Multi-Level Supply-Modulated Chireix Outphasing for LTE Signals

Tommaso Cappello[1,2], Corrado Florian[1], Taylor W. Barton[2], Michael Litchfield[2], and Zoya Popovic[2]

[1]Department of Electrical, Electronic and Information Engineering, University of Bologna, Bologna, 40136, Italy

[2]Department of Electrical, Computer and Energy Engineering, University of Colorado, Boulder, CO, 80309, USA

tommaso.cappello@unibo.it, corrado.florian@unibo.it, taylor.w.barton@colorado.edu, mplitchfield@gmail.com, zoya.popovic@colorado.edu

***Abstract*—This work presents a dynamic characterization of a multi-level Chireix outphasing (ML-CO) power amplifier (PA) with modulated signals. The ML-CO technique combines the advantages of envelope tracking and outphasing architectures by limiting the supply modulation to discrete levels (enabled by an efficient power DAC modulator) and using outphasing for fine amplitude control. We describe the development of an experimental test bench able to supply phase- and time-aligned modulated signals for outphasing and supply modulation simultaneously. Pulse characterization is used to design a multilevel memory-less polynomial DPD. The linearized ML-CO PA is demonstrated with 1.4 MHz and 10 MHz LTE signals at 9.7 GHz. For both signals, the average total power consumption is reduced by a factor of two when supply modulation is used. For the 9.3 dB PAR, 1.4 MHz signal the PA operates with 38% average drain efficiency at 0.54 W average output power.**

***Index Terms*—outphasing, multilevel, Chireix, discrete supply modulation (DSM), power amplifier (PA), power-DAC, supply modulator.**

I. Introduction

As communications systems continue to move towards signals with higher peak-to-average power ratio (PAPR), it is increasingly important for power amplifiers (PAs) to have high efficiency over a wide dynamic range. Efficiency enhancement techniques such as Doherty, envelope tracking (ET) and outphasing have been developed to extend efficient operation into back-off. Individually, however, these techniques may not provide sufficient back-off efficiency for communications signals. The power range over which a PA operates efficiently can be extended by combining multiple efficiency enhancement techniques, whether of the same type as in four-way Doherty [1] and four-way outphasing [2], or multiple approaches of different types.

In this work, we use a combination of outphasing and discrete supply modulation to extend the efficient operating range of an X-band PA. A simplified block diagram of the multi-level Chireix outphasing (ML-CO) architecture is shown in Fig. 1. This approach captures the benefits of both ET and Chireix outphasing systems: by limiting the supply modulation to discrete levels providing coarse amplitude control, the envelope tracker efficiency can be improved compared to a linear tracker, while fine amplitude control is achieved through efficient load modulation of the PAs. Compared to multi-level outphasing techniques employing an isolating (Wilkinson) power combiner [3], the fine-amplitude-control efficiency is comparatively higher due to the lack of an isolation resistor.

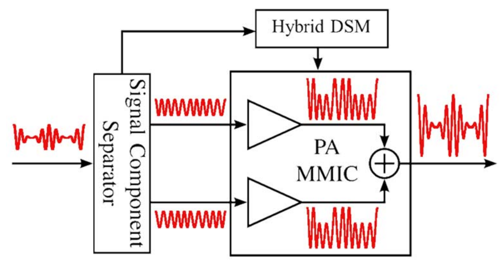

Fig. 1. Simplified diagram of the ML-CO system. The technique uses a multi-level converter to modulate a Chireix outphasing PA [4].

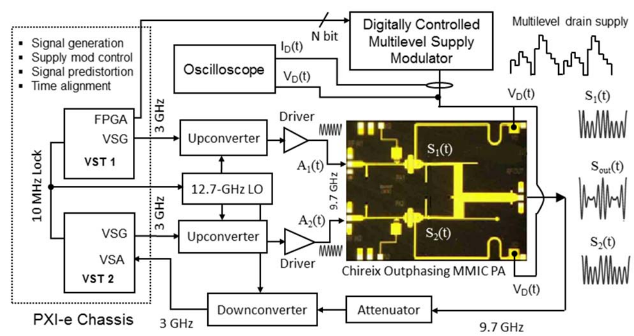

Fig. 2. Block diagram of the experimental test bench. Two VSTs from National Instruments are phased-locked by the PXI-express bus and used to generate the modulated signals. Both PAs are supply modulated together.

