# A fully calibrated NVNA set-up for linearity characterization of RF power devices using Unequally Spaced Multi-Tone signal through IM3 & IM5 measurements

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***Abstract*—This paper presents an innovative experimental method and its associated test bench for assessing the in-band linearity degradation of radiofrequency and microwave power devices, suitable both for on-wafer and connectorized characterization. The Unequally Spaced Multi-Tone (USMT) signal is a tailored signal which presents flexible characteristics depending on the number of pilot tones (e.g. Peak to average radio, IQ enveloppe, and Radiofrequency bandwidth). It behaves like a complex modulation signal with particularity to have a complete separation of pilot tones, IM3 and IM5 and it was used for linearity measurements. The method has been used up to 28 MHz RF Bandwidth on a VNA with the spectrum option (PNA-L from Keysight Technologies).**

**The USMT set-up enables very fast measurements. In only one acquisition, simultaneous criteria are evaluated, like output power, gain, Power Added Efficiency (PAE), in-band degradation such as Carrier to Intermodulation ratio (C/I) induced by the device, by measuring the USMT signal at the input and output ports of the DUT. This novel approach has been validated through the linearity characterization of a commercial power amplifier.**

***Index Terms*—power amplifiers, Linearity, Measurement, Nonlinear devices, RF, NVNA**

## I. Introduction

Power amplifier (PA) block remains the most critical element of all radiofrequency (RF) telecommunications systems. For a while, PA and transistor can be well identified in terms of non linear distortion measurement (CW and two-tone intermodulation). Unfortunatelly, theses characterizations cannot predict the response to complex applicative signal such as OFDM or any others high dynamic and wideband signals. Due to datarate increase to follow 5G requirements, the bandwidth and frequency carrier will have to increase. In order to follow this evolution, several kind of modulated sources have been developped to measure different criteria such as Noise power ratio (NPR) or Error Vector Magnitude (EVM) in order to quantify the in-band signal to noise degradation. Since EVM remains the universal standard to quantify a non-linearity degradation, researches are focused on the development of a generic test signal that is agnostic from any standard.

Several methods exist to assess the in-band linearity degradation with the use of equally spaced injected multi-tone [1] [2] [3]. However, these methods have two drawbacks due to the choice of equally-spaced pilot frequencies. Since the intermodulation products (IM) and pilot tones overlap, the first difficulty is to accurately measure the IM amplitude when they are covering another IM or pilot tone. Similarly, the second issue is the IM phase dependency. These IM phases hugely impact the in-band linearity. Therefore, it is necessary to test numerous of pilot tones random phases in order to integrally measure the linearity degradation.

Unequally Spaced Multi-Tone (USMT) stimulus test signal overcomes these 2 main issues by splitting the signal and the intermodulation noise [4]. Furthermore, the USMT signal makes quasi real-time measurements. This work is an extension of [5] [6], and offers a new tool to measure in-band degradation with a complete separation of IM3 and IM5. It has been implemented in the PNA-L VNA from Keysight Technologies with a full calibration.

This paper is organized as follow: section II deepens the USMT principle for the signal generation and the mathematical part is described. Section III describes the signal property of the USMT. Section IV develops the set-up that is used to measure the in-band signal to noise ratio, and the calibration protocol to get absolute power measurements. Finally the section V presents measurements performed for different bandwidths of USMT signal on a commercial power amplifier.

## II. Signal description

For the whole paper, pilot tones refers to the tones generated by the signal generator. The generic form signal generation [7] of the multi-tone signal is given in (1) and shown in Fig.1:

$$f_k = f_1 + (k-1) \times \Delta f + \epsilon_k \text{ with } (1 \leq k \leq N) \quad (1)$$

The integer $N$ refers to the number of pilot tones. The term $f_k$ represents the frequency of each pilot tone where k is the rank of each frequency. The parameter $\Delta$f refers to minimum frequency spacing and $\epsilon_k$ the frequency shift, between two pilot tones, in order to unequally space them.
All the tones must be chosen on a Digital Fourier Transform (DFT) frequency grid, with a resolution of $f_\epsilon$ and covers the entire period $T_\epsilon = 1/f_\epsilon$ to be measured by the receiver. The frequency bandwidth, defined as the gap between the first and last pilot tones, is given by $BW$ = $f_N$ - $f_1$ and the frame duration lasts exactly $T_\epsilon$.

