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# Vector gain based EVM estimation at mm-wave frequencies

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*Abstract* — **In this contribution we present a method for estimating linearity performance of devices operating in the higher millimeter-wave region, under modulated signals and over different loading conditions. The proposed method uses the power dependent vector gain extracted during continuous-wave large signal (load pull) measurements. The EVM prediction capability of the method is benchmarked with experimental load pull data with realistic modulated signals (QAM16) in the 5 GHz (RF) and in the 26 GHz (5G) bands on a 22nm CMOS FD-SOI device. The EVM estimated by the model correlates to the load pull measurements under complex modulated stimulus and properly predicts the best loading condition for linearity. Finally, the proposed method is used to estimate the EVM performance (QAM16) and the optimal loading condition for a 22nm CMOS-SOI device operating in the higher millimeter-wave region, at 165 GHz.**

***Index Terms*** **— 5G, EVM, linearity, mm-wave characterization, vector gain.**

## I. Introduction

Commercial interest for millimeter-wave communication has increased significantly over the past years, due to the appearance of large volume applications such as automotive radar and telecom applications (i.e., 5G systems operating in the FR2 band and E-band backhaul systems). These developments are enabled by the continuous improvements in silicon-based technologies over the past decades and driven by frequency congestion in low-GHz bands. One of the bands currently under consideration for future millimeter-wave communication (i.e., 6G) is the D-band with available frequency slots assigned from 140 GHz to 180 GHz where the low atmospheric adsorption window allows for medium to long distance communication [1].

To exploit the available frequencies and maximize the system throughput, modern communication standards use non-constant envelope modulation schemes and thus require linear operation of the power amplifier (PA) present in the transmitter chain. Due to the trade-off between linearity and power efficiency, proper transistors models, compact or behavioral [2, 3], are required to accurately predict all the non-linear contributions in order to properly tackle this trade-off early in the design cycle. These models should accurately capture the amplitude to amplitude (AM-AM) and amplitude to phase (AM-PM) distortion in order to reach the (standard defined) linearity target.

Reducing the number of design iterations of millimeter-wave PAs therefore requires accurate characterization and validation of these transistor models employed in the circuit design. Various developments have been made in and calibration/de-embedding techniques and advanced measurement setups in order to accurately characterize the large signal response of the transistors on wafer [4-6]. Non-linear characterization and modelling techniques such as the X-parameters and Poly-Harmonic Distortion model [7, 8], have been applied in the characterization and design phase to support the development of power amplifiers. However, when frequencies approach the upper mm-wave region, i.e., in D-band, characterization of linearity requires complex and rarely available setups [9].

In order to make accurate predictions of the device linearity there is a need to extract figure of merits (FOM) on accessible millimeter-wave characterization test benches. A linearity FOM proposed in [10] based on the AM-AM distortion in single-tone measurement was shown to closely correlate with the linearity performance of a GaN HEMT measured under two-tone as well as modulated excitation at 31.5 GHz. In this work a similar approach is proposed to predict the device linearity performance, including both the AM-AM and AM-PM distortion mechanisms. Moreover, the proposed approach also includes the frequency dependency of the device non-linear transfer function across the operating bandwidth, which plays an important role in the large modulation bandwidths of mm-wave systems.

The method proposed is based on a power swept, single tone vector gain measurements of the transistor. These characterization routines are employed to setup a complex, power dependent, transfer function in the frequency domain. By measuring the load dependent, vector gain over the (signal) operation band at several power levels an estimation can be made of the error vector magnitude (EVM) response of the device under modulated signals. In this contribution the proposed vector gain based EVM estimation method is benchmarked for its prediction capability versus load pull measurements under true modulated signals in the 5 GHz and 26 GHz bands on a 22 nm CMOS FD-SOI.

Finally, vector gain measurement under CW load pull conditions at 165GHz are used to predict the EVM performance of the device for a QAM16 stimulus signal in this band.