ML-CO PAs have previously been demonstrated in [4] and [5], but measured with CW signals only. As in other techniques using a combination of supply and drive modulation [3], in ML-CO the dynamics of and time alignment between the phase and amplitude control paths is critical to reduce memory effects. Furthermore, nonlinearities arise from both the load modulation and envelope modulation paths. This work therefore focuses on the development of a test bench for the characterization of the performance of a ML-CO PA with modulated signals and a preliminary linearization of this architecture. We demonstrate an X-band ML-CO amplifier using a MMIC PA and hybrid multilevel converter in GaN-on-Si [6]-[7], including the first demonstration of modulated signals in a ML-CO outphasing system.

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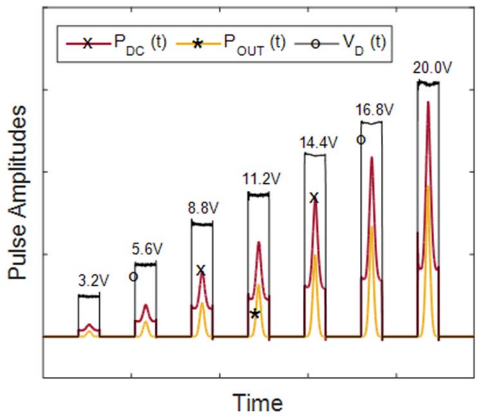

Fig. 3. Pulse characterization measurements used to characterize the PA at different supply levels. The AM Blackman pulse has 10µs duration and 10% duty cycle.

II. ML-CO Testbench for Modulated Signals

A detailed block diagram of the ML-CO architecture is shown in Fig. 2. The PA MMICs are fabricated in Qorvo's 0.15µm process and designed to operate in class F. The Chireix power combiner performs both fundamental matching and phase-dependent load modulation [4]. The hybrid multi-level discrete supply modulator (DSM) is based on a 3-bit power-DAC architecture and has up to 95% efficiency over its output voltage range [6]-[7]. Because of the high efficiency of the supply tracker (a key advantage of discrete supply modulation compared to continuous linear tracking), the composite efficiency of the system is dominated by the PA efficiency.

The focus of this paper is on the dynamic characterization and linearization of this system. A major challenge in modulated outphasing testing is the need to generate multiple dynamic phase- and time-aligned drive signals for the two PAs and for the drain modulator. We use two National Instrument Vector Signal Transceivers (VSTs), phased-locked by the PXI-express bus. The 3 GHz constant-envelope, phase-modulated VSG outputs from the VSTs are upconverted to the 9.7 GHz operating frequency of the PAs. The external LO used for upconversion is also phase-locked to the 10 MHz reference clock of the VSTs. Simultaneously, a time-aligned digital signal generated by the integrated FPGA controls the supply modulator. One VST is also used as an observation receiver.

The performance of the ML-CO PA is first characterized over the multiple supply levels using an amplitude-modulated pulse (with Blackman shape). The pulse signal, expressed generally as $S(t) = A(t)e^{j\phi(t)}$ is decomposed into two constant-envelope signals $A_1(t)$ and $A_2(t)$ with outphasing angle $\theta = \cos^{-1}(A(t))$. The measured output power, dc power consumption, and supply voltage are shown in Fig. 3. In this repeated sequence, the peak voltage at 20 V acts as a pre-pulse that conditions the trap-state of the PAs, allowing an improved extraction of the characteristics (controlled trap-state similar to the multi-level operative regime) [8]. The outphasing behavior is characterized based on the pulsed measurements and is shown in Fig. 4. Note that drain efficiency rather than total efficiency is quoted throughout this paper because we are using a constant 25 dBm drive level for the PAs. In future measurements, a step modulation of the PA input signal envelope (easily implemented with the proposed setup) will be used to maintain a consistent gain across the different supply values, so that total efficiency can be used.

