PA Design for Future Wireless Systems

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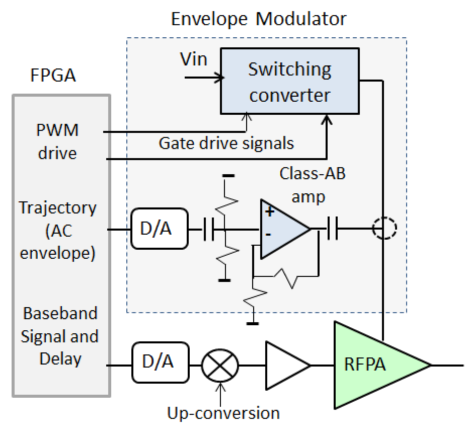
***Abstract*—This paper presents an overview of efficiency enhancement techniques for microwave power amplifiers (PAs) through supply modulation. The focus is on next-generation wireless systems, which are predicted to operate at higher carrier frequencies, with significantly larger signal bandwidths and under conditions that require more functionality and flexibility at the RF front end. Several PAs with supply modulation are presented to illustrate the challenges and propose some solutions. Starting from continuous envelope tracking of a 10-W X-band MMIC GaN PAs with up to 40-MHz signal bandwidth with >40% composite efficiency (CPAE), the approach is extended to signals with bandwidths >100MHz and with PAPR>11dB using slew-rate reduction methods. Further extensions to supply modulation for multiple simultaneous signals, each with a bandwidth of a few tens of MHz, randomly positioned over a 1-GHz band are shown. Supply modulation is also demonstrated to improve efficiency for more complex PA architectures, such as a 10-GHz Chireix outphasing MMIC PA and a 2-GHz linear and efficient harmonically-injected PA. The flexibility of supply modulation is discussed for PAs that can efficiently amplify both communications and radar signals with improved performance.**

Keywords—power amplifier, high efficiency, broadband signals, supply modulation, envelope tracking

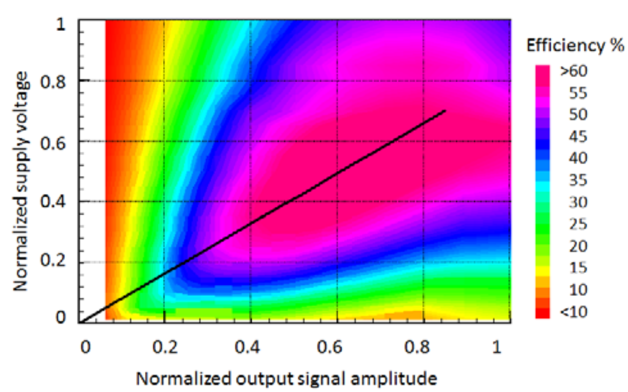
I. Introduction and Background

Signals designed for high-capacity communications result in high peak-to-average power ratio (PAPR) waveforms that the transmitter power amplifier needs to amplify with low distortion. For the next generation wireless systems, the carrier frequencies and signal bandwidths are expected to increase significantly from the current S and C-band allocations. It becomes increasingly challenging to maintain the transmitter power amplifier efficient, since PAE is not constant over output power and highly efficient PAs are usually nonlinear. Here a brief review of supply modulation for efficiency enhancement of several types of power amplifiers is given, along with a discussion of challenges for extending supply modulation to future wireless systems.

The block diagram shown in Fig.1(a) reviews a basic envelope-tracking (ET) PA transmitter, where the power supply voltage provided to the PA is dynamically varied in accordance with the time-varying envelope of the signal so that the PA is kept nearly always in compression, where its efficiency is high [1,2]. Fig.1(b) shows a typical efficiency plot as a function of normalized output signal amplitude and supply voltage. If a dynamic supply could follow the peaks of the



(a)

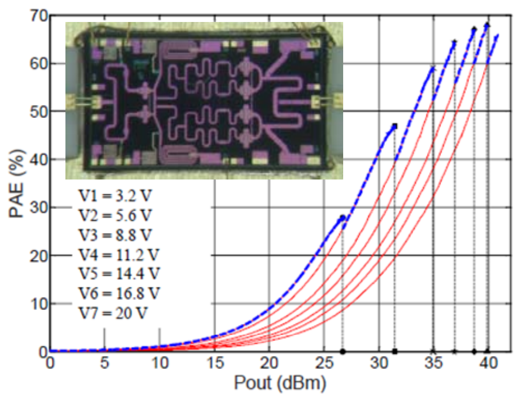


(b)

