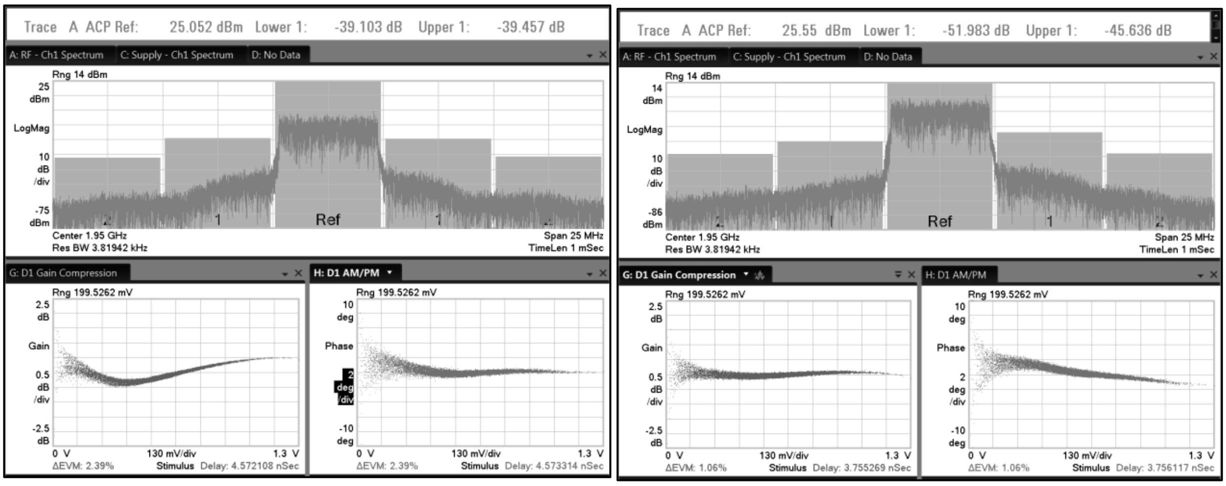


Figure 11: Examples of the linearity improvement possible with the two shaping tables in figure 5b

Performance with impaired IQ signals

A typical UE might have a -30 to -40dB of LO leakage (IQ offset). When applying ET to an LTE signal with small resource block allocation, an image outside the transmission band is exacerbated as shown in figure 12. This can be a particular problem in bands close to released TV transmissions.

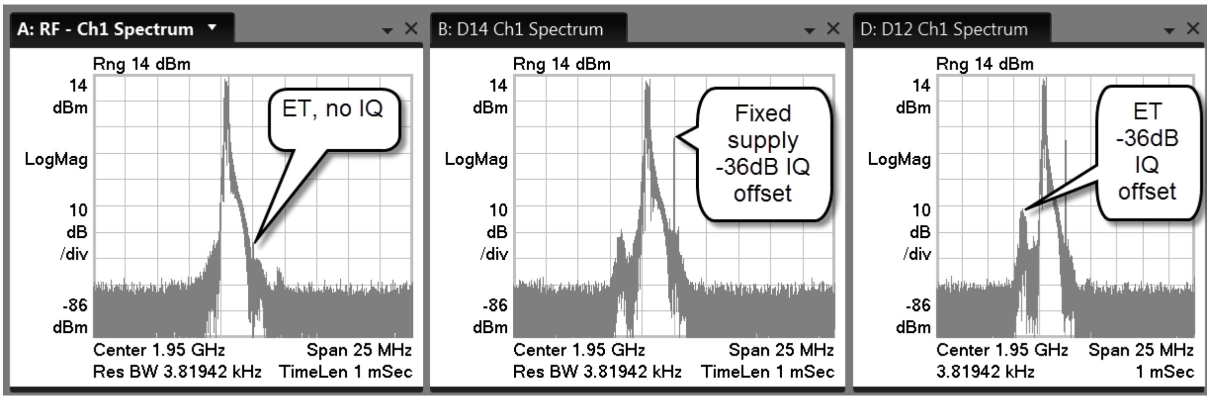


Figure 12: The image introduced with LO leakage can be worse with ET than with a fixed supply