## II. The Vector Gain Model

The vector gain of a two port device can be measured from the ratio of the down-converted waves $b_2/a_1$ in a large signal characterization test bench as was shown in [11]. Following this definition, the vector gain represents a complex transfer

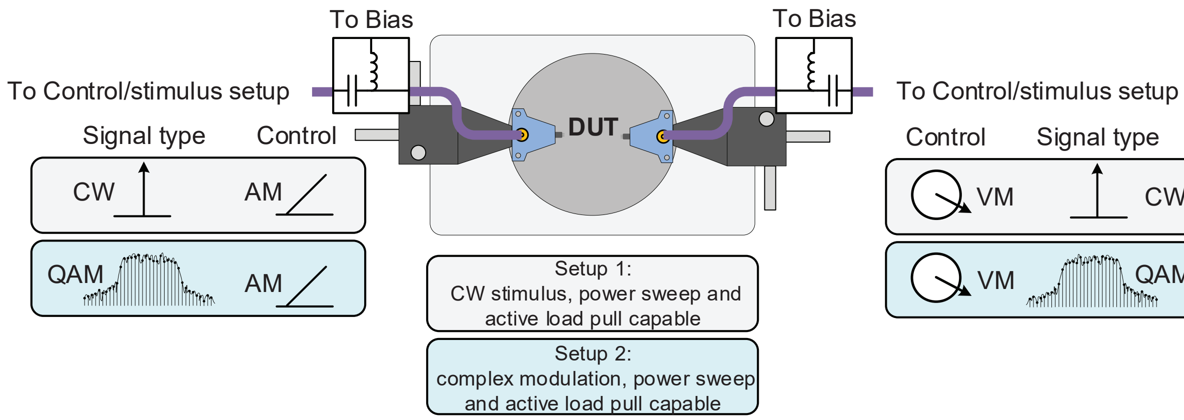


Fig. 1. Two measurement techniques are used in this contribution. A Continuous Wave (CW) load pull measurement is used to measure the vector gain of the DUT at the intrinsic device reference planes and estimate EVM performance using a behavioral model. This approach is benchmarked with a second true modulated wave EVM measurement at 5 GHz and 26 GHz.

function describing the magnitude and phase response from the input to the output of the device. The non-linear nature of this transfer function imposes dependency versus the bias, frequency, drive level as well as loading condition.

This input to output behavior can be described by the complex function in eq. (1), for every bias and load condition. Here both the amplitude and phase response are frequency and power dependent. This transfer function is defined by eq. (1) acquired measuring the vector gain at various power levels, frequency points and for several load conditions (during active load-pull).

$$H(\omega,\ P_{in}) = A(\omega, P_{in}) \cdot\ e^{j\Phi(\omega,\, P_{in})} \tag{1}$$

where $A(\omega,\ P_{in})$ describes the power depending magnitude transfer $\phi(\omega,\ P_{in})$ the power depending phase transfer versus frequency.

While the non-linear device response is acquired under continuous wave (CW) excitation at different frequencies, the input to output behavior for modulated signals is computed (numerically) for a multi-tone signal, with a frequency grid compliant to a user selectable standard definition.

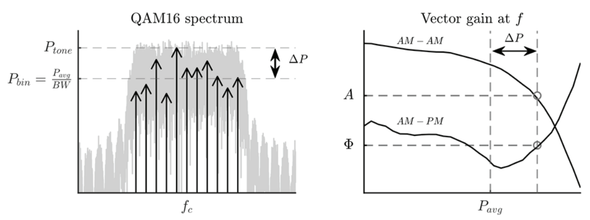


Fig. 2. Each spectral component is scaled in amplitude ($A$) and phase shifted ($\Phi$) as determined by the measured vector gain at that frequency depending on the offset ($\Delta P$) of the power in the frequency component from the average power in the signal.

For this reason, a relation between the CW power level and bin related power level in the modulated signal case needs to be defined. The proposed method employs the constant power (CW case) to the average bin power (modulated case) mapping described in Fig. 2. Each spectral bin component is then compared to the bin average power (i.e., $P_{avg}/BW$) and the relative power offset in the vector gain transfer function is used to apply the effective distortion (AM-AM and AM-PM) to that frequency bin.

After obtaining the now distorted spectrum at the output of the DUT, in the frequency domain, the resulting signal is transformed back to time domain. The EVM can then be calculated from eq. 2.

$$EVM_{rms} = \sqrt{\frac{\sum_n |y_n - x_n|^2}{\sum_n |x_n|^2}}. \tag{2}$$

## III. Benchmarking At 5 GHz and 26 GHz

### A. *Setup Description*

In order to validate the proposed vector gain based EVM estimation, two different test benches are employed, as sketched in Fig. 1.

