Supply Modulation of a Broadband Load Modulated Balanced Amplifier

Tommaso Cappello[1], Prathamesh H. Pednekar[1], Corrado Florian[2], Zoya Popovic[1], and Taylor. W. Barton[1]

[1]Department of Electrical, Computer and Energy Engineering, University of Colorado, Boulder, CO, 80309, USA
[2]Department of Electrical, Electronic and Information Engineering, University of Bologna, Bologna, 40136, Italy

***Abstract*—This work presents multi-level supply modulation of a load modulated balanced amplifier (LMBA). The RF-input LMBA employs dynamic active matching for efficient operation over an octave bandwidth. Supply modulation is a natural candidate to further enhance the back-off efficiency of this broadband amplifier due to its independence on RF carrier frequency. In the ET-LMBA prototype demonstrated here, an efficient hybrid multi-level converter (power DAC) produces supply levels from 10 to 30 V to modulate the drain of the balanced amplifier. Digital predistortion is used to linearize the ET-LMBA behavior at discrete steps and over frequency. This system is demonstrated at 2.1, 2.7 and 3.5 GHz with a 20-MHz, 10-dB PAPR signal showing composite efficiency improvement between 9 and 12 percentage points when supply modulation is employed, while maintaining linearity.**

***Index Terms*—load modulated balanced amplifier, LMBA, envelope tracking, supply modulation, power-DAC, power amplifier.**

I. Introduction

Amplification of wide instantaneous bandwidth, high peak-to-average power ratio (PAPR) signals for multiple carriers is driving the development of radio-frequency (RF) power amplifiers (PAs) which trade efficiency, bandwidth and linearity while maintaining output power. Various PA architectures address a part of this tradeoff space, through e.g. Doherty [1], envelope tracking (ET) [2] and Chireix outphasing [3], usually accompanied by some form of linearization. Combining multiple approaches can provide solutions for wideband linear-efficient operation, e.g. [3].

The load modulated balanced amplifier (LMBA) was introduced recently in [4], [5] as an approach that addresses the bandwidth limitations of conventional Doherty and outphasing techniques, while enabling efficiency enhancement in backoff. The LMBA is based on a classical balanced amplifier with wideband input and output quadrature couplers. A control signal is injected into the normally terminated isolation port of the output coupler, modulating the load presented to the two devices, and producing an active and controllable match. The control signal can optionally be generated from the modulated RF input using an input splitter and appropriately designed control PA, thereby producing an RF-input LMBA [6]. This architecture is attractive for its wide bandwidth and efficiency enhancement through load modulation. In this work, we show that the back-off efficiency of an LMBA can be extended by modulating the supply voltage of the balanced amplifier.

Supply modulation is a natural candidate to further enhance the back-off efficiency of a broadband PA, since the modulator

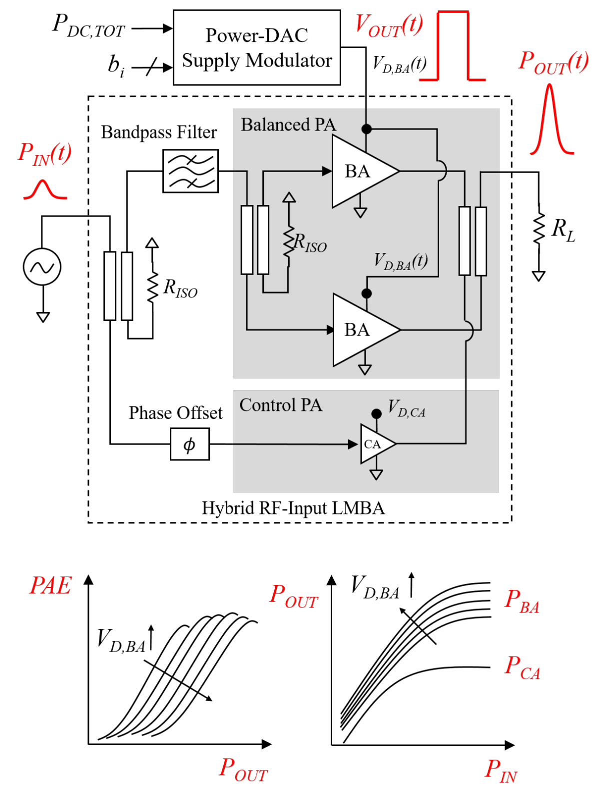


Fig. 1. Simplified schematic of the single RF-input load modulated balanced amplifier (LMBA) with supply modulation. A multi-level power-DAC is used to dynamically vary the supply voltage of the balanced PA part of the LMBA for efficiency enhancement.

is independent of the carrier frequency. We note that static supply modulation of the LMBA has been originally proposed in [5]. Here, we apply dynamic supply modulation of the LMBA using a fast hybrid GaN-on-Si multilevel converter [7], in the first demonstration of modulated signals of the ET-LMBA architecture.