Performance with a non-flat channel response

An in-channel frequency response gives rise to systematic errors in gain compression and AM/PM. In the DPD world, these are included in *memory effects*. Looking at the spectrum plot in figure 13 reveals little. The gain compression & AM/PM traces show something systematic is occurring, but not what. The colour coded distributions, particularly the gain compression trace shows a number of horizontal lines, implying different trajectories for the gain as a function of "something".

Using an LTE demodulation function provides a straightforward way of determining what is happening as a function of frequency. The upper right hand trace shows a frequency response, deliberately introduced using a two path static channel with a 0.5us path delay.

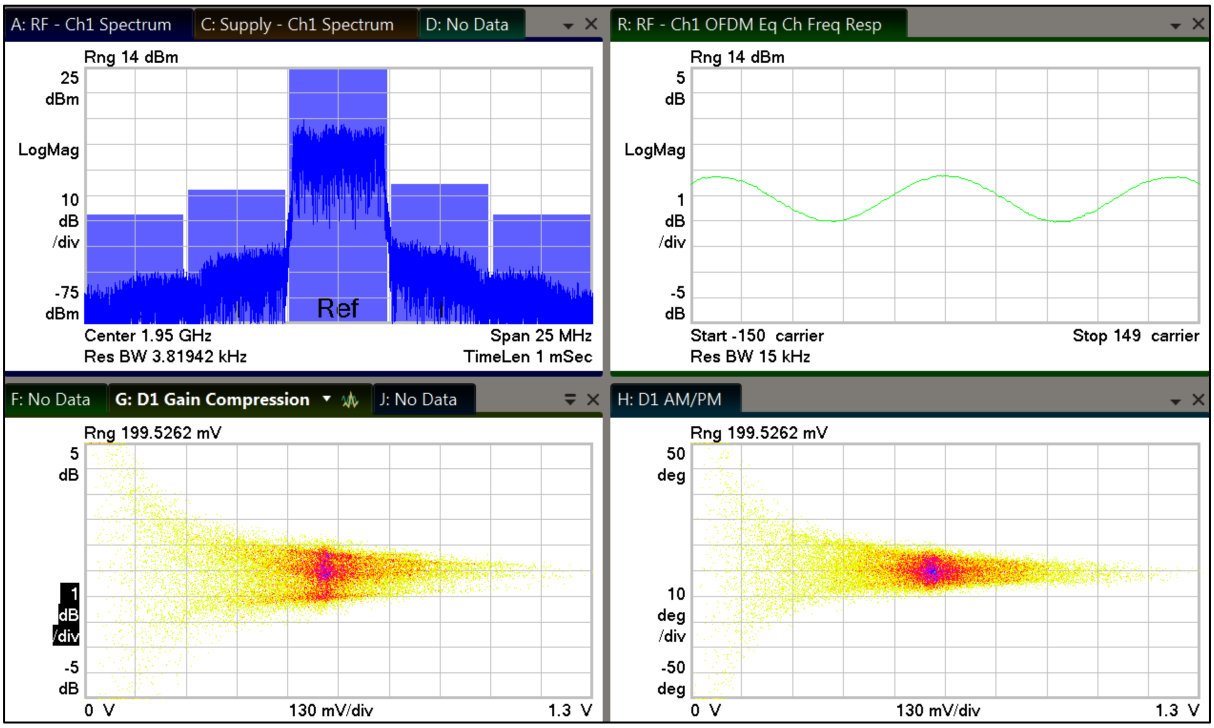


Figure 13: Frequency response, or memory effects can be identified using a demodulation equalizer

Multiple simultaneous measurements

The complexity of modelling and the limited availability of models for all the components mean it can be simpler to make changes to the ET related parameters and measure the effect. Seeing what's happening from several directions can give many insights. Figure 14 shows this is entirely possible using the VSA application.