*Setup 1*, allows the extraction of CW vector gain versus power and at different frequencies, under varying loading conditions.

*Setup 2*, allows to provide a complex modulated signal to the device under varying loading conditions and acquire the true EVM response of the device. For this experiment the Anteverta MT-2000 Series Mixed-Signal Active Load Pull system is employed [12]. The validation is done at 5 GHz and 26 GHz for a QAM16 modulated signal over a 20 MHz band.

Vector Gain Measurements At 5 GHz and 26 GHz

At 5 GHz the vector gain was measured over 21 tones (1 MHz spacing) in the operating band, at 31 source power levels from -30 dBm to 0 dBm (1 dB spacing) and for six different loading conditions around the maximum -1 dB compression point.

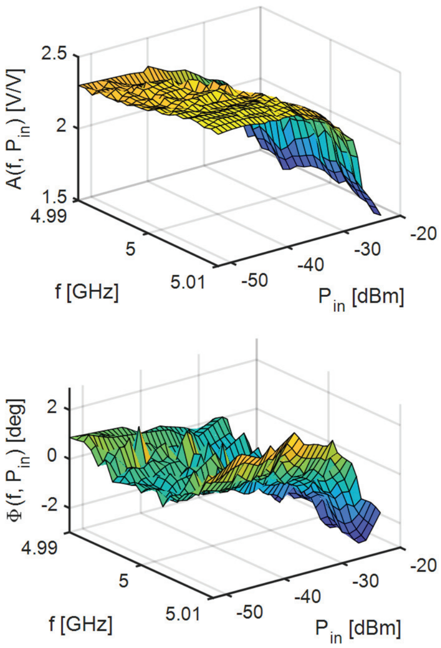


Fig. 3. Magnitude (top) and phase (bottom) of vector gain measured against frequency centered at 5 GHz and output power at the load for $\Gamma_L = 0.5$

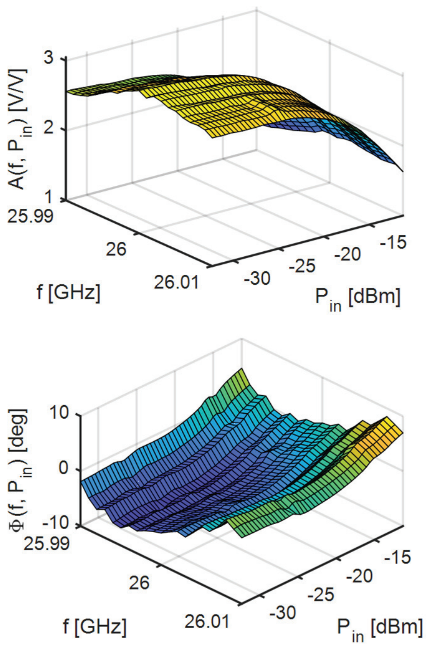


Fig. 4. Magnitude (top) and phase (bottom) of vector gain measured against frequency centered at 26 GHz and output power at the load for $\Gamma_L = 0.64 - 0.11j$

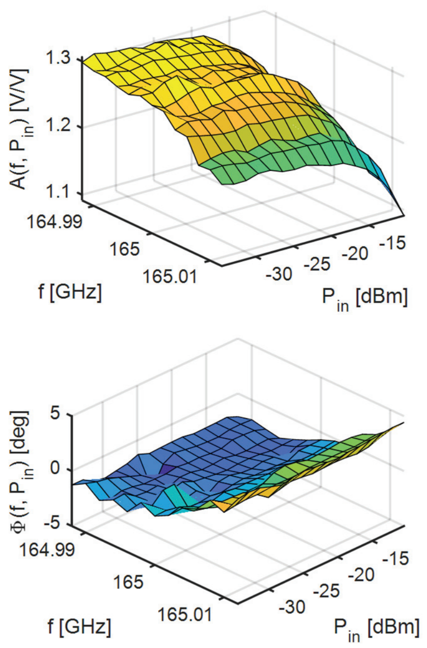


Fig. 5. Magnitude (top) and phase (bottom) of vector gain measured against frequency centered at 165 GHz and output power at the load for $\Gamma_L = 0.60 + 0.35j$

Fig. 3 shows the AM-AM gain compression characteristic and the AM-PM phase variation across the frequency band and input power for one of the six loading conditions.

