Broadband error vector magnitude characterization of a GaN power amplifier using a vector network analyzer

Published Version:
Angelotti A.M., Gibiino G.P., Florian C., Santarelli A. (2020). Broadband error vector magnitude characterization of a GaN power amplifier using a vector network analyzer. Institute of Electrical and Electronics Engineers Inc. [10.1109/IMS30576.2020.9223771].

Availability:
This version is available at: https://hdl.handle.net/11585/805704 since: 2024-02-29

Published:
DOI: http://doi.org/10.1109/IMS30576.2020.9223771

Broadband Error Vector Magnitude Characterization of a GaN Power Amplifier using a Vector Network Analyzer

Alberto Maria Angelotti[1#], Gian Piero Gibiino[1], Corrado Florian[1], Alberto Santarelli[1]
[1]Department of Electrical, Electronic, and Information Engineering (DEI) ”Guglielmo Marconi,”
University of Bologna, 40136 Bologna, Italy
[#]alberto.angelotti@unibo.it

Abstract— **This work investigates the impact of nonlinear dynamic effects due to charge trapping and other long-memory phenomena on the wideband linearity of power amplifiers (PAs) for 5G communications applications. The proposed method uses the well-known best linear approximation framework (BLA) to estimate the error vector magnitude (EVM) of the amplifier for the class of modulated signals sharing the same probability density function (pdf) and power spectral density (PSD) as the 5G waveform standards. The dependency of the EVM and the BLA on the large-signal operating point (LSOP) of the PA is studied using random phase multisine signals belonging to the same class. In particular, we evaluate the impact of different signal repetition periods in order to excite low-frequency dynamic phenomena across a wide range of time scales. Results, using just standard vector network analyzer (VNA) relative measurements, are reported for a Gallium Nitride (GaN) power amplifier (PA) for two different 5G-FR1-compliant bandwidths of 20 and 100 MHz around 5.5 GHz.**

Keywords— **5G, Error Vector Magnitude, Broadband characterization, Gallium nitride, Memory effects**

I. INTRODUCTION

Modern 5G telecommunication radio-frequency (RF) systems foresee the usage of broadband-modulated signals for delivering high-data-rate connections. Hence, suitable testing procedures for quantifying the signal distortion are necessary at both the design level and at the RF system deployment stage. The most widely adopted metric for this purpose is the error vector magnitude (EVM), defined as [1]:

$$\text{EVM } (\%) = \sqrt{\frac{\sum_{n=1}^{N} |S_j - S_n^r|^2}{\sum_{n=1}^{N} |S_n|^2}} \qquad (1)$$

where S_n^r is the n-th received modulation symbol, S_n is the corresponding symbol in the ideal modulation constellation, and N are the symbols considered. In a standard EVM characterization setup based on a Vector Signal Analyzer (VSA), the receiver can automatically recover the signal constellation. Then, the EVM in (1) can be mathematically calculated between the received and equalized modulated signal (S_n^r) and the reference ideal constellation (S_j). Since this procedure requires IQ demodulation, the VSA must feature sufficient instantaneous bandwidth (BW) with respect to the modulation in use. With the advent of 5G, the instantaneous BW requirement is up to 100 MHz for frequency range FR1 and up to 400 MHz for FR2 for a single channel [2]. These specifications not only involve the use of state-of-the-art VSA technology, but will necessarily pose a problematic limitation to the receiver dynamic range as the BW to be measured increases, especially for multi-channel EVM characterization over GHz-wide instantaneous BWs.

In order to overcome these limitations, various techniques have been proposed in order to characterize the EVM from the received RF waveform, without IQ demodulation [3] [4], [5]. The methods exploit the use of custom periodic multisine test signals, derived from the parent 5G standard test waveforms to improve measurement speed, accuracy and ease hardware requirements.

Indeed, the main advantage of these methods consist of removing the need for broadband instantaneous BW, given that a single phase-coherent acquisition is not necessary due to their repetitive nature. Instead they can rely on narrowband acquisitions of mixer-based receivers, such as the ones found in Vector Network Analyzers (VNA). Therefore, they enable EVM characterization across the full BW of the RF test-set, which can easily cover several GHz.

