Discrete-Level Envelope Tracking for Broadband Noise-Like Signals

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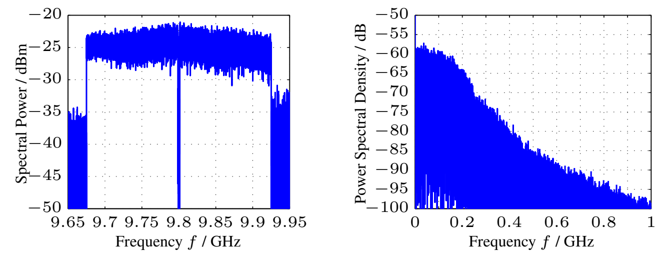
***Abstract*—In this paper we study discrete level supply modulation of an X-band MMIC GaN PA for high-bandwidth signals which statistically resemble band-limited Gaussian noise. 4- and 8-level tracking is compared for various slew rates and the non-linearized NPR is monitored. Two signal bandwidths, 100 and 250 MHz are examined with PAPR of 11 dB and an average PA output power of around 35 dBm. For the 250 MHz signal with 8-level tracking at a slew rate of 1 V/ns a PAE of 40.1 % is measured at 9.8 GHz, compared to 26.2 %, for a fixed 20 V drain voltage.**

***Index Terms*—Power amplifiers, MMICs, efficiency, nonlinear distortion, broadband communication.**

I. Introduction

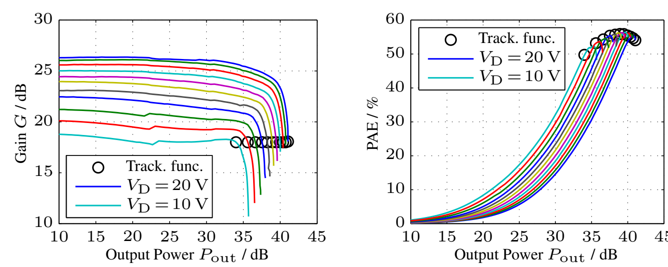
The increasing demand on signal bandwidth for emerging communication systems presents a challenge for high-efficiency operation of microwave power amplifiers (PAs). A possible approach to improve efficiency is envelope tracking (ET), which is challenging for high-bandwidth signals because the envelope is theoretically infinite in bandwidth, and practically up to 10 times the signal bandwidth [1]. Further difficulties arise from the dynamic complex impedance of the drain supply terminal presented to the tracker which needs to have a low impedance itself over the entire envelope bandwidth [2]. Additionally, efficient, high-bandwidth trackers have been limited to tens of MHz of tracking bandwidth. For example, GaN on SiC MMIC buck converters have been demonstrated with 93.2 % efficiency at 100 MHz switching frequency and 72.5 % at 400 MHz with up to 16 W output power [3]. Despite these high switching frequencies, such modulators can continuously track only tens of MHz. The highest reported tracked baseband bandwidth with 70 % tracking efficiency is 100 MHz to the best of our knowledge [4].

A method to increase efficiency with a bandwidth limited supply modulator is demonstrated in [5] and a similar method, referred to as slew-rate reduction is discussed in [6]. Both solutions are applied to 5 MHz signals with a PAPR of 7.6 dB reported in the first case. Here we focus on signals with baseband bandwidths exceeding 100 MHz and PAPRs exceeding 10 dB, modulated onto X-band carriers, as the 250 MHz-bandwidth signal shown in Fig. 1a. We investigate the use of a discrete-level supply modulation [7]. Instead of trying to continuously track the extremely broadband envelope, Fig. 1b, the envelope modulator switches between different static voltages, not to be confused with supply modulators themselves employing different supply voltages as in [8], [9].



(a) NPR Test Signal (b) Continous Tracking Signal

Fig. 1. Measured output spectrum of 250 MHz NPR test signal (a); power spectral density of corresponding continuous constant-gain tracking signal (b).



(a) Gain and tracking function (b) PAE and tracking function

Fig. 2. Measured gain and efficiency data for the used 150 nm, GaN, X-band 10 W, amplifier for a drain voltage swing of 10 V to 20 V in 1 V steps. The circles indicate the picked constant gain ($G = 18$ dB) tracking function.

Efficient implementations with four [10] and eight [11] were recently demonstrated, with efficiencies exceeding 97 % and 94 %, respectively. Discrete trackers overcome the bandwidth limitations of conventional buck converters while maintaining efficiency, but sacrifice the smooth continuous tracking usually employed for ET. To account for the limited rise-time of the discrete level modulator, we model the tracker as purely slew-rate (SR) limited. We use noise power ratio (NPR) as the linearity measure [12], which is an appropriate approach for noise-like, (multi-standard) communication signals.