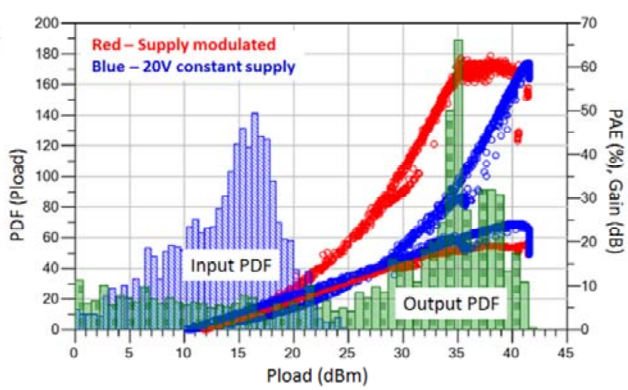
Fig.1. (a) Block diagram of a typical ET transmitter showing the high-efficiency RFPA, and supply modulator that consists of an efficient but slow switching dc-ed converter and a linear amplifier that provides the high-bandwidth signal component. (b) Typical dependence of efficiency on normalized supply voltage and output power of a PA.

efficiency as the signal envelope varies, this approach can result in a substantial increase in average efficiency of the RFPA. However, the overall system efficiency includes losses in both the PA and the dynamic power supply (envelope modulator), which is challenging to implement with high efficiency, high accuracy and high slew rate required for broadband signal amplification. Fig.1(a) shows a typical implementation of the envelope modulator with an efficient slow switching-mode converter combined with a less-efficient but faster linear amplifier, e.g. [3], [4]. This approach was demonstrated with high efficiency by several authors for 20-MHz LTE signals.

In this paper, an overview of supply modulation approaches for broadband signals with high PAPRs is presented, starting from 20/40MHz LTE signals, to 100-MHz and 250-MHz multi-carrier signals and multiple simultaneous signals varying over a 1GHz bandwidth. Fig.2 shows measured static PAE for several drain voltages of a 13-W peak power GaN MMIC (Qorvo 150-nm GaN on SiC process, similar to the PAs in [5]). The relationship between supply voltage and output signal is referred to as a trajectory [6] and is shown in blue line which follows discrete V_{DD} values. For continuous tracking, the simulations in Fig.2(b) show an improvement of 22 points in average efficiency with over 45% average PAE.



(a)



(b)

Fig.2. (a) Measured pulsed PAE vs. Pout for a 13-W 21-dB saturated gain GaN MMIC PA for 7 different supply voltages. (b) Simulated improvement for a 20-MHz LTE signal with 10dB PAPR showing an average 22 point improvement in efficiency for the tracking case vs. the constant supply case, assuming continuous tracking. .

Several very fast (100MHz switching) and efficiency dc-dc converters as supply modulators (SM) were implemented in the same GaN process [7] with 93% efficiency at 100MHz switching with typical results shown in Fig.3. Such an integrated SM-PA can achieve high efficiency, but only up to instantaneous bandwidths that are a fraction (~1/5th) of the switching frequency. For higher switching frequencies, multi-phase tracking achieves 73% efficiency at 400MHz with up to 16W output power [8], but for signals with bandwidths >100MHz, this solution is will not be fast and efficient and other solutions are needed, as described in the next section.

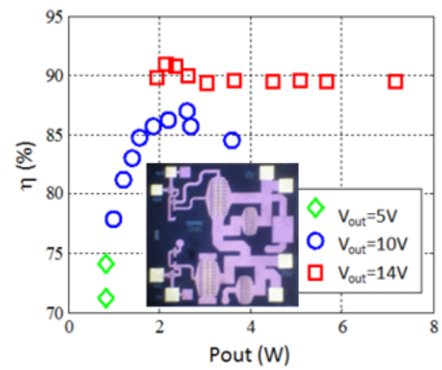
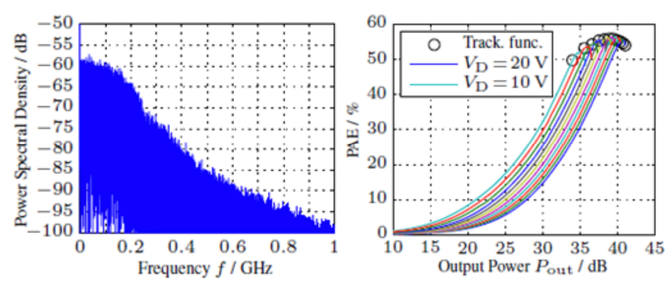


Fig.3. Measured efficiency of a 100-MHz switching GaN MMIC Buck converter (2mm square) for three dc voltages. The efficiency includes the low- and high-side drivers.