Considering the RF transmitter, the power amplifier (PA) is usually the main cause of nonlinear distortion, so it is interesting to evaluate the impact of the prospected PA solutions on the EVM degradation. For the bandwidth requested by 5G base stations, the most promising technology for PAs is Gallium Nitride (GaN), whose properties allow for the highest-available RF power densities at the highest frequencies. At the same time, it is well-known that GaN technology features the presence of charge-trapping dynamic effects with time constants in the order of less than a μs up to tens of ms [6],[7], falling across a similar range with respect to the 5G frame duration (10 ms) and sub-carrier spacing (down to 15 kHz). More in detail, GaN trapping is proportional the dynamic voltage swings applied to the device, so that the maximum trapping corresponds to the RF peak power dynamically reached by the modulated signal, while trapped charges are released during lower power levels. These phenomena combine with others, due to self-heating and parasitic supply-modulation, in the same time-constant range to determine a complex long-term memory behaviour that affects device and PA performance.

In this work, we apply demodulation-free EVM characterization methods to an RF power amplifier based on a 250-nm GaN-on-SiC technology by UMS. Due to GaN nonlinear dynamics, each given test signal featuring a specific envelope trajectory over time for a certain average power and peak-to-average power ratio (PAPR), will enforce a particular large-signal operating regime. Therefore, we investigate the choice of different test signals in order to assess their implications on the EVM estimation in the specific case of GaN for 5G FR1, showing results for a comprehensive set of RF input powers, signal periods, and BW values.

II. VNA-BASED BROADBAND EVM ESTIMATION

The 5G documentation in [2] defines suitable models for EVM measurements, which can be generated for each possible modulation configuration. These test signals, for the frequency-domain-duplexing case used in the FR1 range, are 10-ms-long (i.e., one frame) OFDM-modulated pseudo-random data sequences that approximate a fully aperiodic stochastic process. In the case of a large number of active subcarriers [2], thanks to the central limit theorem, these signals display asymptotically a circular-complex gaussian probability density function (pdf) with a bandlimited white power spectral density (PSD).

In this respect, their statistical characteristics can be closely replicated by a variety of periodic waveforms: such as compact test signals [4], random [5] or full grid random-phase multitones [8]. The use of periodic waveforms matching a given standard-imposed pdf and PSD allows for the use of a variety of techniques that exploit their repetitive nature to improve characterization performance and convenience [4], [3].

For any input A_1 in the aforementioned class of signals with a standard-like pdf and PSD, the output spectrum B_2 can be written at each frequency as [8]:

$$B_2(f) = G_{BLA}(f)A_1(f) + D(f) + N(f). \tag{2}$$

G_{BLA} is the least-square best approximation of a linear dynamic gain of the system across all the excitations in the same equivalence class. $D(f)$, a zero-mean noise contribution with variance $\sigma_D^2(f)$, quantifies the input-uncorrelated nonlinear stochastic distortions, while $N(f)$, with variance $\sigma_N^2(f)$, represents additive measurement noise.

Equation (2) closely mimics the operation of a typical radio receiver, where the equalizer adaptively estimates a frequency response function to compensate for the channel and transmission chain equivalent linear distortion [3], [2]. As such, EVM, as a purely nonlinear distortion metric, should not take into account these linear components.

In compliance with standard definitions [2], EVM can then be measured as the ratio between purely nonlinear distortion power (i.e., the output signal power minus the linearly input-correlated power) and input-correlated signal power across the excitation bandwidth [5]:

$$EVM = \sqrt{\frac{\int_{BW} \sigma_D^2(f)df}{\int_{BW} |G_{BLA}(f)|^2 S_{A_1A_1}(f)df}} \tag{3}$$

where $S_{A_1A_1}(f)$ and $S_{B_2B_2}(f)$ are the input and output PSD respectively.

Several techniques have been proposed to separate the components in (2) and estimate EVM without the explicit use of IQ demodulation hardware. Different approaches typically display different tradeoffs between accuracy and total measurement time and can be best suited in different application cases [4], [8].