II. Tracking Algorithm

Regardless of the tracker hardware implementation, a tracking function needs to be selected. This is typically done by characterizing the PA with a continuous wave (CW) input signal for various drain voltages. The gain and power added efficiency (PAE) characterization measurements of the X-band, two-stage, 10 W, GaN MMIC PA are shown in Fig. 2. The gate voltages of the MMIC are kept constant for a current of 60 mA

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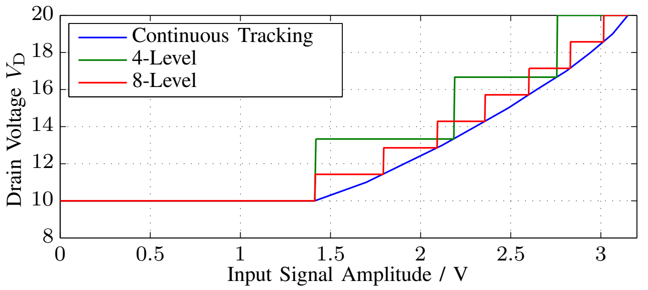

Fig. 3. Tracking functions: the 4 and 8-level tracking functions used in this work are derived from the continuous tracking function.

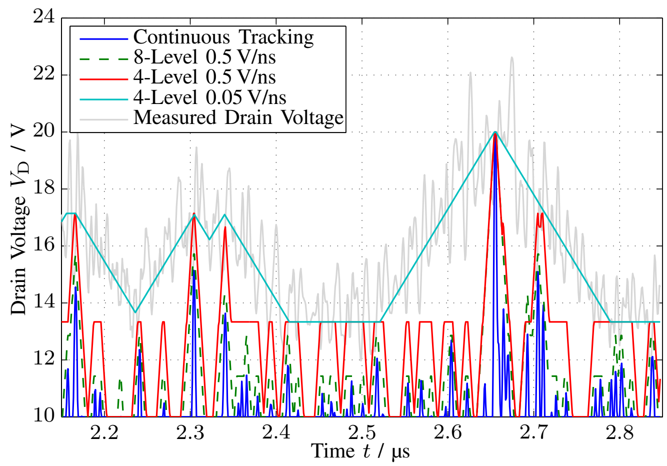

Fig. 4. Drain voltage trajectory for continuous tracking (blue line), and several discrete-level tracking approaches. The measured drain voltage is shown in grey. The signal bandwidth is 250 MHz and the average input power is 14 dB.

at the driver and 250 mA at the final stage at a drain voltage V_D Ω 2ΩΩ. Since the PA employs a large gain variation over drain bias (Fig. 2a), we pick a constant gain tracking function as indicated with the small circles in Fig. 2. This function gets close to the optimum efficiency points and for an ideal continuous tracker ensures a constant 18 dB gain.

This continuous constant gain tracking function is then discretized in four and eight levels , as shown in Fig. 3, resulting in a drain voltage that is always equal to or greater than the initial constant gain approach. Therefore, using these discrete levels a higher gain and lower efficiency is expected. Further, the SR limitation of the tracker needs to be accounted for. Fig. 4 shows the ideal continuous tracking signal, as well as four and eight level tracking signals, for two slew rates of the NPR test signal with a noise bandwidth of B_N Ω 25ΩΩ ΩΩ

III. Measurement Setup

The X-band MMIC is mounted on a CuMo carrier and bonded to alumina 50 Ω lines in a fixture with bias pads, without extra capacitors on the drain supply terminal. A current probe is clamped around a short wire that connects the envelope tracker to the PA drain. The drain voltage is probed directly at the output of the tracker. The drain voltage

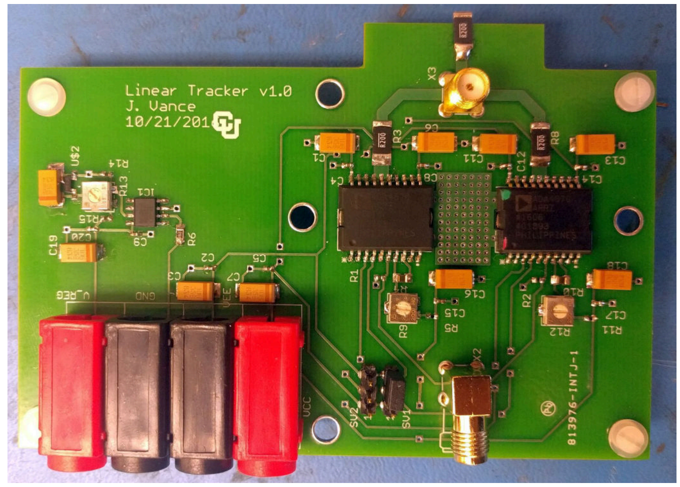

Fig. 5. Photography of linear tracker used for this study, based on two ADA4870 operational amplifiers. The input is the SMA connector at the bottom, the output is the 0.2 Ω series resistor at the top.

and current are sampled at a rate of 1 GS/s, and their product is used to calculate the drain input power to the PA.

