Exploration of Power Amplifier Performance Using A Digital Demodulation Loadpull Measurement Procedure

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***Abstract*— In this paper, an innovative digital demodulation loadpull system setup for power amplifiers and transistors is introduced. It enables the designers to evaluate the system linearity metrics, e.g. error vector magnitude (EVM), of the device-under-test (DUT) performance under different source, load impedances and input power levels. An interesting observation is that the source tuning has more influence on the EVM performance than the load tuning does for the DUT used in this study. Using this new measurement, the designers can have a better understanding of the device performance with respect to system metrics and optimize their designs to them directly, instead of resorting to the traditional analog RF nonlinear metrics only.**

I. INTRODUCTION

Loadpull measurement has been widely used in characterization of devices and components. It provides valuable insight about the device performance under different source / load conditions and different power levels. This is very important information for power amplifier designers. Traditional loadpull measurements include one-tone and two-tone measurements, generating measured datasets for gain compression, 3rd intercept point (IP3), power added efficiency (PAE) and adjacent channel power ratio (ACPR). A thermal imaging loadpull measurement has also been described in [1].

However, with the advanced development in the baseband algorithms as well as the more and more complex modulation techniques, the traditional metrics like P1dB and IP3 obtained through one-tone or two-tone stimuli cannot predict the system performance, simply because these kind of stimuli don't reflect the realistic complex modulated RF signals. On the other hand, the performance of a transistor is closely related to the stimulus signal [2]. Therefore, it is vital to study the transistor using realistic modulated RF signals to get a better understanding of the transistor performance.

In this paper, we introduce an innovative digital demodulation loadpull measurement procedure which directly characterizes system performance of a power transistor (or amplifier) under various test conditions, together with the traditional nonlinear metrics, e.g. AM-AM, AM-PM and intermodulation distortion (IMD). The key parameter under study in this paper is the error vector magnitude (EVM).

II. DEFINITION AND MEASUREMENT OF EVM

EVM is a metric that quantifies the quality of digital modulated signals. It is defined as the magnitude of the phasor differences between an ideal reference signal and the measured transmitted signal after it has been compensated in timing, amplitude, frequency, phase and dc offset [3]. It can be computed (1):

$$EVM_{RMS} = \sqrt{\frac{\sum_{i=1}^{N} |S_{ideal}(i) - S_{meas}(i))|^2}{\sum_{i=1}^{N} |S_{ideal}(i)|^2}} \tag{1}$$

where $S_{ideal}(i)$ and $S_{meas}(i)$ are the i^{th} normalized ideal complex reference constellation point and the measured symbol respectively [4]. Because it changes continuously during every symbol transition, EVM is defined as the root-mean-square (RMS) value of the error vector over time.

Some studies have already been reported to successfully predict the EVM based on one-tone [5] [6] [7] or two-tone distortion [8] of power amplifiers. However, most of the work deal either with matched 50 ohm condition or provides only the simulation results with respect to the load tuning. This new measurement procedure, as demonstrated in the following sections, provides a much more realistic and complete view of the performance of the DUT, including both power and source/load impacts.

Before proceeding to the discussion of the EVM loadpull measurement, let's review how a typical EVM measurement is done. Fig. 1 illustrates the measurement diagram [9]. The input RF signal is first down-converted to the low intermediate frequency (IF) so that the ADC can sample it adequately and down-convert it to baseband for further processing. The LO is not directly phase-locked to the incoming signal (unlike the VNA ratio measurement), therefore, it will introduce some frequency offset. The frequency offset will be translated into phase rotation in time domain and can be estimated and compensated through digital processing algorithm.

In fact, the frequency offset is one of the measurement capabilities of a VSA.

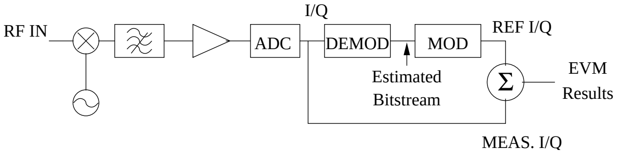

Fig. 1: EVM measurement diagram.