The expression statement (1) is uploaded in the signal generator as (2):

$$f_k = [l + (k-1) \times m + p_{[k]}] \times f_\epsilon \text{ with } (1 \leq k \leq N) \quad (2)$$

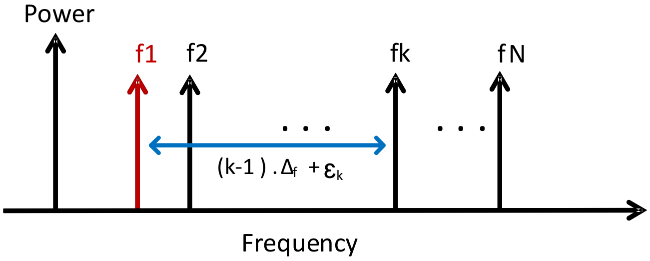


Fig. 1: Spectrum of the USMT signal.

Then all parameters of (1) can be expressed in function of $f_\epsilon$:

$$f_1 = l \times f_\epsilon \tag{3}$$

$$\Delta f = m \times f_\epsilon \tag{4}$$

$$\epsilon_k = p_k \times f_\epsilon \tag{5}$$

Where $l$, $k$, $m$, $p_k$ are integers. The shifting vector $p_k$ is chosen to avoid any overlap between IM3, IM5 and pilot tones as in (6)

$$p_{[k]} = \begin{cases} 0 & \text{for} \quad k = 1 \\ 1 & \text{for} \quad k = 2 \\ 3^{k-2} & \text{for} \quad 3 \leq k < N \end{cases} \tag{6}$$

In the vector $p_k$, power of 3 shows better overlap avoidance that any other even power. The carrier to intermodulation ratio are computed only with the in-band (IB) IM, i.e. between the first and the last tone of the USMT signal as:

$$\frac{C}{IM3_{IB}}(dB) = 10 \times \log 10(\frac{P_{pilottones}}{P_{IM3_{IB}}}) \tag{7}$$

$$\frac{C}{IM5_{IB}}(dB) = 10 \times \log 10(\frac{P_{pilottones}}{P_{IM5_{IB}}}) \tag{8}$$

## III. Study of Signal Properties

The key property of the USMT signal is to avoid overlaps between IM3, IM3 themselves and pilot tones. In this section, the IM5 overlap conditions will be discussed, in order to measure more in-depth the C/I. The tones number is fixed to 8. $f_\epsilon$ is fixed to 1kHz. The $p_k$ vector is [0; 1; 3; 9; 27; 81; 243; 729] and l is fixed to 4000. The IM5 overlap can be controlled by the $\Delta_f$ variation, by means of m variation (4), which produces a RF bandwidth variations.

A numerical simulation has been implemented to illustrate the distortion produced by the 8-tones signal passing through an amplifier which AM/AM characteristics is modeled by a Rapp's model [8]. The result of this simulation is shown in Fig.2 for a RF bandwidth of 2 MHz and in Fig.3 for a RF bandwidth of 28 MHz. These figures illustrate the different intermodulation products: third order (IM3) and fifth order (IM5) around the 8 pilot tones.

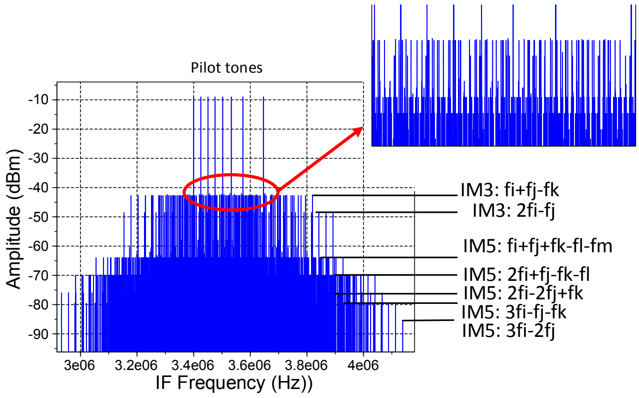


Fig. 2: Spectrum of the output signal obtained for the shifting vector $p_k$=[0; 1; 3; 9; 27; 81; 243; 729] and $f_\epsilon$ = 1kHz, Recordsize of 100k points, RF Bandwidth of 2 MHz.

The figure 3 shows sparse spectrum whereas figure 2 displays the dense spectrum of intermodulation products. This effect is due to the choice of $f_\epsilon$ (1kHz) as the regard of the RF bandwidth (28MHz) for the sparse spectrum. This property of the USMT signal shows, that the choice of the parameter $f_\epsilon$ and RF bandwidth, assuming the other values constant, can product either sparse of dense output intermodulation products spectrum. This modification is not affecting in any way the statistical property (Complementary Cumulative Distribution Function (CCDF), IQ probability density function,...) of the USMT signal.