The NPR test signals are generated using a synchronized pair of arbitrary waveform generators (AWGs). One AWG supplies the baseband signal, which is upconverted to 9.8 GHz and fed to the MMIC through a preamplifier and a directional coupler. The second AWG feeds the linear tracker. The directional coupler is used to measure the spectrum and input power of the PA test signal, using a vector signal analyzer (VSA) and a calibration-free power sensor, respectively. A second directional coupler at the output of the PA provides a sample signal to the VSA, while the PA is terminated with an attenuator connected to the output power sensor.

The baseband and envelope signals are precomputed and selected based on the noise bandwidth, input power, slew rate and number of voltage levels. The NPR signals are digitally generated as described in [12] and have bandwidths of 100 MHz and 250 MHz, respectively, with a notch-bandwidth of 1 %, using 30 001 carriers. This results in peak to average power ratios (PAPRs) of 11.1 dB and 10.3 dB for the two test signals. A 250 MHz pulse shaped test signal is used for time alignment between the RF and tracking signals.

To investigate the impact of different levels and SRs of efficient switch based trackers we use a flexible, inefficient linear tracker, as part of our test bench. The linear tracker shown in Fig. 5, is based on two ADA4870 2.5 V/ns SR, current-feedback operational amplifiers which are connected in parallel using 0.2 Ω series resistors, to provide up to 2 A of peak current to the PA. An additional 0.2 Ω series resistor ensures stability of the tracker when connected to the capacitive PA drains. The measured 3 dB small-signal bandwidth of the tracker is 47.3 MHz, the phase response is linear within this bandwidth.

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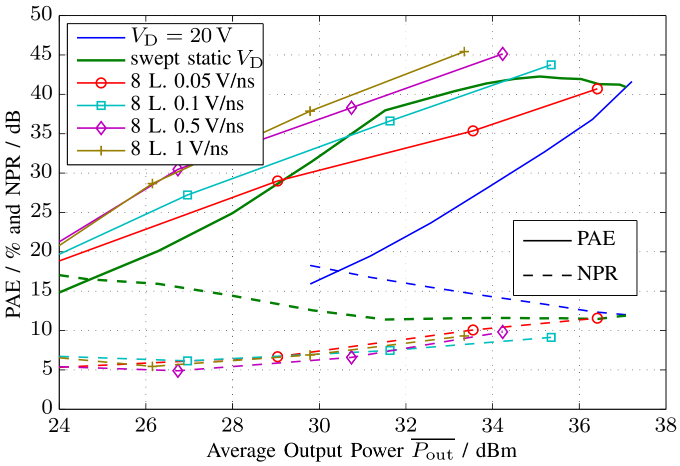

Fig. 6. Measured efficiency and NPR for a 100 MHz noise signal for eight level tracking at various slew rates.

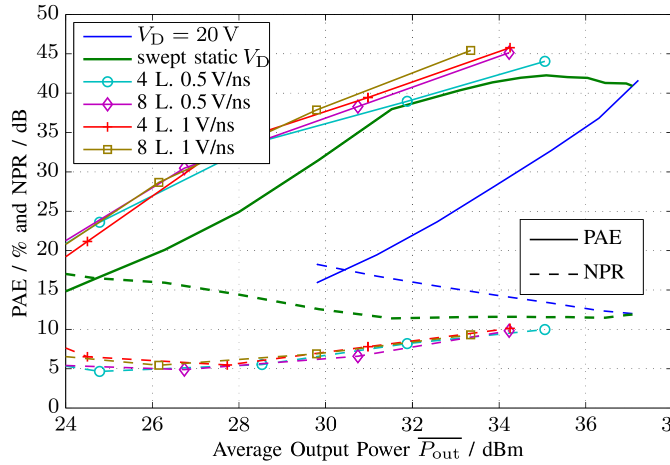

Fig. 7. Measured efficiency and NPR for a 100 MHz noise signal for four and eight level tracking.

