Calibrated Digital Predistortion Using a Vector Network Analyzer as the Receiver

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***Abstract*—This paper reports the first demonstration of the behavior modeling and predistortion linearization of a power amplifier (PA) for periodic modulated signals using a vector network analyzer (VNA) operated in the receiver mode. In this demonstration a PA operated at 2.3 GHz is characterized using a 5 MHz LTE signal with a peak-to-average power ratio (PAPR) of 10.2 dB. The phases of the Fourier spectrum of the periodic signal measured by the VNA receiver are calibrated using a 20 MHz OFDM signal. The calibrated phases and amplitudes of the 5 MHz LTE signal in the frequency domain are then used to reconstruct the signal in the time domain. After synchronization, the NMSE, dynamic AM-AM and AM-PM, ACPR, EVM, and BER of the PA before and after predistortion can then be calculated from the measured data. The predistortion linearization of the PA validates the accuracy of the VNA phase calibration and synchronization methodology used for the modulated waveforms. This work demonstrates that the same VNA and calibrated testbed can be used to characterize both the (1) continuous-wave (CW) and (2) modulated nonlinear response of a device without breaking electrical contacts with it.**

***Index Terms*—Digital predistortion, Vector network analyzer, Power amplifiers, ACPR, EVM, BER.**

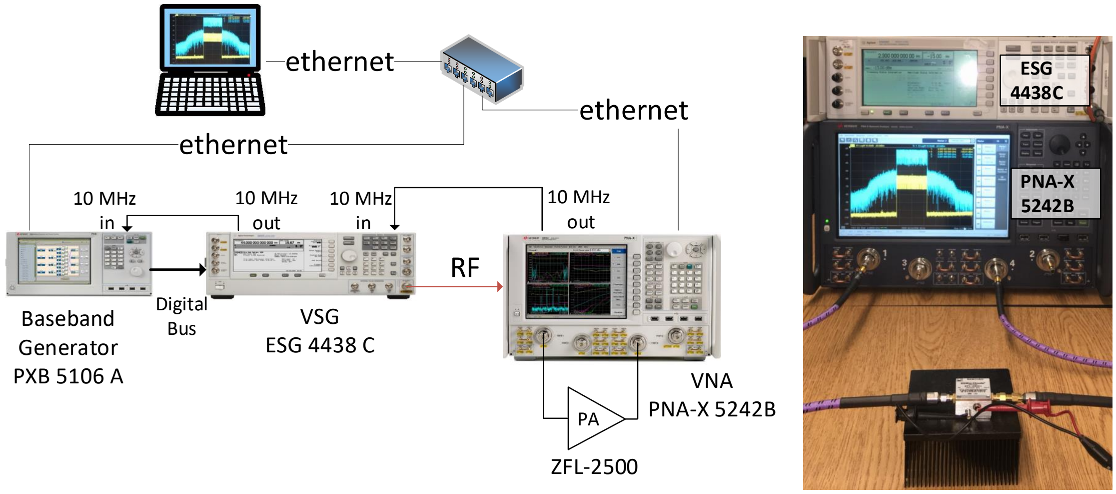
I. Introduction

Today's mobile communication systems use complex modulation formats like orthogonal frequency division multiplexing (OFDM) to deliver the high data-rate required by the downlink. However OFDM employed in the LTE wireless broadband communication standard relies on a large number of closely spaced sub-carriers (15 KHz spacing) yielding a signal with a high PAPR. The resulting non-constant envelope signals with high PAPR generated by this standard require the use of linear PAs. However PAs are more efficient when operated near or beyond their 1 dB compression point (P1dB) where they exhibit a nonlinear behavior and produce output signals with in-band distortion and spectral regrowth in the adjacent channels.