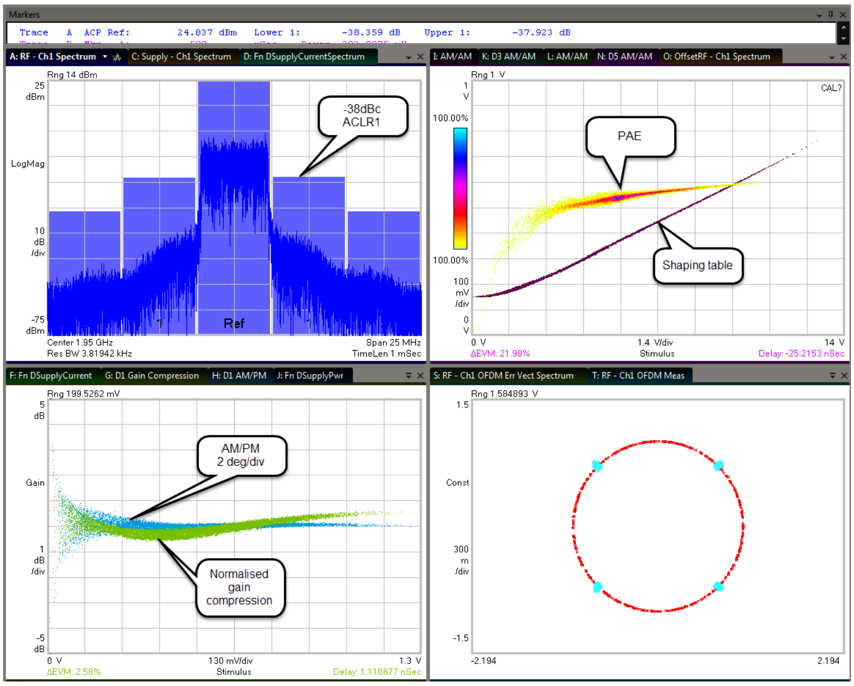


Figure 14: Simultaneous spectrum, linearity, shaping & demodulation results

Power Added Efficiency

As has been shown, PAE improvements are not the only benefit, but they are clearly a goal for an envelope tracking system. Figure 15a shows a rather optimistic dotted line goal with the amplifier running at 100% efficiency, along with the efficiency typical of a good PA design using a fixed supply, and a typical result using envelope tracking.

Measuring the efficiency of the combined ET modulator and PA is straightforward. It can be done with a bench supply with current measurement, such as the N6705B. Measuring the instantaneous efficiency is more problematic. A common technique is to use a high side current sense resistor. The value of the resistor has to be very low to avoid changing the performance of the PA. Use of 50 or 100 milliohms is common. The difficulty is the magnitude of the common mode voltage.