IV. Measurement Results

The results for eight level tracking and the 100 MHz noise signal are compared to constant drain voltage operation in Fig. 6. We limit the average input power to the amplifier to 18 dBm to avoid destruction due to the high PAPR test signal. The "swept static V_D" curve is obtained by first keeping the drain voltage at 10 V up to the 31.5 dBm $\overline{P_{out}}$ point where the average input power of 18 dBm is reached. From there on the input power is kept constant and the drain is statically sweeped to 20 V. We see that the ET signals with a SR of 0.5 V/ns and 1 V/ns beat this curve with PAEs of 45.4 % and 45.1 %, respectively, when compared to 32.7 % and 42.3 % for the 20 V and 15 V optimal drain voltages, all for an average output power of approximately 35 dBm. This comes at the price of a reduction in NPR, as summarized in Table I, but penalties to the relatively efficient, compressed, static 15 V operation are only 1.8 dB and 2.3 dB, respectively. The average gain $\overline{G}$ is 16.2 dB and 15.3 dB lower than expected, which is caused by the relatively high output impedance of the tracker. This causes the drain voltage to momentarily drop when high power spikes are demanded, as shown in Fig. 4. Reducing the output impedance of the tracker will improve efficiency and NPR for both static and especially tracked drain voltages.

Fig. 7 compares the performance of the four and eight level ET. Due to the relatively low SR (relative to the signal bandwidth) and the additional averaging effect due to the linear tracker output impedance the differences are low, but the eight level ET gives slightly better PAE, as expected.

The results for the 250 MHz noise signals are shown in Fig. 8. The plot shows the general trend of lower efficiencies, both for constant V_D and ET. Since the tracker SLs are kept constant, only the fastest setting of 1 V/ns provides a clear benefit in terms of PAE. The results for average output powers around 34 dBm are summarized in Table II.

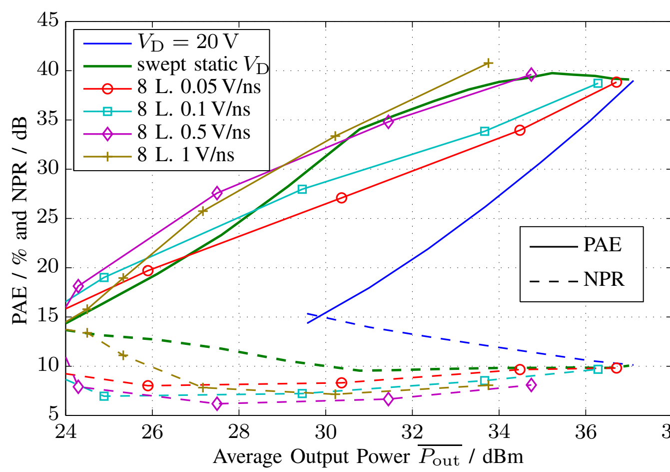

Fig. 8. Measured efficiency and NPR for a 250 MHz noise signal for eight level tracking at various slew rates.

TABLE I
Measurement Results $B_N = 100$ MHz

V_D	SR	$\overline{P_{out}}$	NPR	PAE	$\overline{G}$
20 V	0 V/s	35.2 dBm	13.3 dB	32.7%	21.2 dB
15 V	0 V/s	35.1 dBm	11.6 dB	42.3%	17.1 dB
4 Lev.	0.05 V/ns	34.5 dBm	11.1 dB	36.3%	18.7 dB
8 Lev.	0.05 V/ns	33.6 dBm	10.1 dB	35.4%	18.4 dB
4 Lev.	0.5 V/ns	35.1 dBm	10.0 dB	44.0%	17.0 dB
8 Lev.	0.5 V/ns	34.2 dBm	9.8 dB	45.1%	16.2 dB
4 Lev.	1 V/ns	34.3 dBm	10.1 dB	45.8%	16.2 dB
8 Lev.	1 V/ns	33.4 dBm	9.3 dB	45.4%	15.3 dB

TABLE II
MEASUREMENT RESULTS $B_{\mathrm{N}} = 250\,\mathrm{MHz}$

V_{D}	SR	$\overline{P_{\mathrm{out}}}$	NPR	PAE	$\overline{G}$
20 V	0 V/s	33.7 dBm	12.1 dB	26.2%	21.7 dB
14 V	0 V/s	34.0 dBm	9.8 dB	38.9%	16.0 dB
4 Lev.	0.05 V/ns	35.1 dBm	10.0 dB	34.5%	18.9 dB
8 Lev.	0.05 V/ns	34.5 dBm	9.7 dB	34.0%	18.7 dB
4 Lev.	0.5 V/ns	35.4 dBm	9.3 dB	39.9%	17.3 dB
8 Lev.	0.5 V/ns	34.7 dBm	8.1 dB	39.6%	16.7 dB
4 Lev.	1 V/ns	34.6 dBm	8.2 dB	40.6%	16.5 dB
8 Lev.	1 V/ns	33.8 dBm	8.1 dB	40.8%	15.7 dB

