# Estimation of Error Vector Magnitude Using Two-Tone Intermodulation Distortion Measurements

Hyunchul Ku and J.S. Kenney

School of Electrical and Computer Engineering,
Georgia Institute of Technology, Atlanta, GA 30332-0250

*Abstract* - **In this paper, a new method for estimating error vector magnitude (EVM) degradation of power amplifier using the intrinsic kernel function derived from two-tone intermodulation distortion (IMD) measurements is presented. The kernel function represents the incremental distortion characteristics of the power amplifier driven by a signal with small amplitude deviation. With knowledge of the complementary cumulative distribution function (CCDF) of an arbitrary input signal, the Carrier-to-Interference Ratio (CIR) of the power amplifier can be derived and the EVM degradation of the power amplifier may be calculated. For the experimental validation, the EVM of the 16-QAM signals passed through 1.9GHz HFET nonlinear amplifier is derived by suggested method and compared with the measured results. The derived EVM shows a good agreement with measured results. The rms error between two results over a 20dB input range is less than 2%.**

## I. INTRODUCTION

One of the main goals in digital communication systems is to send the digital bit streams efficiently in the transmitter and to recover them accurately in the receiver. These digital wireless systems adopt more complex transmitters and receivers to acquire spectrum efficiency. The benefit of increased spectrum efficiency needs the fidelity of the digital modulated signal through the transmitter, particularly through the power amplifier (PA). The nonlinearity of the power amplifier introduces the compression and phase distortion, and causes the deviations of the received signal constellation from ideal reference signal constellation. These deviations, which can be measured quantitatively by error vector magnitude (EVM), increase as the nonlinearity of the PA increases. EVM is an effective method of calculating system performance[1].

EVM can be defined as the difference between the theoretical ideal points and the received symbol locations as a percentage to the peak signal level[2]. The EVM is commonly employed to insight into RF system performance in the wireless system such as Global System for Mobile communications (GSM), North America Digital Cellular (NADC), and Personal Handyphone System (PHS)[3]. To predict the EVM in the digital system, some direct time-domain methods were proposed using AM-AM and AM-PM characteristics[4][5].

The analytical method is proposed to estimate the EVM degradation due to the nonlinearity of the PA using the intrinsic kernel function and complementary cumulative distribution function (CCDF) of input signal in Section II. The intrinsic kernel function can be derived from two-tone intermodulation distortion (IMD) and two-tone CCDF. Using proposed method, the EVM of the 16-QAM digital modulated signal is calculated for the 1.9GHz HFET PA in Section III. In Section IV, the EVM is derived by direct-time domain method using PA characteristics and compared to the result derived in Section III. The EVM is measured using vector signal analyzer (VSA) and compared with the previous results in Section V. A conclusion is presented in Section VI.

## II. FORMULATION OF EVM

To analyze nonlinear effects of the PA on EVM, the measured PA output is compared to the reference output. The EVM at the PA output can be defined as the difference between the measured output vector $(I_{mo} + jQ_{mo})$ and the reference output vector $(I_{ro} + jQ_{ro})$. By convention, EVM is usually described as percentage of average error magnitude normalized to the outer most symbol magnitude[3].

$$EVM(\%) = \frac{\text{average error magnitude}}{\text{peak signal magnitude}} \times 100 \quad (1)$$

For the PA, EVM in (1) can be related to the carrier-to-interference ratio (CIR) and peak-to-average-power ratio(PAPR) of the PA which is similar result in [6].

$$EVM(\%) = \frac{1}{\sqrt{\text{PAPR}}} \times 10^{\frac{CIR(dB)}{20}} \times 100 \quad (2)$$

$$\text{where } CIR = 10\log\frac{\text{average interference power}}{\text{average carrier power}} \quad (3)$$

0-7803-6540-2/01/$10.00 (C) 2001 IEEE

The CIR of the output of power amplifier can be calculated using intrinsic carrier-to-interference (ICIR) kernel function of the device. Physically, the ICIR kernel represents the IMD produced by a small incremental deviation in signal amplitude. The CIR at an average input power level $\overline{p}$ , of an output signal from a nonlinear device is related to the ICIR function through a weighted average given by [7]:

$$\mathrm{CIR}(\overline{p}) = \int \mathrm{ICIR}(p) f_P(p/\overline{p})dp \qquad (4)$$

where ICIR($p$) is the value of the kernel function at the instantaneous envelope power $p$, and $f_P(p/\overline{p})$ is the probability density function (PDF) of the envelope power (relative to the average power $\overline{p}$ ). The ICIR($p$) can be derived analytically by two-tone signal CCDF function and two-tone IMD. Usually, two-tone IMD can be measured by spectrum analyzer and two-tone CCDF function can be acquired by analyzing two-tone signal as follows:

$$v_i(t) = a\cos(\omega_1 t) + a\cos(\omega_2 t)\ , \qquad (5)$$

where we assume that the frequency spacing is much smaller than either RF frequency. In the narrowband assumption, the conditions at any instant can be considered to be quasi-static[8]. Thus the input signal power is

$$p(t) = A\cos^2(\omega_d t), \qquad A = \frac{4a^2}{R}, \omega_d = \frac{\omega_1 - \omega_2}{2} \qquad (6)$$

where $R$ is the load impedance.
For two-tone power, the PDF can be derived analytically. The average power $\overline{p}$ in (6) is $A/2$. The PDF of two-tone for $\overline{p}$ is

$$f_P(p) = \frac{1}{\pi\sqrt{p(2\overline{p} - p)}}, \quad 0 \le p \le 2\overline{p} \qquad (7)$$

Using (7), the CCDF of the two-tone can be calculated

$$CCDF(p) = 1 - \int f_P(p)dp$$
$$= 1 - \frac{2}{\pi}\arctan\left(\frac{\sqrt{2p/\overline{p} - (p/\overline{p})^2}}{2 - p/\overline{p}}\right), \quad 0 \le p \le 2\overline{p} \qquad (8)$$

## III. EVM Calculation

To estimate EVM, the ICIR function for the 0.5W GaAs/AlGaAs HFET power amplifier was derived. The schematic of the PA was shown in the Fig. 1. The device (SHF-189) and amplifier PCB were supplied by Stanford Microdevices[9]. The nominal small signal gain was about 15.5dB. The circuit was biased with a quiescent drain current of 100mA at 8V $V_{DS}$. Under these conditions, the output power at 1 dB gain compression was measured to be +25.4dBm.

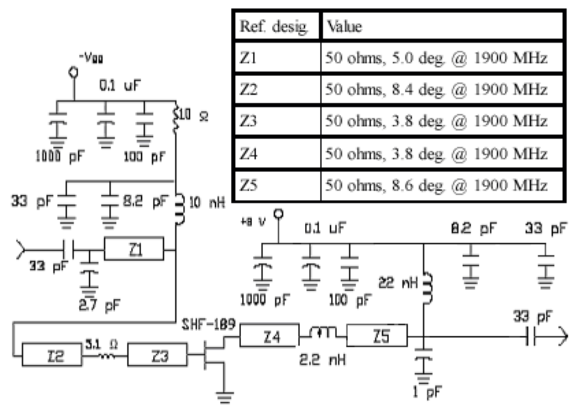



Fig. 1. Schematic of amplifier under test: SHF-189, manufactured by Stanford Microdevices

A driver amplifier preceded the SHF-189 amplifier stage. It was confirmed that the driver amplifier did not significantly contribute to the output CIR. Two-tone IMD measurements were made at 1.9GHz, with a tone spacing of 1.25MHz over an input power range of 25dB, which extends from the small-signal regime to well beyond P1dB. No significant memory effects (*i.e.* variation of IMD level vs. tone spacing) were observed in this device from 10 kHz tone spacing to 10 MHz tone spacing. All significant IM products are added to evaluate the total interference power. Fig. 2 shows the measured two-tone IMD. The ICIR function was extracted from the two-tone IMD data and the CCDF for two-tone signal. A plot of the ICIR function is shown in Fig. 3.

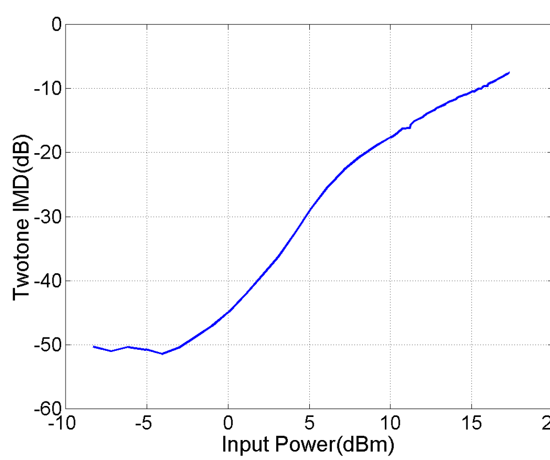



Fig. 2. Measured two-tone IMD vs. input power of the SHF-189 power amplifier at 1.9GHz