II. ET for Large Envelope Bandwidths

Envelope tracking becomes challenging for high-bandwidth signals because the envelope is theoretically infinite in bandwidth, but 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 [6]. A method to increase efficiency with a bandwidth limited supply modulator is demonstrated in [9] and a similar method, referred to as slew-rate reduction is discussed in [10]. Both reported solutions are applied to 5MHz signals with a PAPR of 7.6 dB for the first case. Here we focus on signals with baseband bandwidths exceeding 100MHz and PAPRs exceeding 10 dB, modulated onto X-band carriers, Fig.4(a).



(a) (b)

Fig.4. (a) Spectrum of a 250-MHz band-limited Gaussian noise signal that is continuously tracked. (b) MMIC PA from Fig.2 measured PA as a function of output power at 10GHz with points showing the tracking trajectory for constant gain.

Instead of continuously tracking the extremely broadband envelope, the envelope modulator is a multi-level supply which switches between different static voltages. Efficient implementations with 4 [11] and 8 levels [12] were recently demonstrated, with efficiencies exceeding 97% and 94%, respectively. Discrete trackers overcome the bandwidth limitations while maintaining efficiency, but sacrifice the smooth continuous tracking usually employed for ET.

The X-band MMIC PA from Fig.2 measured with digitally generated NPR (noise power ratio) signals with bandwidths of 100MHz and 250MHz, and a notch-bandwidth of 1%, using 30 001 carriers. This results in PAPR of 11.1 dB and 10.3 dB for the two test signals. A 250MHz pulse shaped test signal is used for time alignment between the RF and tracking signals. A flexible, inefficient linear tracker is used, based on two ADA4870 2.5V/ns SR current-feedback operational amplifiers which are connected in parallel using 0.2Ω series resistors, to provide up to 2A of peak current to the PA.is used as part of our test bench. A second 0.2Ω series resistor ensures stability of the tracker when connected to the capacitive PA drain.

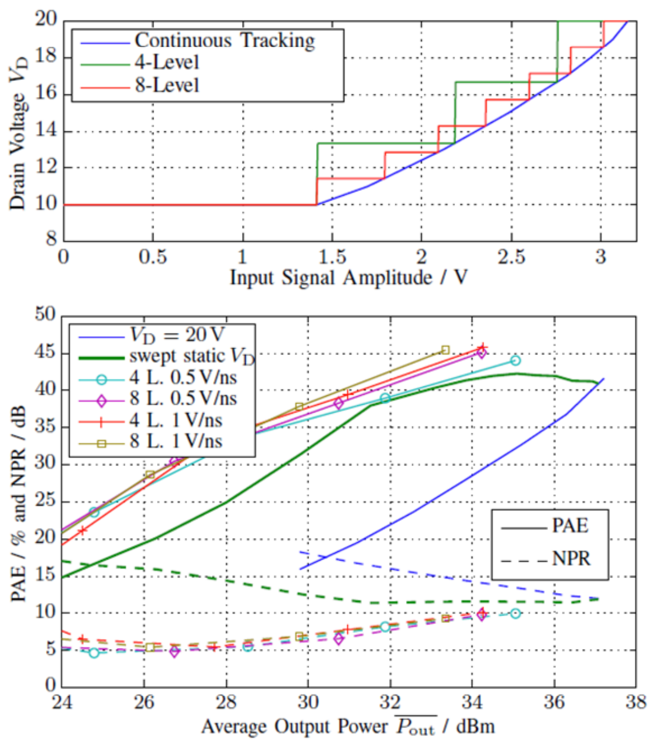


Fig.5. Trajectory for various types of tracking (top) and measured performance (bottom) for the MMIC PA from Fig.2. PAE and NPR are plotted as a function of average output power for a 100-MHz 11-dB PAPR signal.