In this work, we adopt the so-called robust approach described in [8]. The DUT is excited using a random-phase flat-amplitude multisine with the same bandwidth as the communication standard of interest. Input and output spectra are measured using a power-calibrated VNA for P periods of M different phase realizations of the same signal. For the p-th period of the m-th phase realization, the following frequency response function (FRF) is computed at each excited frequency f_k of the multitone:

$$G_{BLA}^{[m,p]}(f_k) = \frac{B_2(f_k)^{[m,p]}}{A_1(f_k)^{[m,p]}}; \quad m = 1 \ldots M; \quad p = 1 \ldots P. \tag{4}$$

Averages of (4) across the P periods provide an estimation of the noise variance $\sigma_{BLA,n}^2(f_k)$, while averages across the M realizations can be used to quantify the distortion power $\sigma_{G_S}^2(f_k)$ and the overall $G_{BLA}(f_k)$ [8]. These quantities, together with input-output measured PSDs, can then be used to compute the quantities needed for the EVM measurement (3). In the periodic multitone case, the integration simplifies to a sum on the excited frequencies.

Fig. 1a shows an example of the method applied to a GaN PA (see Sec.III), reporting input and output spectra together with the estimated distortion component, for $P = 2$ periods and $M = 25$ phase realizations. The measured G_{BLA} together with its nonlinear stochastic and noise variance components is shown in Fig. 1b.

In general both G_{BLA} and $\sigma_D^2(f)$ depend on the large signal operating point (LSOP) of the device and have to be re-estimated accounting for its variations using the previously outlined procedure. While the dependence on the input RMS power has been studied [5] in order to generate EVM tradeoff curves, to the best of the autors' knowledge there has been no attempt in evaluating the impact of the test-signal tone spacing on the BLA and EVM of a power amplifier. Indeed, it has been shown that LSOP critically depends on the periodicity of modulated excitations in presence of significant long-memory effects, such as supply modulation, self-heating or charge trapping in GaN [6], [9] PAs. In such cases, periodic multitone signals sharing the same asyntotic pdf and PSD but having different tone spacings may excite different dynamical effects in the DUT [9]. As such, this work proposes to use the previously introduced techniques to assess the impact of these long-memory effects on the EVM and BLA a GaN PA under realistic wideband modulated regimes.

III. GaN PA MEASUREMENTS

The setup used in this work (Fig. 2) is composed by a broadband Vector Signal Generator (VSG), Keysight N5182B MXG, a pre-amp (Mini-Circuits ZVE-3W-183+) for properly amplifying the a_1 input signal, and a VNA, Keysight N5242A PNA-X, which is calibrated by a classic short-open-load-thru

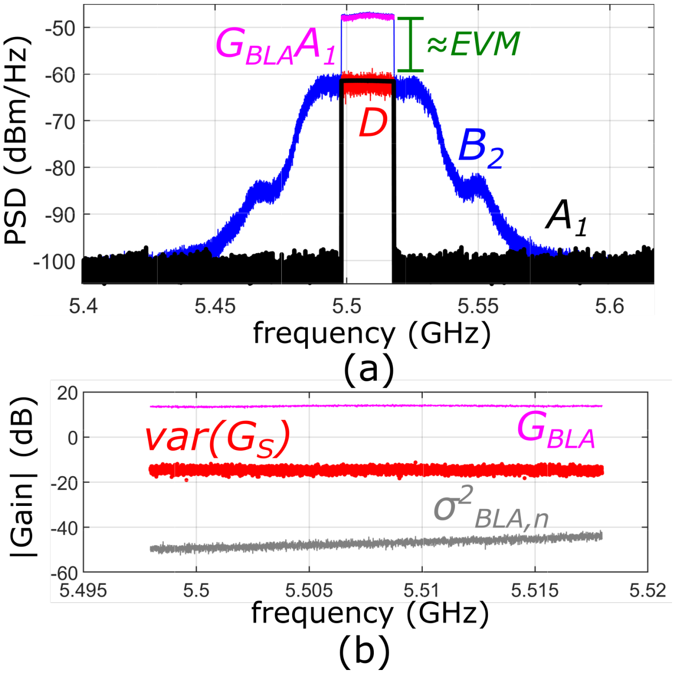

Fig. 1. a) Estimated input (black) and output (blue) power spectra for an input RMS power of 11.2 dBm in case of a 3 kHz-spaced 20-MHz-wide random phase multitone excitation. Two measurement periods and 25 phase realizations are used. The correlated output (magenta) and uncorrelated distortion (red) spectra used in the EVM computation are outlined. b) Estimated BLA gain for the amplifier (magenta), together with the noise variance (gray) and the variance of the stochastic nonlinear contributions (red).