II. ET-LMBA Architecture

A simplified block diagram of the ET-LMBA is shown in Fig. 1. Supply modulation is implemented with an efficient 8-level power-DAC, which produces discrete power supply steps ranging from 10 V to 30 V. The hybrid RF-input LMBA is implemented with Wolfspeed GaN-on-SiC packaged devices. The control PA is scaled in both device size (6-W compared to 10-W balanced amplifier devices) and supply voltage (20 V

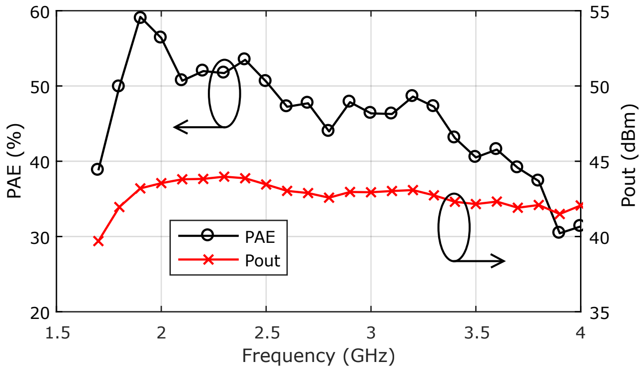


Fig. 2. Measured (CW) maximum PAE and P_{OUT} of the RF-input LMBA with fixed bias between 1.7 to 4 GHz [6].

compared to 30 V). As a result, it compresses at a lower input power than the PAs in the balanced amplifier, resulting in a input-power-dependent relative injected signal level and thus a power-dependent match presented to the main PAs. This nonlinear characteristic, along with frequency-dependent phase compensation, maintains dynamic active matching over greater than an octave bandwidth with a fixed supply voltage, summarized in Fig. 2.

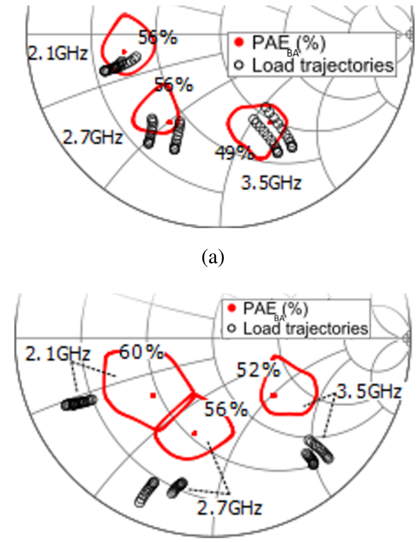
In order to maintain asymmetry between the balanced and control amplifiers, only the drain supply voltage of the balanced amplifier PAs is varied, while keeping a fixed 20-V control PA supply. This approach degrades the match provided by the control PA as the drain supply of the balanced amplifier is varied. Fig. 3 shows the simulated load trajectories presented to the balanced amplifier devices across frequency for supply voltages of 30 V and 15 V. The active match provided by the control signal is optimized for the design voltage of 30 V. However, the overall system efficiency remains high due to the higher absolute PAE values.

III. Experimental Setup

A photograph of the experimental setup is shown in Fig. 4. The input RF signal is generated and analyzed by a National Instrument PXIe-5840 ("VST2") which features 1 GHz I/Q bandwidth for carrier frequencies up to 6.5 GHz. The output of the VST2 is linearly amplified by an instrumentation driver amplifier with up to 32 dBm at the input reference plane of the LMBA. The output of the LMBA is then attenuated before the input port of the VST2. Power calibration of the experimental setup is performed at the two edge frequencies of 2.1 and 3.5 GHz and at a frequency of 2.7 GHz within the band.