Based on the sampled data stream, the ideal constellation points are recovered by first demodulating the incoming stream and then re-modulating the obtained digits. The RMS EVM is computed through averaging all the frames used in the measurement. To make the RMS EVM accurate, a large number of frames are required, e.g. 802.11a WLAN specification [10] requires at least 20 frames.

III. MEASUREMENT SYSTEM AND CALIBRATION CONSIDERATION

The EVM loadpull measurement system is developed based on the Automatic Tuner System (ATS) from Maury Microwave and the 89610A Vector Signal Analyzer (VSA) from Agilent Technologies. Fig. 2 shows the integrated system setup. The ATS controls all the instruments in the measurement system and coordinates the measurement procedure. The digital demodulation measurement is performed by the VSA. An in-house program is developed to access the VSA measurement results through the common object model (COM) API interface. The program can automatically adjust the input range setup for the VSA so that the input signal can be sampled and evaluated at proper levels to obtain the optimal measurement results. The RMS EVM is averaged over several readings and then collected by the program and ported to ATS for contour analysis.

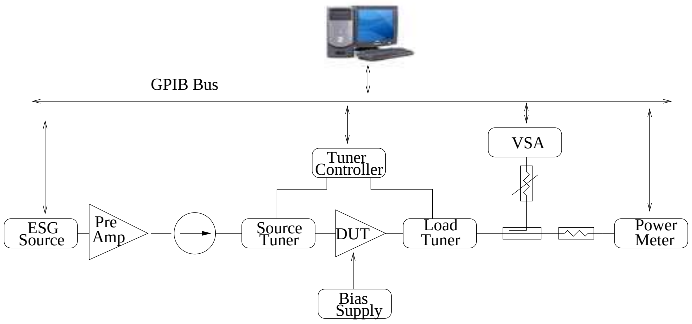

Fig. 2: Illustration of the digital demodulation loadpull measurement system.

As the digitally modulated RF signal passes through the measurement system, some errors will be introduced, mainly due to the distortion effects of the driver amplifier preceding the DUT and the down-converter. The system EVM (acting as the EVM noise floor for the measurement system) should be calibrated before performing further measurements. A simple calibration procedure was designed:

1) The THRU is used to connect the source and load tuners; the EVM associated with this setup is measured thereafter. The obtained EVM quantifies the distortion caused by the measurement system.
2) Once the residual EVM is obtained, the DUT can be plugged into the system for measurements. The extra degradation in the EVM will be treated as contributed by the PA only.

Fig. 3 compares the system EVM and that associated with the DUT. The difference is considered to be the EVM caused by the DUT. This calibration procedure is based on the assumption that the system distortion (error) adds linearly and in-phase with the DUT distortion. Therefore we can treat the difference of the EVM as the contribution from the DUT only. More work needs to be done to improve the calibration or consider alternative approaches in the future. The ACPR measurements of the system and DUT are also given out in Fig. 4, as an analog measurement reference to Fig. 3. It shows that the driver amplifier introduces detectable distortion in the mid and higher power range; more linear component is needed to mitigate this effect and give better calibration.

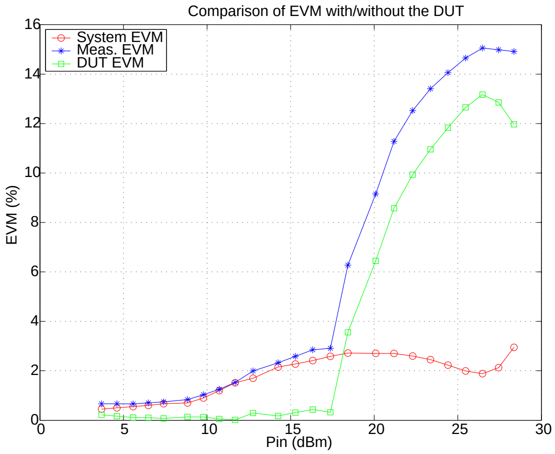

Fig. 3: Comparison of the system EVM and measured EVM of the DUT.