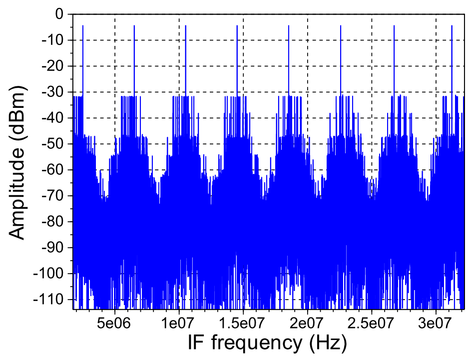


Fig. 3: Spectrum of the output signal obtained for the shifting vector $p_k$=[0; 1; 3; 9; 27; 81; 243; 729] and $f_\epsilon$ = 1kHz, Recordsize of 100k points, RF Bandwidth of 28 MHz.

In Fig.4, we present the IM5 overlap in (%) in function of the RF bandwidth. Obviously when the RF bandwidth increases the overlap decreases. For a RF Bandwidth greater than 7.7 MHz, the pilot tones, IM3 and IM5 overlaps turn off.

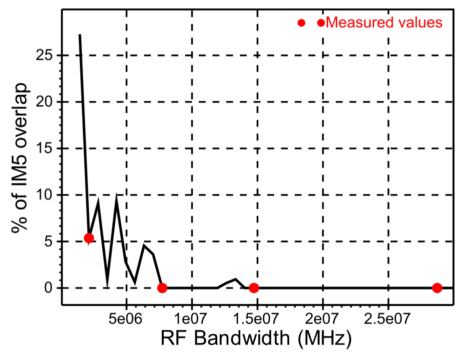


Fig. 4: Number of IM5 that overlap for $p_k$ vector [0; 1; 3; 9; 27; 81; 243; 729].

## IV. USMT SET-UP DESCRIPTION

The set-up has been done with several commercial instruments gathered in Fig.5. The RF Arbitrary Waveform Generator (MXG N5182B) from Keysight Technologies 9 kHz-6 GHz delivers the USMT test signal, previously loaded in memory, with 8-tone for a maximum of 160 MHz bandwidth. A RF passive load tuner iCCMT-5020 from Focus Microwave is available to sweep the impedance at the output of the device under test (DUT). A Vector Network Analyzer (PNA-L) from Keysight Technologies with spectrum analyzer option, is used as 4-port mixer-based receiver. This receiver has a typical dynamic range of 100 dB and an IF maximum bandwidth of 38 MHz.

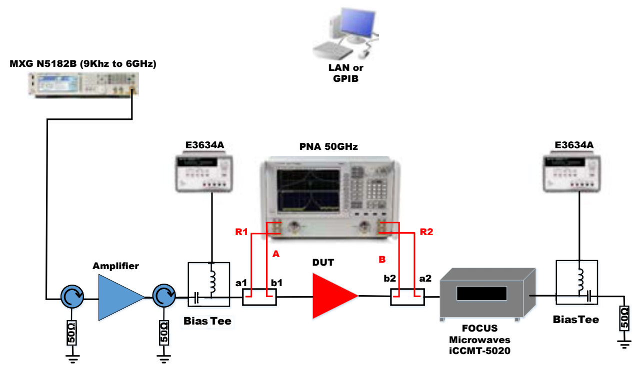


Fig. 5: Mixer-based receiver test set-up.

A SOLR (Short Open Load Reciprocal) relative calibration has been applied to the receiver. This calibration, described in [9] assumes that the "thru" connexion is performed with an unknown reciprocal device. An absolute calibration has been done in power and phase to get a full calibrated receiver. All the instruments are remotely controlled using the free software Scilab.

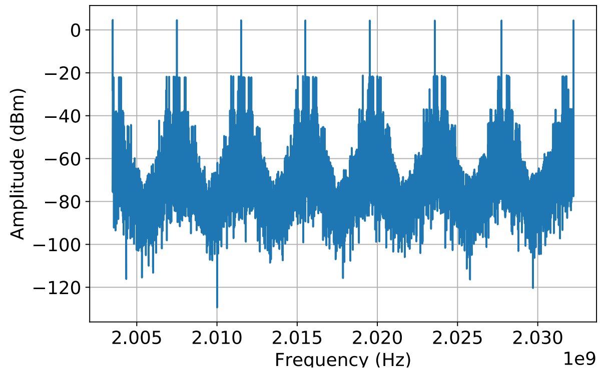


Fig. 6: Measurement with the PNA-L for a Pout average of 29 dBm.

## V. USMT MEASUREMENTS RESULT

Measurements are performed on a commercially available connectorized power amplifier Qorvo TQP9111.