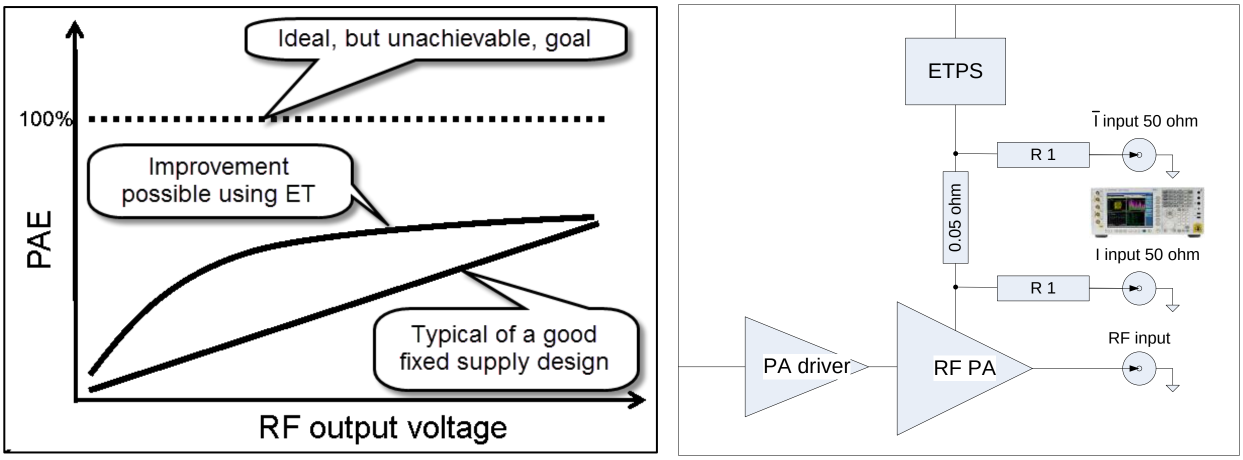


Figure 15a PAE performance with/without ET. 15b High side current sense using differential BB input

With a peak current of 0.5A, and a 2.5V voltage swing, the common mode signal is 40dB higher than the differential voltage developed across a 50 mohm resistor. Fortunately, a high resolution baseband input with switchable single ended and differential modes is a good fit to address the issue. As shown in figure 15b, the addition of two resistors provides the signals needed to make the measurement.

Figure 16 shows an example of a measurement, with the coloured trace of the PAE result superimposed on the shaping table used for the signal generation. The shaping table determines the compression level the PA operates in as a function of output power, so it controls the efficiency as well as the linearity. The distribution of the signal amplitude determines the average efficiency. The colour coding, with the darker section in the centre, shows the distribution of this particular LTE uplink signal. A signal that has been compressed prior to amplification will have a lower PAPR, and hence enjoy operation at the higher efficiency levels.

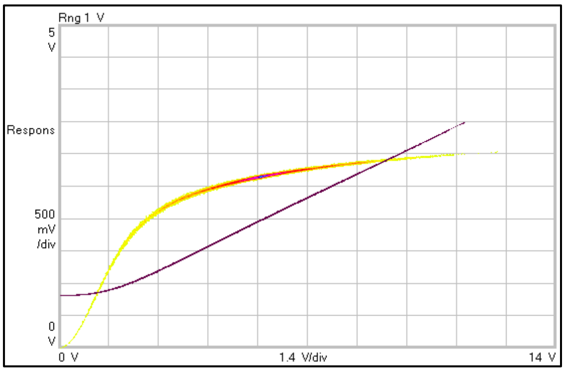


Figure 16: Instantaneous RF PA PAE, with colouring to show the power distribution

Digital pre-distortion applied to handsets

One way to confront the design trade-offs inherent in an ET system is to apply a separate technique to address “whatever is left” after ET been applied. The enormous increase in baseband processing available in a smartphone, means digital pre-distortion is now a viable technique. It’s even being applied in WLAN chipsets.

As shown in figure 17, the results can be staggeringly good on a one-off basis. The IQ modulation bandwidth available in the phone transceiver, component variations and IQ impairments will ultimately limit what can be achieved. Either phase only or combined amplitude and phase corrections may be applied.

In this example, both AM/AM and AM/PM errors were corrected, using an application to provide a complete closed loop function. IQ data from an X series signal analyzer, processed with 89600 VSA, was used to pre-distort the IQ data in the LTE Signal Studio waveform generation & control software.