One issue concerning the calibration is the setup of attenuator used between the coupler and the VSA. The value of the attenuator should be selected so that the EVM readouts from the VSA are minimal under certain input power conditions. If the attenuation is too high, the VSA won’t be able to sample the incoming signal adequately due to the low power level; if the attenuation

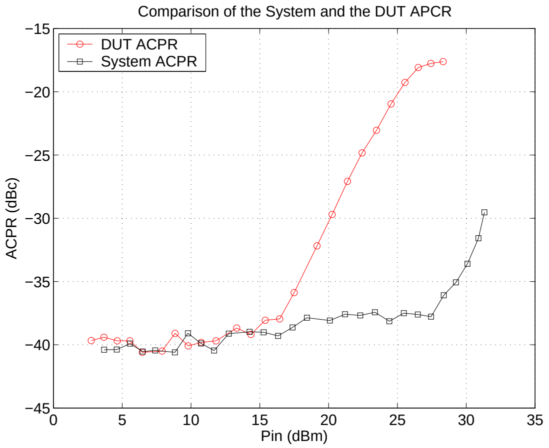

Fig. 4: Comparison of the system ACPR and measured ACPR of the DUT.

is too low, the signal might compress the down-converter or the ADC, causing inaccurate high EVM. Therefore, it is better to have a step attenuator and adjust the attenuation for different power ranges, which is how the system EVM was obtained as shown in Figure 3.

IV. DISCUSSION OF EXAMPLE DUT MEASUREMENTS

An L-band high power GaAs FET was studied to test the measurement procedure. The typical output power at 1dB compression point is 40 dBm with a gain of 10 dB. The PAE is around 40%. Fig. 5 shows the transducer gain (GT) and AM-PM variation vs. different load impedances with the source set at the conjugate matching point. The drain voltage is set at 10 volts for this measurement.

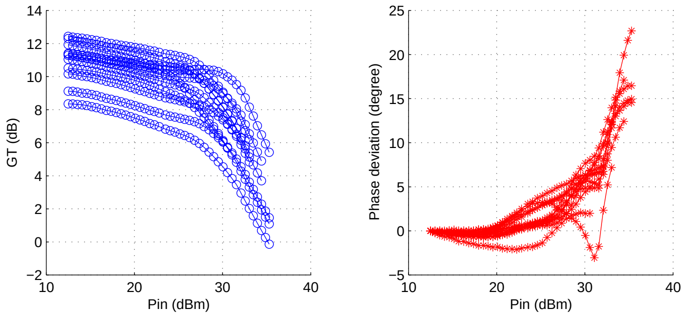

Fig. 5: Transducer gain and AMPM variation vs. load impedances.

The FET was studied at 2.14 GHz using an OFDM modulated signal to explore its capability to handle multi-carrier signals which have high peak-to-average power ratio (PAPR). High PAPR signals pose high requirements on the linearity of the power amplifiers. Great care has to be taken to get a good EVM performance. Fig. 6 compares the transducer gain (GT) and EVM performance in an example sourcepull measurement. The load is set at conjugate match and the input power is set at 22 dBm. Similar comparison is shown in Fig. 7 for a loadpull measurement. In both case, the test signal was a 64 carrier OFDM modulated signal.

Typically, the goal of the source tuning is to get the best gain out of the DUT, while the load tuning optimizes the total output power. If a multi-carrier signal passes through the DUT with high gain, the chance is much higher for the peaks of the signal getting distorted due to the limited power handling capability of the DUT.

On the other hand, by tuning the load to obtain the maximal output power, the signal is allowed to swing to the largest extend, which preserves the fidelity of the signal to the best. Therefore, we might expect the EVM performance to degrade when the source impedance approaches the conjugate match, and better EVM performance for load impedance optimizing the output power. This point is demonstrated in Fig. 6 and Fig. 7.

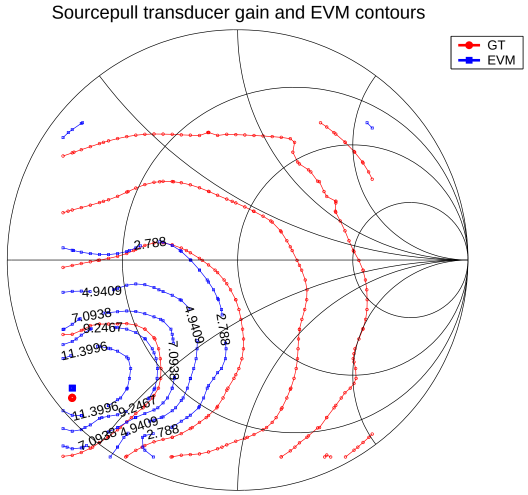

Fig. 6: Transducer gain and PAE contours for example sourcepull measurement.