The PAE and linearity (NPR) results for 4- and 8-level tracking for the 100MHz noise signal are compared to constant drain voltage operation in Fig.5. We limit the average input power to the amplifier to 18dBm to avoid destruction due to the high PAPR test signal. The PAE is raised from 42.3% for an optimum static 15V supply to 45.8% using 4-Level ET with a SR of 1V/ns. The NPR is slightly reduced from 11.6dB to 10.1dB. The PAE break-even point between ET and a static supply for this bandwidth lays at 0.2V/ns. As expected, tests with the 250-MHz signal result in lower efficiency [13]. The next step is to perform tests with efficient existing multi-level MMIC supply modulators.

III. Multi-Signal ET

Multi-band power amplifiers (PA) for carrier aggregation and multi-function transmitters can help reduce cost and size in many applications. However, efficiency enhancement techniques tend to restrict bandwidth. When multiple signals of arbitrary modulation type and separated carrier frequencies are amplified simultaneously, the total signal bandwidth exceeds what can be achieved using conventional ET. Multi-band ET is explored in [14] for a frequency-tunable PA, but the bands are not used concurrently. In [15]–[16], ET is demonstrated on two concurrent signals. These works focus on 3D linearization of two relatively closely spaced signals, for example for dual-band carrier aggregation. In this work we instead examine the bandwidth of multiple concurrent, arbitrarily-spaced signals as might be required for a multi-band, multi-function transmitter [17].

The frequency-domain analysis is shown in Fig.6(a). The envelope of three 16QAM signals with bandwidths of 1, 3, and 5MHz separated by 70 and 130MHz and centered around 9.8GHz are combined. Conventional ET requires 800MHz tracking, while tracking the sum of envelopes requires only 17 MHz. For the analyzed ideal class-B PA, efficiency when the sum of the envelopes is tracked is 52%, whereas linear class B operation at peak output power results in only 23% efficiency.

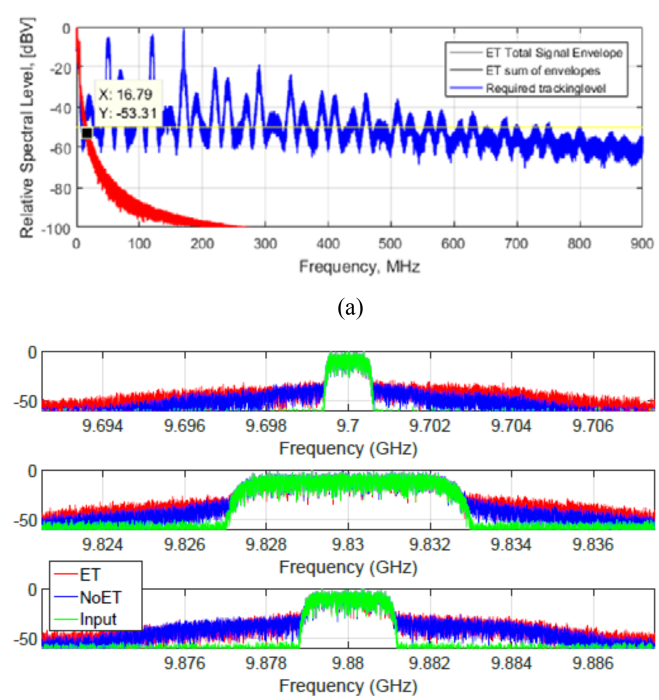


Fig.6. (a) Ideal spectra of combined envelope (blue) and summed envelopes (red). (b) Measured normalized individual signal spectra at the input of the PA (green), output of PA with no supply modulation (blue) and output of PA with reduced bandwidth supply modulation (red).

The measurements were performed with the same MMIC PA and linear tracker as in the previous section for the signals shown in the table below. The measured results are shown in Fig.6(b) and summarized in the table. A substantial increase in efficiency is seen and the EVM results are without any predistortion.

f_1,f_2,f_3 (GHz)	P_1,P_2,P_3	Drain	PAE (%)	EVM (%)		
				1	2	3
9.7, 9.83, 9.88	0.33, 0.33, 0.33	Track	42.4	13.8	16.7	18.8
		Fixed	29.7	8.7	11.3	14.4

IV. Conclusions

In conclusion, this paper addresses envelope tracking for challenging signal bandwidths and scenarios applied to GaN MMIC PAs with a carrier in the 10-GHz range. In the final version of the paper, information about multi-level tracking for Chireix outphasing PAs and harmonically injected PAs will be added in order to show the versatility of the efficiency-enhancement approach to more advanced PA topologies.

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