V. CONCLUSION

In this work the applicability of discrete level envelope tracking of very large signal bandwidths up to 250 MHz is investigated practically by performing ET measurements on an X-band GaN PA. We emulate the discrete tracking method by feeding a linear tracker with a SR-limited signal. For a 100 MHz noise signal the PAE is raised from 42.3 % for an optimum static 15 V supply to 45.8 % using four level ET with a SR of 1 V/ns, not taking the tracker efficiency into account. The NPR is slightly reduced from 11.6 dB to 10.1 dB. The PAE break-even point between ET and a static supply for this bandwidth lays at 0.2 V/ns. At 250 MHz a slight efficiency improvement from 38.9 % to 40.8 % is observed. As the used linear tracker was found to have a rather large output impedance, both NPR and PAE results are expected to improve significantly by the use of supply modulators with very low output impedance.

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REFERENCES

[1] P. Asbeck and Z. Popovic, "ET comes of age: Envelope tracking for higher-efficiency power amplifiers," *IEEE Microw. Mag.*, vol. 17, no. 3, pp. 16–25, 2016.

[2] J. Hoversten, S. Schafer, M. Roberg, M. Norris, D. Maksimovic, and Z. Popovic, "Codesign of PA, supply, and signal processing for linear supply-modulated rf transmitters," *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 6, pp. 2010–2020, 2012.

[3] A. Sepahvand, Y. Zhang, and D. Maksimovic, "High efficiency 20–400 MHz PWM converters using air-core inductors and monolithic power stages in a normally-off GaN process," in *Applied Power Electronics Conference and Exposition (APEC)*. IEEE, 2016, pp. 580–586.

[4] D. Kimball, H. Kazeimi, J. Yan, P. Theilmann, I. Telleiz, and G. Collins, "Envelope modulator & X-band MMICs on highly integrated 3D tunable microcoax substrate," in *Compound Semiconductor Integrated Circuit Symposium (CSICS)*. IEEE, 2015, pp. 1–4.

[5] J. Jeong, D. F. Kimball, M. Kwak, C. Hsia, P. Draxler, and P. M. Asbeck, "Wideband envelope tracking power amplifiers with reduced bandwidth power supply waveforms and adaptive digital predistortion techniques," *IEEE Trans. Microw. Theory Tech.*, vol. 57, no. 12, pp. 3307–3314, 2009.

[6] G. Montoro, P. L. Gilabert, J. Berenguer, and E. Bertran, "Digital predistortion of envelope tracking amplifiers driven by slew-rate limited envelopes," in *Microwave Symposium Digest (MTT), 2011 IEEE MTT-S International*. IEEE, 2011, pp. 1–4.

[7] M. Vasic, O. Garcia, J. A. Oliver, P. Alou, D. Diaz, and J. A. Cobos, "Multilevel power supply for high-efficiency RF amplifiers," *IEEE Trans. Power Electron.*, vol. 25, no. 4, pp. 1078–1089, 2010.

[8] F. H. Raab, "Average efficiency of class-G power amplifiers," *IEEE Trans. Consum. Electron.*, no. 2, pp. 145–150, 1986.

[9] J. S. Walling, S. S. Taylor, and D. J. Allstot, "A class-G supply modulator and class-E PA in 130 nm CMOS," *IEEE J. Solid-State Circuits*, vol. 44, no. 9, pp. 2339–2347, 2009.

[10] A. Sepahvand, P. Momenroodaki, Y. Zhang, Z. Popović, and D. Maksimović, in *Energy Conversion Congress and Expo (ECCE)*. Milwaukee, WI: IEEE, Sep. 2016.

[11] C. Florian, T. Cappello, R. P. Paganelli, D. Niessen, and F. Filicori, "Envelope tracking of an RF high power amplifier with an 8-level digitally controlled GaN-on-Si supply modulator," *IEEE Trans. Microw. Theory Tech.*, vol. 63, no. 8, pp. 2589–2602, 2015.

[12] T. Reveyrand, D. Barataud, J. Lajoinie, M. Campovecchio, J.-M. Nebus, E. Ngoya, J. Sombrin, and D. Roques, "A novel experimental noise power ratio characterization method for multicarrier microwave power amplifiers," in *ARFTG Conference Digest-Spring, 55th*, vol. 37. IEEE, 2000, pp. 1–5.

 978-1-5090-6360-4/17/$31.00