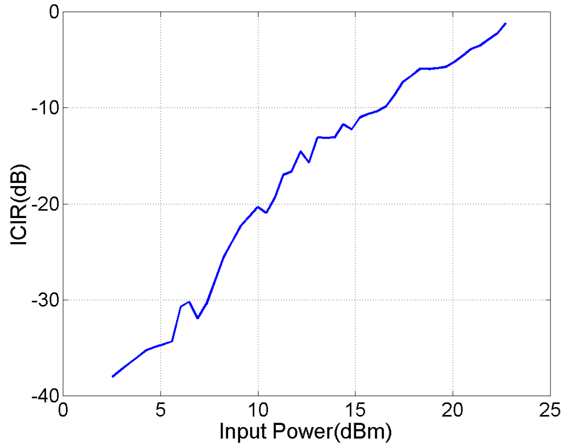
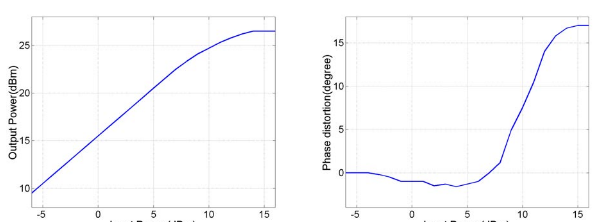


Fig. 3. Extracted ICIR kernel function vs. input power of the SHF-189 power amplifier at 1.9GHz

Next, the input signal for the PA is determined and EVM is calculated by (2). The test input signal used 16-QAM for the digital modulation. The signal was filtered by the raised root cosine filter with 0.5 roll-off factor. The CCDF distribution of this 16-QAM input signal was acquired. In the CCDF distribution, the PAPR for this input is 5.9dB. Usually the PAPR depends on the filter characteristics. Using the ICIR function for the PA and CCDF for the 16-QAM input signal, the CIR was derived using (4) and then the EVM degradation for the PA was acquired. The predicted EVM using this method is shown in Fig. 8.

## IV. Verification Through Direct Time-Domain Simulation

To analyze the effect of the PA nonlinearity on EVM and constellation, the computer simulation was executed using the MATLAB. The PA can be modeled using the AM-AM and AM-PM characteristics in Fig. 4. The AM-AM and AM-PM characteristics were measured with RF network analyzer.



(a) AM-AM (b) AM-PM

Fig. 4. Measured device characteristics

Using the CCDF distribution of 16-QAM signal and PA characteristics, the EVM was calculated. Fig. 5 shows the constellation of the PA for several input powers for this model. The simulated constellation points represent the normalized received constellation positions.

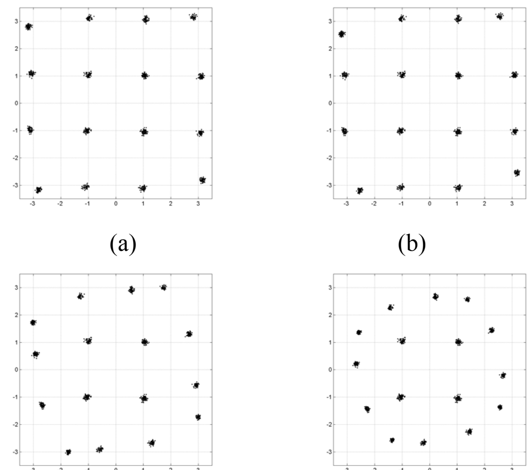

(a) (b) (c) (d)

Fig. 5. 16-QAM simulated constellation with input power (a):6dBm (b):8dBm (c):10dBm (d):12dBm

The EVM calculated by direct time-domain simulation is shown in Fig. 8.

## V. Experimental Validation

Fig. 6 shows a block diagram of the EVM experimental configuration. The input power was measured at the input of the PA by the power meter (HP4419B), and the error vector was measured at the output of the PA. To get the EVM, vector signal analyzer (VSA HP89410A) was used.

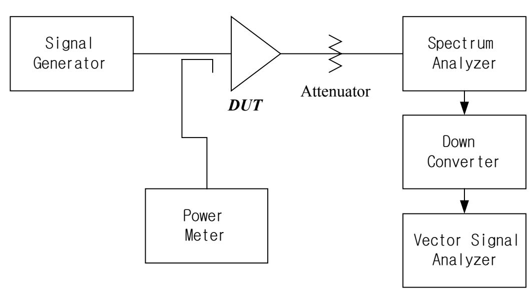


Fig. 6. EVM test setup

Fig. 7 shows the measurement in the VSA. To convert the 1.9GHz of the PA output to the desired frequency of the VSA, the spectrum analyzer (HPE4404A) and down-converter (HP 89411A) were used. The modulation format was 16-QAM and the roll-off-factor was 0.5. The EVM was measured for the input power between -5dBm and 15dBm with 1dBm steps. The measured results were shown in Fig. 8 with the predicted results. The rms error between the measured EVM and estimated EVM in this region was about 1.95% and the rms error between the direct time simulated EVM and the estimated EVM was 1.83%.