relative calibration with connectorized standards. Also, a power calibration referenced to a power meter is employed to correctly measure the tone amplitudes. The maximum measured modulation bandwidth, centered at 5.5 GHz, is 200 MHz, corresponding to the maximum BW of the VSG. Nevertheless, there is no specific limitation on BW on the receiver side, up to the 10 MHz - 26.5 GHz range of the VNA test-set. The DUT is a monolithic microwave integrated circuit (MMIC), two-stage broadband PA in 250-nm GaN-on-SiC technology biased at $V_{DS} = 20$ V and $V_{GS} = -3.20$ V.

Figure 3 shows the EVM and RMS ouput power as a function of the input RMS power and tone spacing for the amplifier under exam. Two FR1 5G-compliant signal BWs of 20 and 100 MHz have been tested, with the wider bandwidth remarkably displaying a lower EVM and higher linearity for the same input power. Nevertheless, in both cases, EVM and output power seem to be negligibly affected by the a variation of the tone spacing from 3 KHz up to 150 kHz.

The dc current of GaN HEMTS is known to be particularly sensitive to trapping and dynamic-bias state variations [6] and is therefore a prime candidate to gain valuable information on the LSOP of the DUT. The dc current, averaged across all the periods and realizations of the input signal, is reported for each input power and tone spacing in Fig. 3. The two signal bandwidths again display remarkable differences in behaviour. The 20 MHz BW displays a relevant current collapse, which is a well known trap-induced signature [6]. Moreover, the collapse significantly depends on the tone spacing which again seems to point to the presence of long-memory effects in the PA. The effect is not observed for the wider excitation BW.

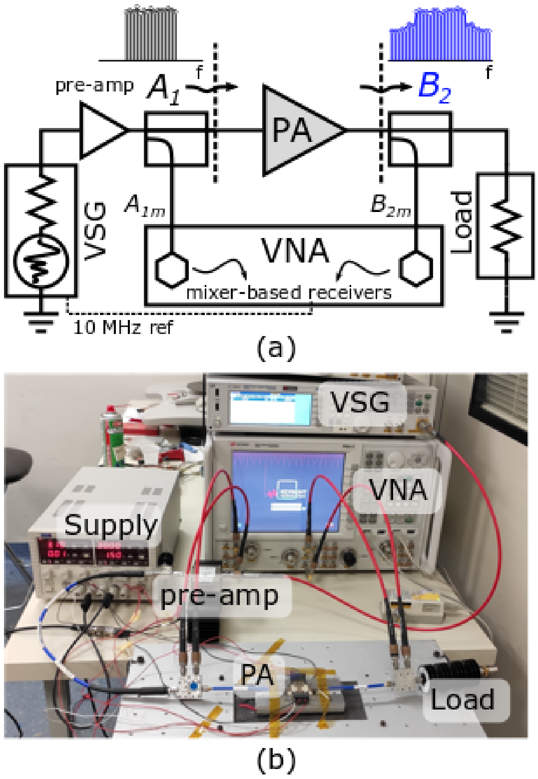

Fig. 2. (a) Block diagram of the VNA-based measurement setup. (b) Photo of the setup.

Figure 5 reports the measured BLA as a function of input power and tone spacings for the two examined bandwidths. The estimated $G_{BLA}(f)$ profile across frequency displays a marked shape variation across the input power levels and a significant difference between the two excitation bandwidths. Indeed, the BLA is a pdf-and-PSD-dependent combination [8] of both the small signal linear response (seen at low input power) with higher-order Volterra kernels, which are clearly relevant for the LSOPs under considerations. This points to a rich nonlinear dynamic behaviour for the PA, which cannot be described or efficiently linearized using widespread memory-polynomial or Wiener-Hammerstein models [10].