The digital control bits of the Power-DAC are generated by the FPGA within the VST2, which is customized to include the control of the supply modulator synchronized with the RF signal generation. The I/Q sampling frequency is 1.25 GHz while the power-DAC control signals are sampled at a lower frequency of 312.5 MHz.

Fig. 3 shows the simulated frequency variation of the PAE contours and the load trajectories of the balanced amplifier at 30 and 15 V, while the drain voltage of control PA is held constant at 20 V. Since the PA is originally designed to operate the



(b)

Fig. 3. Simulated PAE and load trajectories at 2.1, 2.7 and 3.5 GHz. (a) Simulated PAE at $v_D = 30$ V. (b) Simulated PAE at $V_D = 15$ V. The control PA supply voltage is held constant at 20 V.

balanced PA at 30 V, the load trajectories are better matched in this case as reported in Fig. 3. As the drain supply of balanced amplifier is lowered, the active match provided by the control signal degrades, which in turns degrades the efficiency. However, the simulated LMBA efficiency still improves as a result of supply modulation. Therefore, in this ET-LMBA architecture, we choose to keep the drain of the control PA fixed at 20 V while the drains of the balanced PA are connected together and supply modulated between 10 and 30 V.

An efficient 8-level supply modulator (i.e. Power-DAC) is used to this purpose [7] and its output voltage can be expressed as

$$V_D = V_{OS} + \sum_{i=1}^{3} b_i V_{DCi}, \tag{1}$$

where $V_{OS} = 10$ V is the offset voltage at the output of the supply modulator; $V_{DC1} = 3.2$ V, $V_{DC1} = 5.6$ V, and $V_{DC3} = 11.2$ V are three isolated voltage sources at the input of the Power-DAC. With such voltage selection it is possible to generate eight voltage levels (one is 10 V) up to $V_D = V_{D,MAX} = V_{OS} + V_{DC1} + V_{DC2} + V_{DC3} = 30\,V$.

DPD of the ET-LMBA is extracted and applied off-line on the computer controlling the setup. Pre-pulsing characterization [8] is employed to extract the nonlinear behavior with memory of the LMBA at every supply level and at the three carrier frequencies. A generalized memory polynomial is employed to describe the intra-level behavior of the LMBA, parametrized with the non-linearity order of five and a cross-term and memory order of two.

A. ET-LMBA Characterization

The ET-LMBA architecture is characterized in pulsed RF- and DC-mode at 2.1, 2.7 and 3.5 GHz. The total LMBA efficiency is defined as $(P_{OUT} - P_{IN})/(P_{CA} + P_{BA})$ where

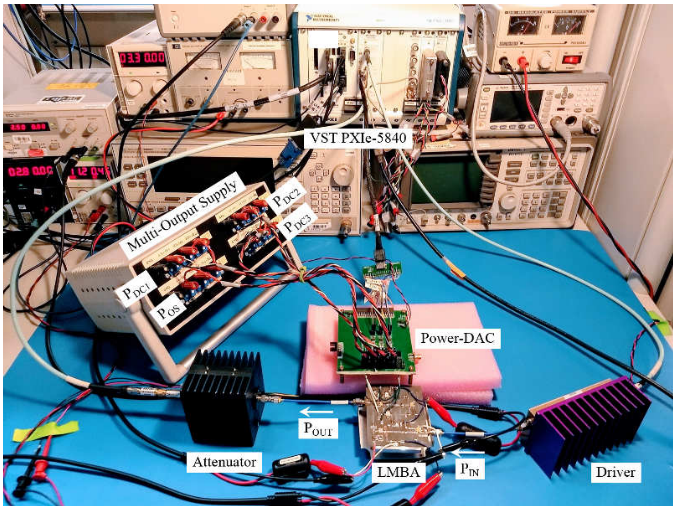


Fig. 4. Photograph of the setup (oscilloscope not visible).