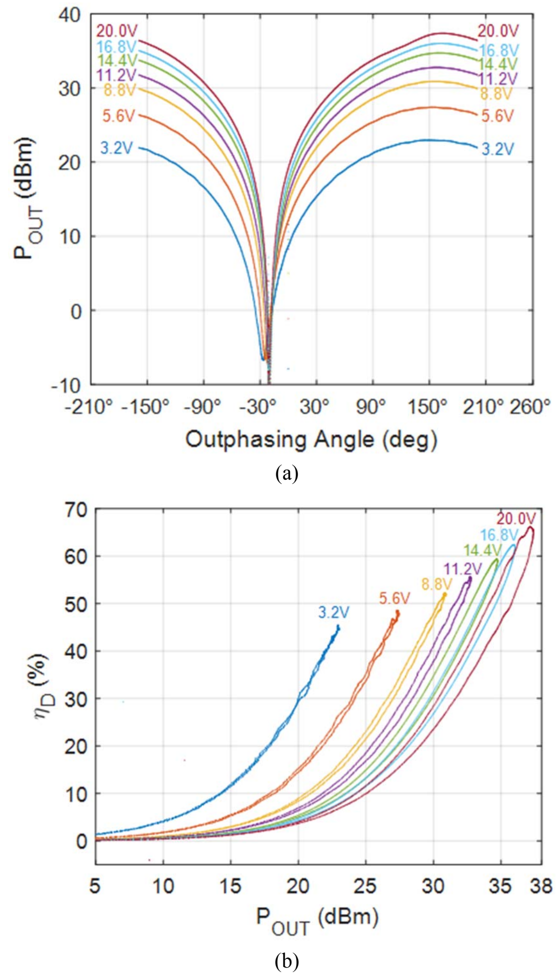

Fig. 4. PA characterization over discrete supply voltages at 9.7 GHz; (a) – output power vs. outphasing angle and (b) – efficiency vs. output power.

The dynamic multilevel characterization is used to determine the shaping function for the supply modulation. The PA input signals, $A_1(t)$ and $A_2(t)$, are pre-distorted (at baseband) by a multi-level memory-less polynomial DPD. This DPD approach is described in [6]-[7] and reproduced as (1)-(3) here, where $x(n)$ is the baseband signal at the ~~PA input~~ transmitter input, $z(n)$ is the baseband predistorter output, and $\mathcal{F}_D$ is the discretized tracking trajectory. The complex coefficients $a_{k,i}$ depend on the instantaneous bias voltage V_i and on the order of the polynomial ($K_i = 9$). The thresholds at which the V_i voltage commutates corresponds to the peak η_D within each voltage level.

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$$z(n) = \sum_{k=1}^{K_i} a_{k,i} x(n) |x(n)|^{k-1} \quad (1)$$

$$a_{k,i} = |a_{k,i}| e^{j\angle a_{k,i}} = a_{k,i}(V_i) \quad i = 1, \dots, N \quad (2)$$

$$V_i = \mathcal{F}_D(|x(n)|) \quad i = 1, \dots, N \quad (3)$$

The model coefficients are determined by complex polynomial fitting of the inverse of the measured AM/AM and AM/PM characteristics, shown in Fig. 5 along with the DPD correction corresponding to each supply level. The AM/AM characteristics clearly show both varying gain and varying distortion of the PA as the supply voltage changes.

III. Measurements

The complete experimental setup is shown in Fig. 6. With the testbench and DPD fully characterized as described above, this setup is demonstrated using LTE signals. Fig. 7 shows the time-domain signal decomposition with envelope tracking. The outphasing signals (not shown) are used to compensate for the discrete steps of the supply voltage, V_{DC}, to obtain a continuous output signal, P_{OUT}. The discontinuities in the instantaneous dc power consumption, P_{DC}, highlight the benefits of multi-level supply modulation.