Fortunately, the nonlinear effects in PAs can be compensated through linearization schemes such as digital predistortion (DPD). In [1] a linearity characterization of a millimeter-wave GaN HEMTs is carried out using vector signal generator (VSG) and a vector signal analyzer (VSA) that consists of spectrum analyzer (PSA) and the Agilent 89600 VSA software running in an external computer. In [2] the DPD is performed in real-time and the extraction of its coefficients are obtained from the PA model directly using a *quasi-exact inverse* (QEI). The test bench consists of a field-programmable gate array (FPGA) which predistorts the signal and sends it to an up-converter board to generate the RF signal. The RF signal is sent to the PA for amplification and then returned to a down-converter board, simulating a real base-station.

There has been growing interest in using VNAs and NVNAs (nonlinear VNA) to directly evaluate the nonlinearity of amplifiers [3], [4] or even transistors in a loadpull testbed [5] [6]. In [3], the nonlinear characterization is done using an unequal space multitone signal (USMT) and a large-signal network analyzer (LSNA) as the receiver. In [4] a calibrated NVNA is used with the *SA option* [7] to characterize PAs or transistors. In both cases, a VSG is used to generate the USMT The USMT signal guarantees that the frequencies of the 3rd order intermodulation products neither overlap with one another nor with the input-signal frequencies. The exact power of each intermodulation product can then be measured. These methodologies provide the test engineer with an efficient way to evaluate the nonlinearity of a device with a VNA in the receiver mode without needing to acquire the tone phases.

In this paper we investigate the alternate use of a VNA to perform the function of a vector signal analyzer (VSA) for the acquisition of OFDM waveforms so as to facilitate the PA behavioral modeling and DPD linearization of an amplifier (or a transistor in a loadpull testbed). The motivation for this approach is to use the same VNA and calibrated tested for both (1) the CW nonlinear response (NVNA) and (2) the modulated vectorial response (VSA) of a device without breaking contact. The feasability of this approach hinges on the fact that a VNA operated in the receiver mode with a fixed local oscillator (LO) [7] can provide the test engineer with both the amplitude and phases for each tone of a periodic modulated signal. In the present SA configuration, the tone amplitudes are calibrated whereas the acquired tone phases are highly stable but not calibrated. In this paper a procedure is developed to perform the phase calibration with a VSG to enable an effective VSA operation. To demonstrate the efficacy of this phase calibration, the behavioral modeling and the linearization of the ZFL-2500 amplifier from Mini-Circuits is demonstrated for a 5 MHz LTE signal using a VNA and no other receivers. The dynamic AM-AM, AM-PM and spectral regrowth of a LTE waveform are measured for the PA at 2.3 GHz before and after predistortion. The normalized mean square error (NMSE), adjacent channel power ratio (ACPR), error vector magnitude (EVM), and bit error rate (BER) are used as figures of merit to characterize the overall deviation between the expected and measured data.



(a) (b)

Fig. 1: (a) Schematic and (b) picture of the testbed used for the measurements.

The paper is organized as follows. In Section II the testbed used to obtain the dynamic response and the linearization of the ZFL-2500 amplifier will now be described. In Section III, the measurement results for LTE/OFDM waveforms are presented. The benefits of this new measurement technique are then summarized in Section IV.

II. Description of the Test-Bed

A schematic and a photograph of the testbed setup used for the PA characterization and linearization is shown in Fig. 1. The measurement procedure and testbed is described next.

An LTE signal with a periodicity of 1 ms (one subframe) is generated in Matlab using the LTE *Test Model Tool* with a bandwidth of 5 MHz, a sample frequency of 7.68 MHz, and a PAPR approximately of 10.2 dB. The dynamic range (DR) of this signal is around 25 dB. In order to improve it, the signal is oversampled to 30.72 MHz and filtered with a finite-duration impulse-response (FIR) filter with a passband of 2.25 MHz, eliminating 10 % of the guard-band presents in LTE signal so as to better observe the spectral regrowth. As a result the signal has a bandwidth of 4.5 MHz and 55 dB of DR.