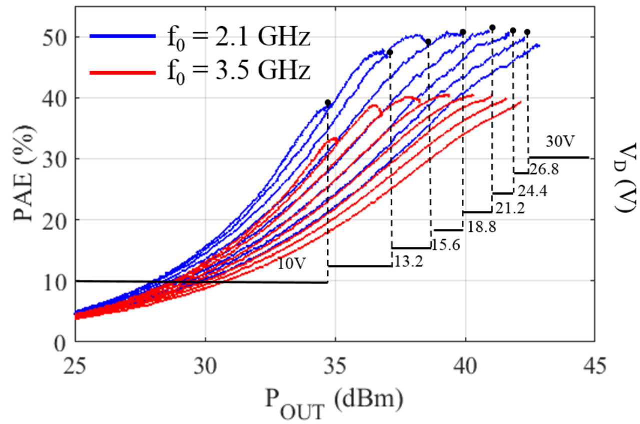


Fig. 5. PAE characteristics of the ET-LMBA at the eight voltage levels and at two carrier frequencies at the band edges, 2.1 and 3.5 GHz. The discretized supply shaping table for 2.1-GHz also shown.

the denominator is the sum of the DC power drawn by the control and balanced amplifiers. The PAE characterization gives trajectories shown in Fig. 5 for the two edge frequencies at 2.1 and 3.5 GHz. The plot highlights the benefits of supply modulation with the LMBA architecture as also shown in [5] with static measurements. The PAE reaches 50% for a wide range of output powers at 2.1 GHz and 40% at 3.5 GHz. We note that moving towards higher frequencies the efficiency degrades as can be seen in Fig. 2. Here, the backoff efficiency of the LMBA is further enhanced by means of supply modulation and the benefits are evident in the plot.

Supply-modulator efficiency is included in the composite power-added efficiency of the supply modulated balanced PA (with fixed control PA bias) as

$$CPAE = \frac{P_{OUT} - P_{IN}}{P_{CA} + P_{DC,TOT}} \tag{2}$$

where $P_{DC,TOT} = P_{OS} + \sum_{i=1}^{3} P_{DCi}$ is the total DC power at the input of the supply modulator, P_{OS} is the power supplied by the offset voltage (10 V) and P_{CA} is the DC power drawn by the control PA. These input powers are measured accurately with a wide-band 120-MHz current probe (Tek TCP0030) and a digital oscilloscope (Tek DPO2024).

IV. Measurement Results

With the setup fully calibrated as described above, the ET-LMBA architecture is demonstrated with a 20-MHz, 10-dB PAPR signal at three carrier frequencies and the results are summarized in Table I and Fig. 6. Fig. 7 shows the time-domain operation of the amplifier, showing the predistorted input power, the supply modulator control signal (not to scale) and the generated output power superposed with the ideal envelope of the transmitted signal. The discontinuities that correspond to supply voltage level commutation are approximately compensated with DPD. Future work will address reducing parasitics of the interconnect between the supply modulator and PA, which is currently a connection between two separate boards.

In Table I, we compare the supply-modulated LMBA to the same LMBA operated at a fixed supply voltage. Linearity, both in terms of NRMSE/EVM and ACLR is slightly degraded from the fixed supply case while the total DC power $P_{DC,TOT}$ is significantly reduced. The average output power is somewhat improved most likely due to the pulsed mode of operation of the supply-modulated case. We note also that the DC power consumption ratio between the balanced PAs and the control PA changes over frequency; this phenomenon is most likely due to the varying load impedance of the balanced PAs over frequency as also shown in the load trajectories of Fig. 3.

V. Conclusion

This paper details the operation of an envelope-tracked load-modulated balanced amplifier (ET-LMBA). A broadband experimental setup based on a National Instruments VST is used to explore the characteristics of the ET-LMBA at 2.1, 2.7 and 3.5 GHz. Results with and without supply modulation are compared and show an improvement between 9 and 12 percentage points with good linearity when discrete supply modulation is employed together with digital predistortion of the wideband RF-input LMBA.

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TABLE I
PERFORMANCE SUMMARY OF THE ET-LMBA WITH DPD FOR A 20-MHZ, 10-DB PAPR LTE-LIKE SIGNAL.