The variations of the BLA for different tone spacings is negligible in the 100 MHz case, while some measureable variations can be seen for the 20 MHz BW. This behaviour matches the one observed for the dc current, pointing to a possible common origin for both phenomena.

The reported results cannot rule out that more pronounced dependencies of the EVM/BLA on the tone spacings could arise if narrower spacings (i.e., longer memory effects) were considered for the proposed characterization. However, this possibility has to take into account that in typical receivers, a new equalization/BLA is computed for each 10 ms frame [2]. This means that if the DUT time constants are longer than the frame length, the trapping dynamic behaviour is seen at the

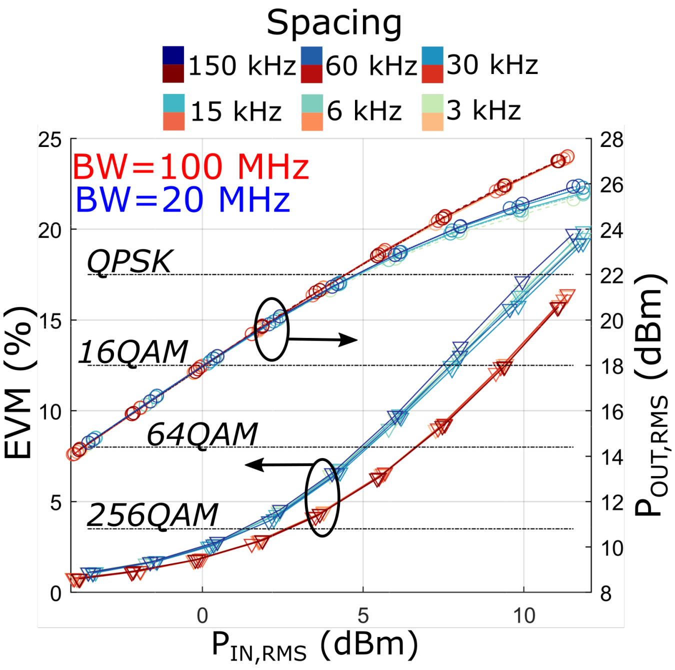

Fig. 3. EVM and output RMS power for the amplifier under test as a function of the input RMS power. Two different random phase multitone bandwidths (20 and 100 MHz) and six different tone spacings (3 kHz to 150 kHz) are reported. Reference EVM levels for different modulation formats as per 5G [2] specifications are superimposed.

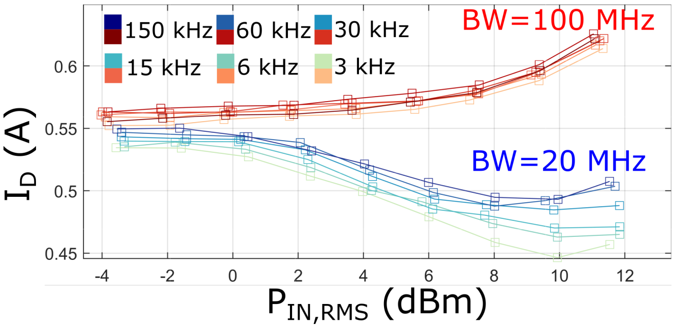

Fig. 4. Dc drain current for the amplifier under test as a function of the input RMS power. Two different random phase multitone bandwidths (20 and 100 MHz) and six different tone spacings (3 kHz to 150kHz) are reported.

receiver side as a long-term drift of the DUT response that can be compensated with an update of the equalizer coefficients. So, extremely slow (10 ms-s range) memory transients should not have a significant impact on the overall EVM in a realistic transmission-reception chain.

IV. CONCLUSION

A characterization method to evaluate the impact of long-memory dynamic phenomena on the wideband linearity of GaN PAs is proposed. For the PA under examination, EVM shows little dependence on the actual tone spacing of the multisine used in its evaluation, despite some indication, mainly from the dc current and the BLA gain, that a different LSOP is achieved. Results on the BLA profile still show a behaviour that strongly depends on the modulation bandwidth and input rms power, pointing to complex nonlinear dynamic behaviour to be accounted for during system level modeling and linearization. Further investigations are required in order to assess the actual impact of charge trapping and other memory effects on transmitter performance under different modulated conditions.