The enhanced LTE signal is downloaded to the baseband generator (PXB 5106A) with a resolution of 16 bits and sent via a digital bus to the Vector Signal Generator (E4438C) for up-conversion to the carrier frequency of 2.3 GHz. The RF signal is inserted in the rear panel of the VNA (PNA-X) and sent to the input of the PA connected in port 1 of the instrument. The receivers R1 and D are used to measure the input and output of the amplifier respectively. To ensure phase synchronization, all the instruments are phase-locked to the 10 MHz reference provided by the VNA. Both the PXB and PNA-X are controlled by a set of Matlab functions which (1) generate the required digital waveforms in the format required for the instruments, (2) download the test waveforms to the PXB, and (3) upload the waveforms captured by the PNA-X to the Matlab environment for further processing.

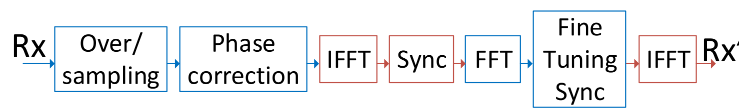


Fig. 2: DSP flowchart for the received signals.

The SA measurement class of the VNA is configured to operate with a span of 20 MHz centered at 2.3 GHz and a resolution bandwidth (RBW) of 84 Hz (12 ms measurement). In addition, the option Multitone signal was configured with a waveform periodicity of 1 ms, the reference tone set to the center frequency and a vector averaging of 60 used to reduce the noise and increase the dynamic range. To remove the error boxes of each receiver, a power and a short-open-load-thru (SOLT) calibration was performed at the reference planes of the PA.

A. *Processing the acquired data from the PNA-X*

To obtain the dynamic AM-AM, AM-PM and to linearize the PA, some digital signal processing (DSP) of the received signals is required. A simplified flowchart of the DSP used is shown in Fig. 2.

The first step adds zeros in the frequency domain to the original signal generated in Matlab (Tx) and the received signal from the PNA-X (Rx) to guarantee that both signals have the same FFT length. Indeed, due to the sampling frequency of 30.72 MHz and its 1 ms period, the Tx signal has 30720 samples, whereas the Rx signal has 20000 samples because of the SA configuration described above.

The Rx' and Tx' baseband signals are next synchronized in time domain. A calibration correction of the phase is then carried out in the receivers R1 and D of the PNA-X. To accomplish it an OFDM signal of 20 MHz is introduced in the rear panel of the PNAX in port 2. The phase calibration correction is computed in the frequency domain as the difference $\phi_{\mathrm{CAL}}(i)$ for each tone i of radial frequency ω_i between the phases of the received 20 MHz signal (using receiver R2) and the expected VSG 20 MHz signal:

$$\phi_{\mathrm{CAL}}(i) = \phi_{raw}(i) - \phi_{\mathrm{VSG}}(i) + (\omega_i - \omega_{\mathrm{LO}})\Delta\tau + \Delta\phi_0.$$

The group delay difference $\Delta\tau$ and LO phase offset $\Delta\phi_0$ are obtained when the VGS and VNA signals are time synchronized. This phase correction factor can then be subtracted from the received input and output signals of the amplifier.

In order to characterize the repeatability of this phase calibration, 11 measurements were performed with an OFDM signal of 20 MHz. Fig. 3 shows the phase calibration correction computed for the 11 different measurements of the OFDM signal. The average standard deviation over the 20000 tones was of 0.42 degree with a maximum standard deviation of 3.7 degrees.

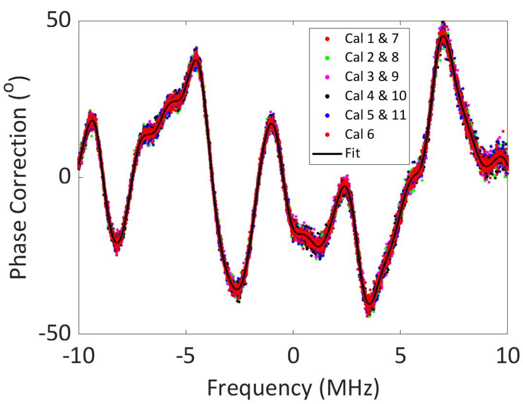


Fig. 3: Phase calibration ϕ_{CAL} corrections obtained for 11 different measurements.