USMT measurements have been performed with a load impedance of 50 ohm. The signal has been generated with the $p_k$ vector [0,1,3,9,27,81,243,729] and a frequency resolution $f_\epsilon$ has been chosen to be 1 kHz. An example of 28 MHz wide signal measured after the PA is shown in Fig.6. The receiver has been configured with a recordsize of 100 kpoints and an ADC frequency of 100 MHz.

From the USMT large signal measurements for different values of RF Bandwidth, the AM/AM conversion of the power amplifier is plotted in Fig.7, by computing the average power (mean power of pilot tones) at the input and output ports of the DUT. The first value of the RF bandwidth (2 MHz) is the first to reach the compression, followed by the 7.7 MHz RF bandwidths, and it seems that the two other RF Bandwidth (14 and 28 MHz) attain the compression at the same input power level.

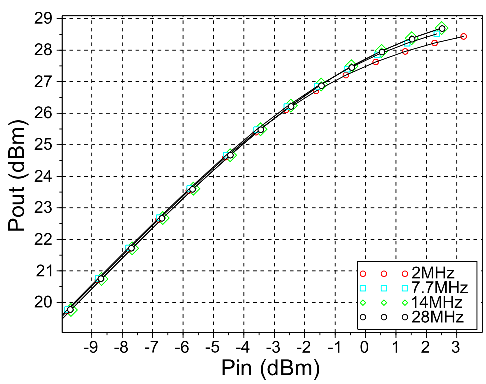


Fig. 7: AM/AM measured with 8 pilot tones USMT signal for different RF bandwidths.

Linearity measurements have been performed for the same 4 RF bandwidth values between 2 MHz and 28 MHz as shown in Fig.4 to quantify its impact on the linearity Fig.8, ensuring a minimum in terms of IM5 overlap. Further investigations will be performed to assess if these discrepancies are related to memory effects.

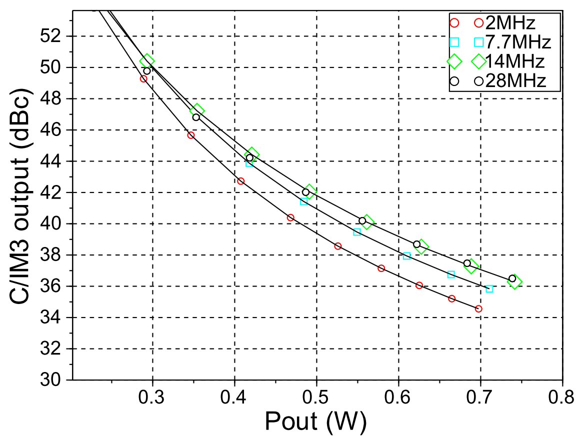


Fig. 8: Measurements done with the PNA-L for a Pout average of 29dBm.

As defined in (8), the linearity is assessed by calculating the $\frac{C}{IM3_{IB}}$ intermodulation ratio between the pilot tones power and the in-band intermodulation products power [10]. Comparing the input and output of the DUT makes possible to deduce the degradation introduced by it.

The in-band degradation is plotted for the two main intermodulation products for 28 MHz of RF bandwidth: IM3 and IM5 in Fig.9

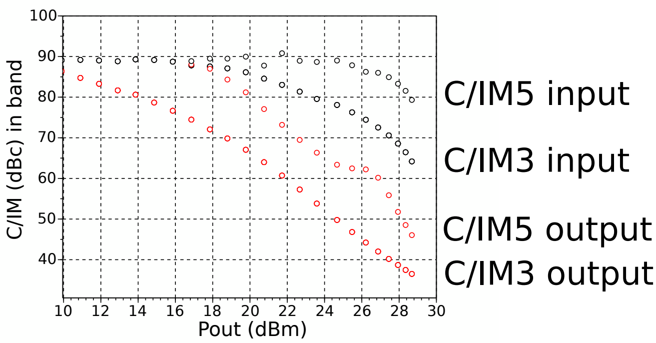


Fig. 9: Comparison of C/IM3 and C/IM5 for a RF bandwidth of 28 MHz .

## VI. Conclusion

This paper proposes a method to generate a modulated RF signal which allows to distinguish IM products of order 3 and 5. Those products can be accurately measured using a fully calibrated four ports receiver. The choice of bandwidth and frequency resolution of the signal allows to obtain dense or sparse spectra without changing the statistical properties of the signal. The USMT test signal combined with a network stimulus-response spectrum analyzer measurement system provides a great flexibility for an in-depth analysis of nonlinear phenomena exhibited by nonlinear devices and circuits.

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