As indicated in the summary in Table I, the dc power consumption is halved with multi-level envelope tracking, compared to a fixed supply level, for both 1.4 MHz and 10 MHz LTE signals. In this table, η_D is the drain efficiency of the outphasing PA, η_{pDAC} is the efficiency of the power-DAC supply modulator, and C-EFF is the composite efficiency, $\eta_D \times \eta_{pDAC}$. There is a clear efficiency benefit to ML-CO compared to outphasing only (fixed supply). Although the multi-level supply modulation causes nonlinearities, as seen in the spectrum plots in Fig. 8, DPD is able to restore the linearity of the system.

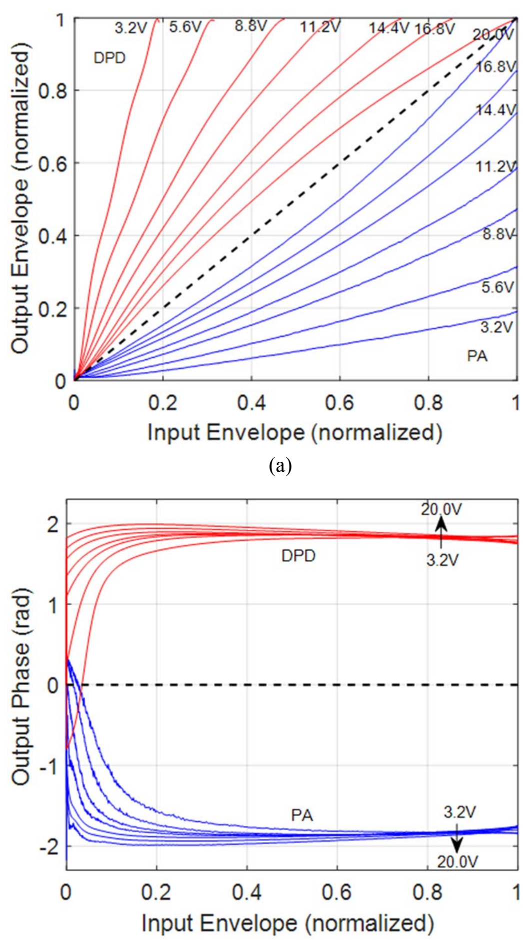

Fig. 5. Normalized measured AM/AM (a) and AM/PM (b) characteristics of the ML-CO PA at different drain supply levels, and DPD correction. The normalized input envelope refers to the envelope of the original signal $S(t)$ before decomposition into $A_1(t)$ and $A_2(t)$.

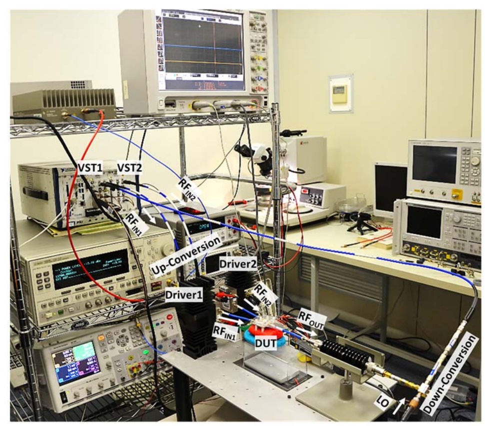

Fig. 6. Photograph of the experimental setup.