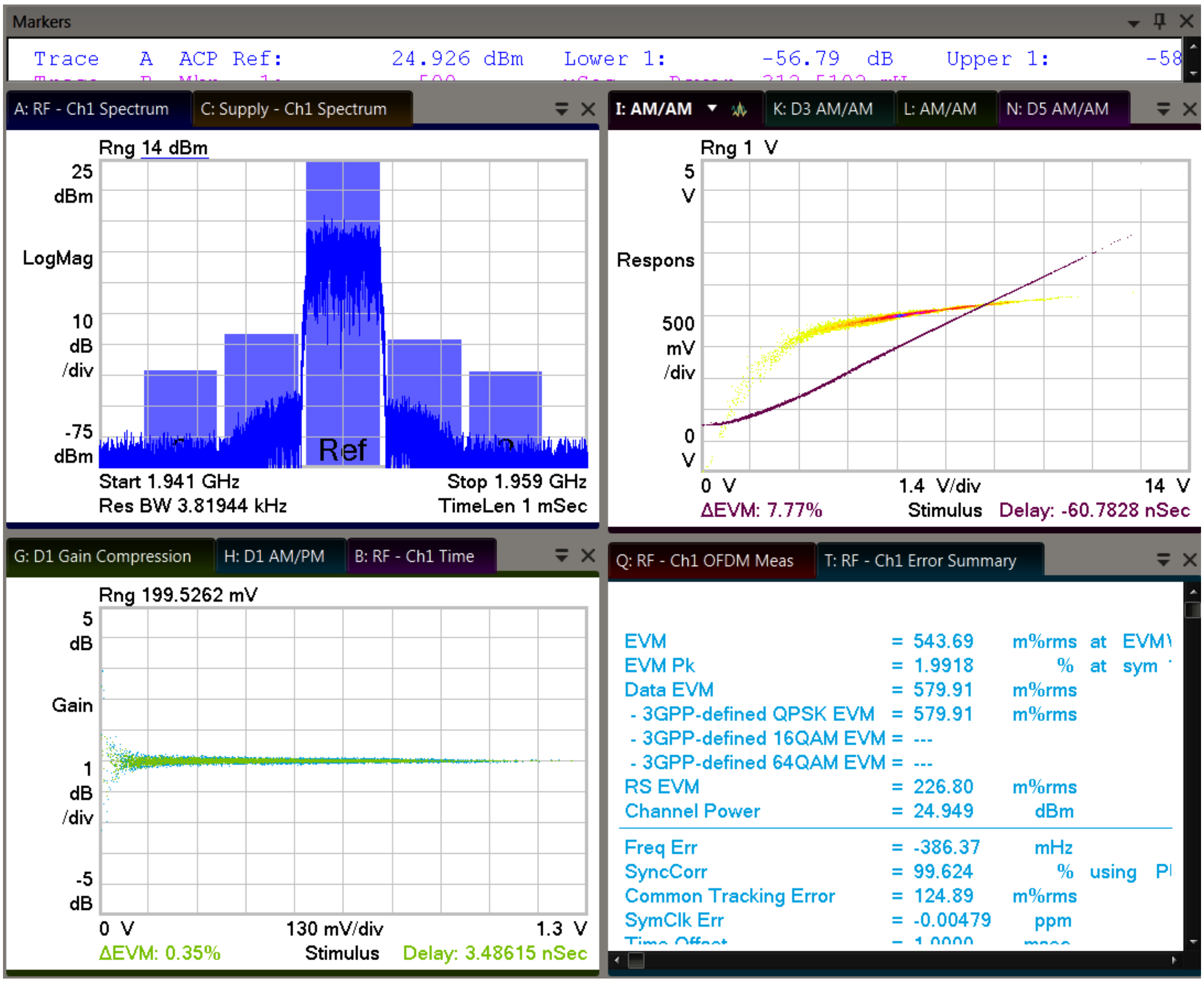


Figure 17: Astonishing spot performance can be achieved combining ET and DPD

Conclusion

The commercial availability of high performance envelope tracking power supplies, and modified RF PAs to go with them, is opening up new possibilities in the on-going trade-offs made by the designer of a smartphone transmitter system. The potential will no doubt appeal to other technologies with signals having high PAPR.

This paper has shown how the "third" component, the shaping table, has a marked effect on the operation of the system. It has also shown how standard equipment, with updated generation and analysis applications, provides a way for developers to explore and assess the use of ET & DPD.