At 26 GHz the vector gain was measured at 21 tones (1 MHz spacing) in the operating band, at 26 source power levels from -25 dBm to 0 dBm (1 dB spacing) and at sixteen loading conditions around the maximum -1 dB compression point.

Fig. 4 shows the AM-AM gain compression characteristic and the AM-PM phase variation across the frequency band and input power for one of the six loading conditions.

### B. *EVM Comparison At 5 GHz*

Fig. 6 shows estimated EVM using the vector gain proposed approach versus the direct measured EVM using setup 2 at 5 GHz for a QAM16 signal for four of the six measured loading conditions. Between the lines marked A and B in the figure the difference in the estimated and measured EVM is less than 1 dB for all four loading conditions, however it is important to note that the absolute value can partially depend on renormalization choices made at firmware level by the equipment providing true EVM which are difficult to replicate in the processing of the CW measured data. For this reason, the authors are more inclined to evaluate the agreement across loading conditions between the proposed approach and the direct measured EVM values than the absolute accuracy. The prediction of the constellation points for the loading condition $\Gamma_L = 0.5$ at an input power of -37.85 dBm are shown in Fig. 7In the region between A and B region the estimate is mostly lower than the measured EVM which is explained by the fact that the estimation does only capture the frequency bin self-non-linearities while the cross bin non-linearities are neglected. Left of point A, the measured EVM using setup 2 starts to increase due to the low signal-to-noise ratio in the measurement. To the right of point B, the difference between estimated and measured EVM increases due to limited non-linearities captured by the proposed approach as mentioned before. Across the whole characterized range, the vector gain EVM estimation can predict which of the loading conditions would achieve the lowest EVM. This shows that the approach is useful in providing a first-order estimation of the best loading condition for EVM, directly from measurements without the need of a model/circuit simulation framework.

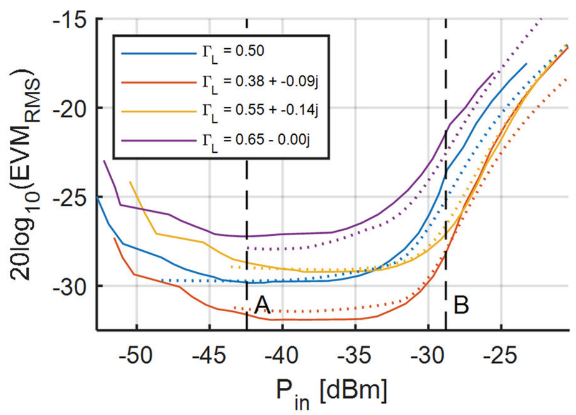


Fig. 6. Correlation between estimated and measured EVM for a QAM16 signal at four loading conditions at 5 GHz. Solid lines are true

modulated wave EVM measurements, dashed lines are estimations of the EVM using the vector gain.

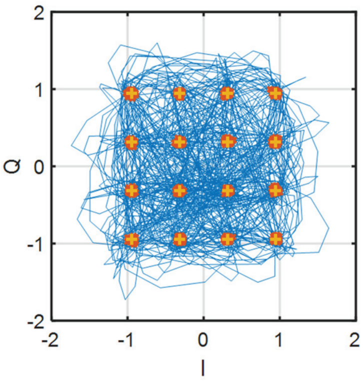


Fig. 7. Constellation points estimated during using the vector gain at 5 GHz for a QAM16 waveform ($P_{in} = -37.85\ dBm, \Gamma_L = 0.5$) using 1000 random symbols.

### C. *EVM Comparison at 26 GHz*

A similar experiment as the one conducted at 5 GHz was carried out at 26 GHz, with multiple CW tones as described in section III-A. In this measurement the vector gain based EVM estimation was consistently higher than the direct measured EVM using setup 2 however the agreement across the loading conditions and input power was consistent. This is for example shown in the two contour plots of Fig. 8 illustrating the EVM trend for one power condition $P_{in} = -22\ dBm$. The two contours show a good correlation between the best loading condition predicted and measured. Similar contour plots can be made using only large signal CW measurement to evaluate bias conditions, frequencies, drive levels and loading conditions allowing the optimum operation point to be estimated.