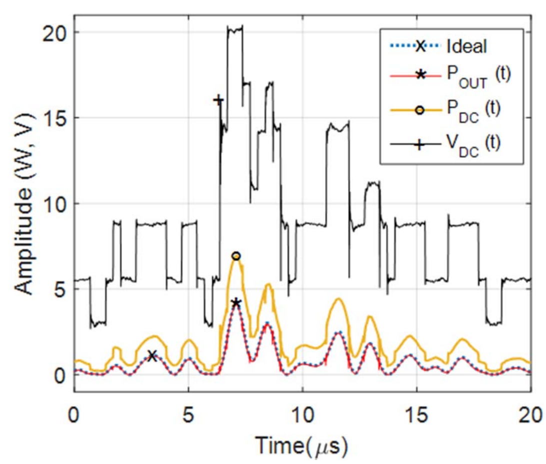

Fig. 7. Time-domain drain voltage, output power, and dc power consumption waveforms for a 1.4 MHz LTE signal.

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TABLE I

PERFORMANCE SUMMARY WITH LTE SIGNALS, WITH AND WITHOUT ENVELOPE TRACKING.

Signal (PAPR)	Supply Modulation	EVM	ACLR (dBm)	$P_{DC,AVG}$ (W)	$P_{OUT,AVG}$ (W)	$_{D}$ (%)	$_{pDAC}$ (%)	C-EFF
LTE 1.4 MHz (9.3 dB)	Fixed Supply + DPD	2.6%	-47.2 dB	2.80 W	0.54 W	19.3%	100%	19.3%
LTE 1.4 MHz (9.3 dB)	**ET + DPD**	**4.7%**	**-41.6 dB**	**1.42 W**	**0.54 W**	**38.0%**	**93%**	**35.3%**
LTE 10MHz (11.3 dB)	Fixed Supply + DPD	4.7%	-39.0 dB	2.62 W	0.35 W	13.4%	100%	13.4%
LTE 10 MHz (11.3 dB)	**ET + DPD**	**7.0%**	**-31.5 dB**	**1.37 W**	**0.35 W**	**25.6%**	**89%**	**22.8%**

IV. CONCLUSION

This work demonstrates the feasibility of linearizing a multilevel ML-CO system operating on modulated communications systems. A testbench based on a GaN X-band PA MMIC, hybrid discrete supply modulator, and two National Instruments VSTs is developed and characterized with pulse-modulated signals. The combination of supply modulation and outphasing halves the dc power consumption, leading to 16 percentage points higher efficiency for a 1.4 MHz LTE signal and 9.4 percentage points for a 10 MHz LTE signal. DPD based on a multi-level memory-less polynomial is used to restore the linearity of the system when supply modulation is used.

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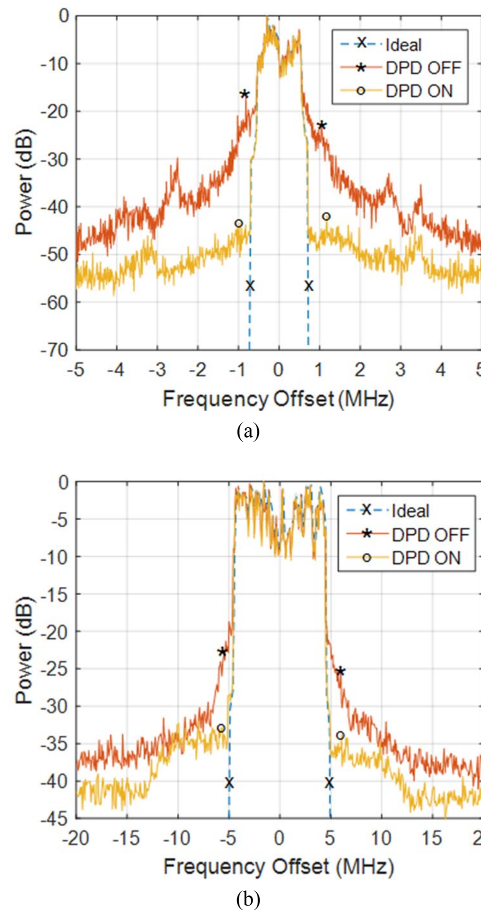

Fig. 8. Ideal spectrum and output spectrum of multi-level supply modulated-signals with and without DPD; (a) – 1.4 MHz LTE signal with 9.3 PAR, and (b) – 10 MHz LTE signal with 11.3 PAR.

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