Fig. 8 presents a better illustration of the source/load influence. Shown in the figure are two EVM surfaces.The lower surface is for the source pulling measurement. Comparing to Fig.6 and Fig. 7, one can see that the EVM degrades significantly around the high gain region on the source Smith chart.The EVM load contour is relatively smoother.

Fig. 9 shows an load tuning example to obtain the improved EVM. Two sets of swept power EVM measurements are compared. In one case, the load is tuned to obtain the optimum GT, while in the other case, the load is tuned for better EVM. The source is kept at conjugate matching point. The tuned EVM is about 2.5-3.5% better than the former case, with 0.5 dB loss of gain.

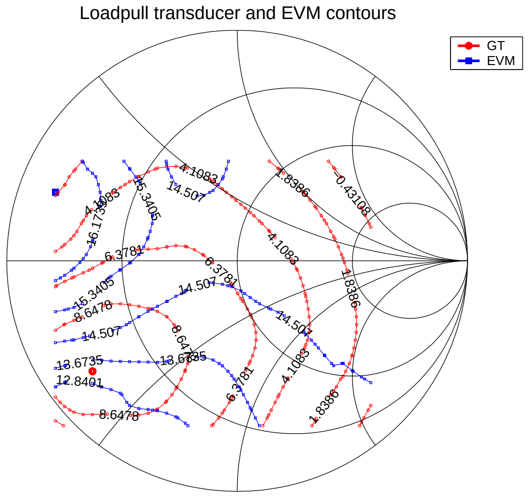

Fig. 7: Transducer gain and PAE contours for example loadpull measurement.

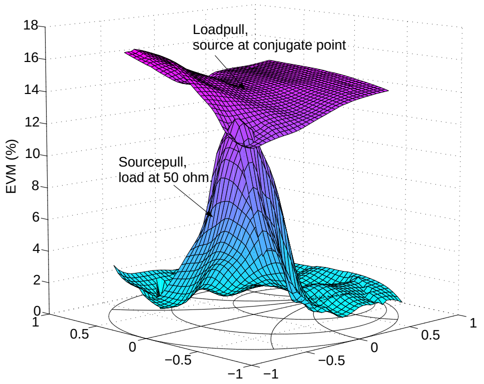

Fig. 8: Sourcepull / loadpull EVM measurements; Pin is set at 22 dBm.

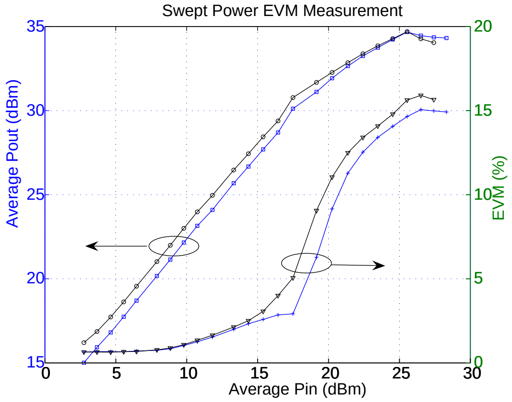

Fig. 9: Improvement of the EVM performance by tuning the load.

V. CONCLUSION

A new digital demodulation loadpull measurement procedure is introduced in this paper. A simple calibration procedure is given out to remove the system effect on the EVM. Example measurement results show that the source impedance has more influence on the EVM performance than the load impedance does. The designers might be able to use this information to improve their designs by combining the source and load tuning together to find the better performance with respect to the EVM. This practice also helps the designers communicate with system engineers using common metrics to come up with the system specification. To improve the current work, further theoretical study needs to be carried out to find a better vector calibration procedure for the system.

ACKNOWLEDGMENT

The authors would like to thank Modelithics,inc. and Cree, inc. for providing power amplifier and device samples for this study.

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