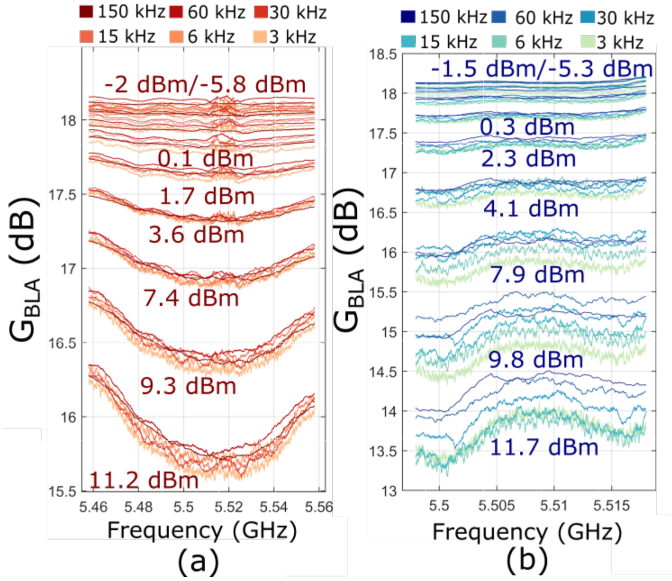

Fig. 5. Magnitude of the estimated best-linear approximation for the amplifier under test as a function of the input RMS power and tone spacing (3 kHz to 150kHz). Signal bandwidths of a) 100 MHz and b) 20 MHz are reported.

REFERENCES

[1] M. D. Mckinley, K. A. Remley, M. Myslinski, J. S. Kenney, and S. B. Nauwelaers, "EVM calculation for broadband modulated signals," in *ARFTG Microw. Meas. Conf. Dig., 2004*.

[2] *Technical Specification Group Radio Access Network 38.104, 38.141*, 3GPP, 9 2019.

[3] K. Freiberger, H. Enzinger, and C. Vogel, "SLIC EVM — error vector magnitude without demodulation," in *ARFTG Microw. Meas. Conf. Dig.*, June 2017, pp. 1–4.

[4] J. Verspecht, A. Stav, J. Teyssier, and S. Kusano, "Characterizing amplifier modulation distortion using a vector network analyzer," in *ARFTG Microw. Meas. Conf. Dig.*, June 2019, pp. 1–4.

[5] Y. Rolain, M. Zyari, E. Van Nechel, and G. Vandersteen, "A measurement-based error-vector-magnitude model to assess non linearity at the system level," in *IEEE MTT-S Int. Microw. Symp. Dig.*, June 2017, pp. 1429–1432.

[6] J. L. Gomes, L. C. Nunes, C. F. Gonçalves, and J. C. Pedro, "An accurate characterization of capture time constants in GaN HEMTs," *IEEE Trans. Microw. Theory Techn.*, vol. 67, no. 7, pp. 2465–2474, July 2019.

[7] G. P. Gibiino, A. M. Angelotti, A. Santarelli, and C. Florian, "Microwave characterization of trapping effects in 100-nm GaN-on-Si HEMT technology," *IEEE Microw. Wireless Compon. Lett.*, vol. 29, no. 9, pp. 604–606, Sep. 2019.

[8] R. Pintelon and J. Schoukens, *System Identification: A Frequency Domain Approach.* John Wiley and Sons, 2012.

[9] V. Gillet, M. Bouslama, J. Teyssier, M. Prigent, J. Nallatamby, and R. Quéré, "An unequally spaced multi-tone load–pull characterization technique for simultaneous linearity and efficiency assessment of rf power devices," *IEEE Transactions on Microwave Theory and Techniques*, vol. 67, no. 7, pp. 2505–2513, July 2019.

[10] D. R. Morgan, Z. Ma, J. Kim, M. G. Zierdt, and J. Pastalan, "A generalized memory polynomial model for digital predistortion of rf power amplifiers," *IEEE Transactions on Signal Processing*, vol. 54, no. 10, pp. 3852–3860, Oct 2006.