Central Frequency	*Control Strategy*	*NRMSE*	*EVM*	*ACLR*	P_{DC1}	P_{DC2}	P_{DC3}	P_{OS}	$P_{ETBA,TOT}$	$P_{CTRL,PA}$	$P_{DC,TOT}$	$P_{IN,AVG}$	$P_{OUT,AVG}$	*CPAE*
2.1 GHz	Fixed Bias (FB) + DPD	0.7%	0.7%	-56 dB	-	-	-	-	6.21 W	1.28 W	7.49 W	0.12 W	2.03 W	26%
2.1 GHz	**Supply Mod. (SM) + DPD**	**1.8%**	**2.0%**	**-45 dB**	**0.20 W**	**0.79 W**	**0.24 W**	**1.23 W**	**2.46 W**	**2.20 W**	**4.66 W**	**0.30 W**	**2.06 W**	**38%**
2.7 GHz	Fixed Bias (FB) + DPD	0.5%	0.6%	-57 dB	-	-	-	-	5.27 W	2.11 W	7.38 W	0.13 W	1.82 W	23%
2.7 GHz	**Supply Mod. (SM) + DPD**	**1.6%**	**1.7%**	**-43 dB**	**0.18 W**	**0.38 W**	**0.30 W**	**0.54 W**	**1.40 W**	**3.10 W**	**4.5 W**	**0.27 W**	**1.85 W**	**35%**
3.5 GHz	Fixed Bias (FB) + DPD	0.9%	0.9%	-54 dB	-	-	-	-	4.88 W	2.80 W	7.68 W	0.11W	1.70 W	21%
3.5 GHz	**Supply Mod. (SM) + DPD**	**1.4%**	**1.5%**	**-42 dB**	**0.21 W**	**0.36 W**	**0.31 W**	**0.56 W**	**1.44 W**	**3.60 W**	**5.04 W**	**0.21 W**	**1.74 W**	**30%**

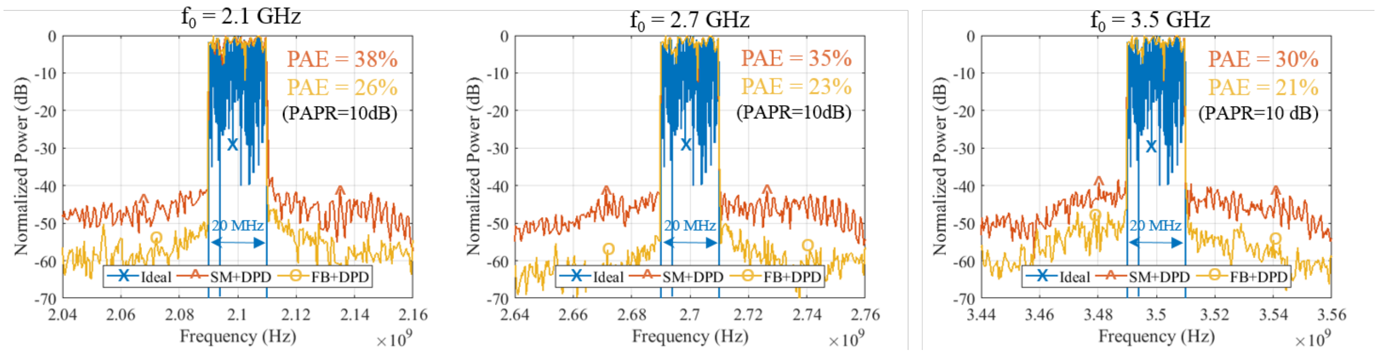

Fig. 6. Measured output spectra of the ET-LMBA at 2.1, 2.7 and 3.5 GHz for a 20-MHz, 10-dB PAPR signal. Supply modulation (SM) and fixed bias (FB) operation are compared, both with DPD.

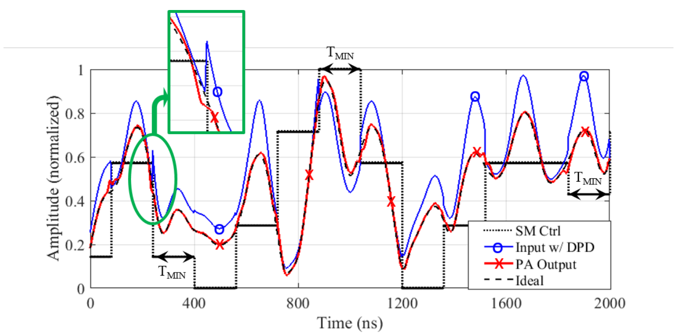

Fig. 7. Measured output envelope of the ET-LMBA for a 20-MHz, 10-dB PAPR signal at 2.1 GHz. The DPD successfully linearizes the ET-LMBA behavior at multiple supply levels.

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