III. Measurements with LTE signal and Linearization

The amplifier ZFL-2500 has a linear gain of 28 dB, and an output power of 16 dBm at the 1 dB compression point. To characterize its dynamic response, an LTE signal of 5 MHz with a PAPR of 10.2 dB and input average power of -20.5 dBm was used. A DPD linearization is then applied to linearize the PA.

A. Linearization Results

The ZFL-2500 amplifier was linearized by predistorting the input signal $x(n)$ using the technique of indirect learning. Here n is the discrete time index. The input data $x(n)$ were modeled in terms of the output data $y(n)$ using generalized memory gain-functions G_m with a memory depth M of 3:

$$x(n) = \sum_{m=0}^{M-1} G_m(|y(n-m)|^2)y(n-m). \tag{1}$$

The memory gain functions $G_m(|y|^2)$ are implemented using a cubic-spline basis with 25 segments [8]. A total of 78 coefficients were used. The nonlinearities and the memory effect of this device is shown in the AM-AM and AM-PM curves in Fig. 4, as well as the result of the DPD.

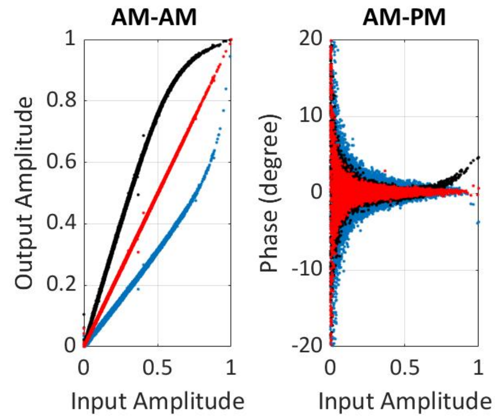


Fig. 4: Dynamic AM-AM and AM-PM curves of ZFL-2500 amplifier without (black) and with (blue) DPD (red).

The spectra of the output signal of the amplifier before and after the predistortion is shown in Fig. 5.

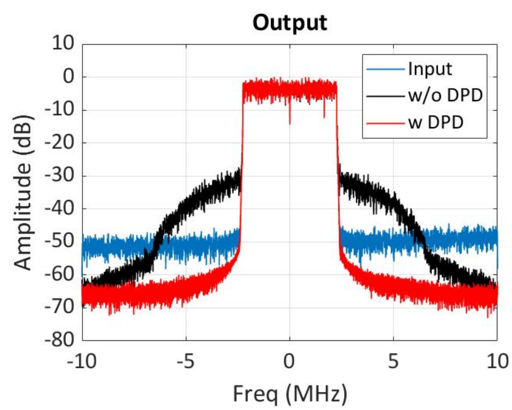
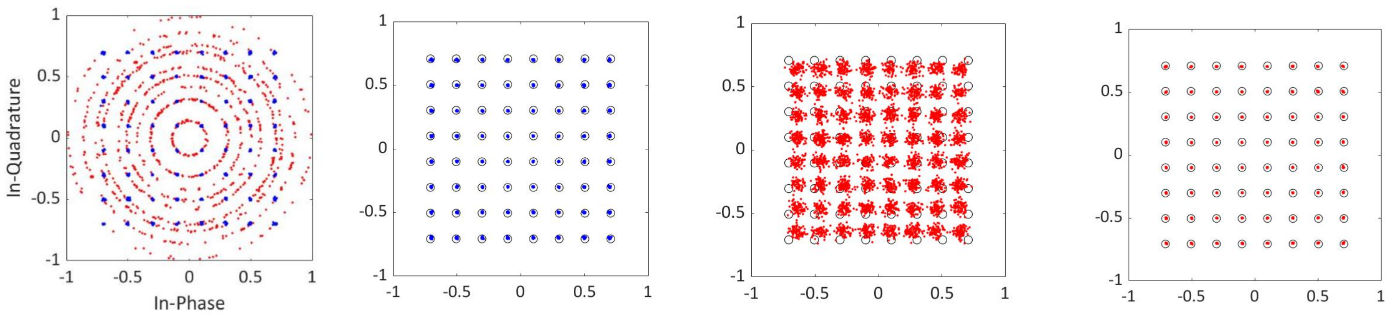


Fig. 5: Spectra of ZFL-2500 amplifier before and after DPD.