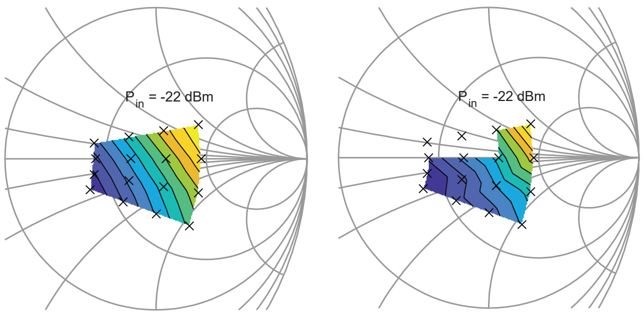


Fig. 8. Comparison between the contour plots of the EVM estimated by the vector gain (left) and measured using setup 2 (right) for one power condition $P_{in} = -22\ dBm$. Two loading conditions in the direct the EVM measurement did not converge (across the whole power range) and have therefore missing values in the right figure.

## IV. Optimal Loading Condition Estimation At 165 GHz

To demonstrate the use of the EVM estimation approach, the vector gain of the CMOS devices is measured in a 20 MHz band centered at 165 GHz using a Vertigo mmWave Studio active load pull setup. The vector gain is measured using single tone CW load pull measurements and is used to estimate the EVM for a QAM16 signal.

The vector gain is measured at 11 tones (2 MHz spacing) across the operating band, at 16 source power levels from -37.1 to -7.1 dBm (2 dB spacing) and at six loading conditions. Fig. 5 shows the AM-AM gain compression characteristic and the AM-PM phase variation across the frequency band and input power for one of the six loading conditions at 165 GHz. The EVM for a QAM16 modulated signal is estimated for each of the loading conditions and the result is shown in Fig. 9.

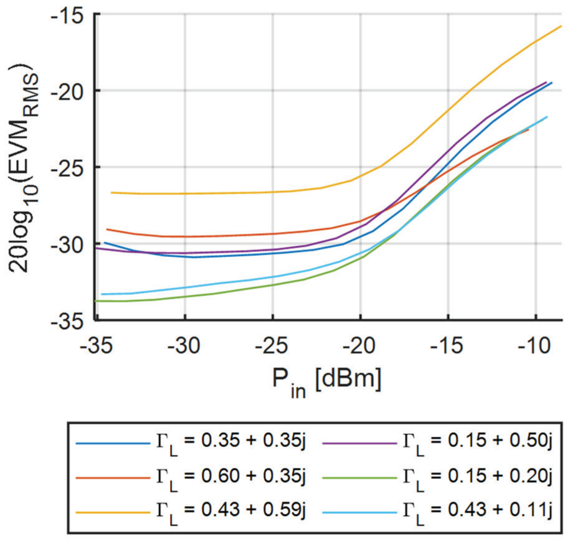


Fig. 9. Vector gain based EVM estimation at 165 GHz for a QAM16 signal at six loading conditions.

With the proposed approach it is possible to predict the optimal loading condition for lowest EVM, $\Gamma_L = 0.15 + 0.20j$ in this case. With the proposed approach of using the vector gain to estimate EVM performance it is possible to evaluate bias conditions, frequencies, drive levels and loading conditions during a large signal CW measurement in the upper millimeter-wave regime without requiring a complex modulated wave setup or the need of a circuit simulator.

## V. Conclusion

In this contribution a method is presented for the evaluation of linearity performance under modulated signals of devices operating far into the millimeter-wave regime. The method uses the power dependent vector gain that is extracted during a continuous wave large signal (load pull) measurement of the device under test to directly estimate the EVM performance of the device. The behavioral model was benchmarked at 5 GHz and 26 GHz with modulated wave measurements on a 22nm

FD-SOI device transistor. The vector gain approach shows good correlation with measured EVM versus power and applied loading conditions for a QAM16 waveform however the absolute accuracy in predicting the EVM is limited.

As a demonstration the method is used to estimate EVM performance at 165 GHz where other non-linear characterization methods such as a two-tone test or modulated signal measurements are difficult to perform. The vector gain based EVM estimation could therefore be used for prediction of optimal bias conditions, frequencies, drive levels and loading conditions during a large signal CW measurement in the upper millimeter-wave regime.

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