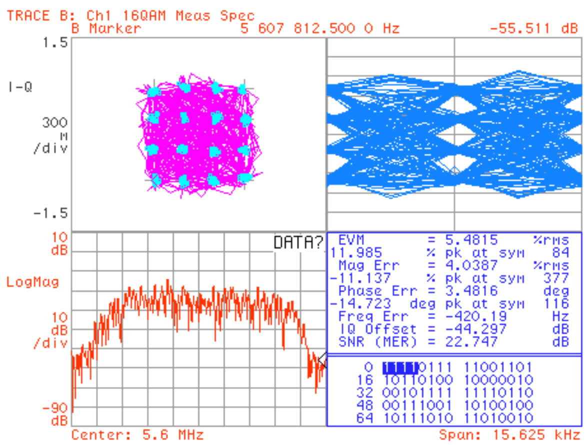



Fig. 7. 16-QAM EVM Measurement

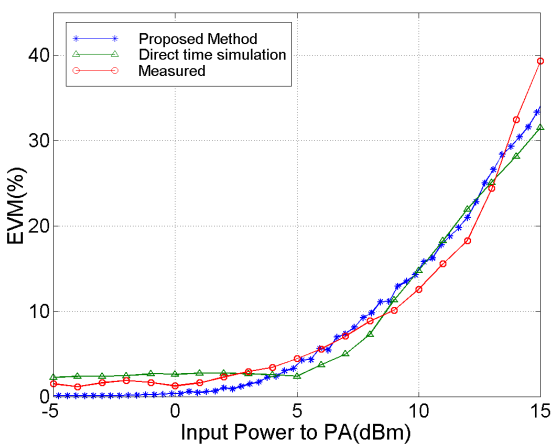



Fig. 8. Estimated, Simulated, and Measured EVM

## VI. Conclusion

In this paper, we developed an analytical method to estimate EVM degradation of digitally modulated signals passing through a nonlinear PA. An ICIR function was extracted from two-tone measurements over a range of input power extending from the linear region well into saturation. Using this function and knowledge of the input signal CCDF distribution, the EVM of a nonlinear PA may be calculated.

A computer simulation was performed to compare the EVM calculated using the analytical model just described, to direct time-domain simulation. The AM-AM and AM-PM characteristics were extracted from a 1.9 GHz HFET PA, and the EVM was calculated by averaging error vectors that occurred due to the PA nonlinearity. Good agreement was seen between the EVM calculated from the analytical method and that calculated from the direct time-domain method.

For the experimental verification of the analytical EVM estimation method, measurements were performed using 16-QAM digital modulated signals on a 1.9 GHz HFET PA. The constellation of demodulated output signal, and hence EVM values, were acquired and compared to the estimated results. The rms error between the measured and predicted results was about 2% over a 20 dB range of input power.

## References


[1] R. Hassun, M. Flaherty, R. Matreci, and M. Talyor, "Effective Evaluation of Link Quality Using Error Vector Magnitude Techniques," *Wireless Communications Conference*, 1997, pp.89-94.

[2] "Using Error Vector Signal Magnitude Measurements to Analyze and Troubleshoot Vector Modulated Signals," Agilent Product Note 89400-8.

[3] K. M. Voelker, "Apply Error Vector Measurements in Communication Design," *Microwaves & RF*, December 1995, pp. 143-152.

[4] M. S, Heutmaker, "The error Vector and Power Amplifier Distortion," *Wireless Communications Conference*, 1997, pp.100-104.

[5] F. Lin, S. Chen, L. Chen, and H. Chung, "Computer Simulation and Measurement of Error Vector Magnitude (EVM) and Adjacent-Channel Power Ratio (ACPR) for Digital Wireless Communication RF Power Amplifiers," *VTC99*, pp2024-2028.

[6] "Testing and Troubleshooting Digital RF Communications Receiver Designs," Agilent Application Note 1314

[7] H. Ku, W. Woo, and J.S. Kenney, "Carrier-to-Interference Ratio Prediction of Nonlinear RF Devices," *Microwave Journal*, Vol. 44, No.2, pp154-164, Feb. 2001.

[8] S. Cripps, *RF Power Amplifiers for Wireless Communications*, Artech House, 1999.

[9] Stanford Microdevices, Inc., 522 Almanor, Dr., Sunnyvale, CA, 94086, http://www.stanfordmicro.com