B. Figures of Merit

The AM-AM and AM-PM characteristic plots presented in Fig. 4 cannot be generated if the phase calibration is not performed. The time synchronization shown in Fig. 2 must also be repeated after the phase calibration is applied, as the envelop is strongly dependent on the tone phases. Note that the synchronization performed is based on the peak amplitude of the cross-correlation $[x \star y](m) = \mathbf{x}(n)^{*\top} \cdot \mathbf{y}(n-m)$ without any windowing, since the modulation is periodic. The QAM64 constellations obtained from the 20 MHz OFDM signal before (red dots) and after (blue dots) the calibration correction and the synchronization are applied to the raw data, are shown in Fig. 6 (a). The constellations obtained from 5 MHz OFDM signal with no circular prefix at the PA input and the PA output before and after DPD are shown in the constellation diagram in Fig. 6 (b), (c) and (d) respectively.



(a) Calibration / 20 MHz OFDM (b) PA input / 5 MHz OFDM (c) PA output / 5 MHz OFDM (d) PA output with DPD / 5 MHz OFDM

Fig. 6: Constellations (a) for a thru: raw(red dots) and calibrated (blue dots)) with 20 MHz OFDM, and for the PA input (b) (blue dots) and output with (c) and without (d) DPD for 5 MHz OFDM (red dots).

The resulting calibrated OFDM complex RF envelope acquired using the VNA allows one to quantify the nonlinearities of the PA in (1) the time domain with the NMSE, (2) the frequency domain with the EVM and (3) the digital domain with the BER. These figures of merit for the 5 MHz QAM64 constellation of Fig. 6 are given Table 1.

TABLE I Figures of Merit for the OFDM Measurements.

Measurement Conditions	PAPR (dB)	$ACLR_{L,H}$ (dBc)	NMSE (dB)	EVM (%)	BER (%)
PA Input	10.47	-48.65,-47.15	-38.78	1.49	0
Output w/o DPD	5.42	-28.92,-29.09	-1.96	12.41	26.8
Output w DPD	10.53	-61.70,-59.99	-43.37	0.988	0

IV. Conclusion

To assist with the accurate characterization of the nonlinearity of devices under realistic large-signal operation, a testbed featuring a VNA (PNA-X), and a VSG (ESG) was reported for evaluating the nonlinear response of devices to modulated waveforms. This testbed benefits from the large dynamic range of the VNA and the availability of a SA software option for the acquisition of the Fourier amplitudes and phases of periodic modulated signals. For the accurate recovery of the modulated waveforms in the time-domain, a phase calibration in the frequency domain and a waveform synchronization in the time domain was developed to compensate for the IF filter response and group delay of the VNA receiver and testbed-respectively. Using the 20 MHz calibrated Fourier data, the AM-AM and AM-PM characteristics of a PA for a 5 MHz OFDM signal could be retrieved and the NMSE, EVM and BER calculated. The accuracy of the calibration and modulated waveforms recovered in the time-domain are verified by the successful behavioral modeling and digital predistortion (DPD) linearization of the PA. To our knowledge this is the first report of the phase-calibrated vector measurement of periodic OFDM modulated signals performed using a mixer-based VNA. An important advantage of the proposed approach is that the same VNA can be used to characterize both the (1) CW and (2) modulated nonlinear responses of a device. Note that the VNA used (PNA-X) offers 5 SA channels. This measurement scheme could thus be applied in future work to the DPD linearization of dual-input PAs excited by modulated waveforms. It is expected that the proposed approach could provide GHz bandwidth with a proper control of the LO frequency.

Acknowledgment

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