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Digital Predistortion for Dual-Input Doherty Amplifiers

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***Abstract*— This paper presents a digital predistortion technique for dual-input Doherty power amplifiers. The proposed technique utilizes both RF inputs of the main and peak amplifiers in the digital predistorter. The effectiveness of the resulting dual-input predistorter is evaluated on a two-way Doherty amplifier operating at 2.14 GHz with 53.5 dBm peak output power. The experimental results demonstrate that the dual-input approach outperforms the conventional single-input predistortion technique by ∼3 dB in terms of adjacent channel leakage ratio.**

I. Introduction

In order to accommodate as many users as possible within a limited frequency-band, advanced modulation schemes have been employed in Wideband Code Division Multiple Access (WCDMA) and Long-Term Evolution (LTE) standards. However, the use of these standards yields communication signals with high peak-to-average ratio (PAR) and thereby putting high constraints for linearity and efficiency on power amplifiers (PAs) [1].

To enhance the average power-added efficiency (PAE) of PAs operating with high PAR communication signals, various PA architectures have been proposed that offer an improved efficiency in power backoff operation [2]. Some of the most promising PA concepts are: Envelope Tracking (ET) [3], Varactor-Based Dynamic Load Modulation (VB-DLM) [4], Doherty PAs (DPAs) [5] and outphasing PAs [6]. As can be seen from Fig. 1, all these high-efficiency PA architectures basically rely on two signal paths (e.g. two RF signal paths like in dual-input Doherty and outphasing PAs, or an envelope signal and an RF signal like in ET and VB-DLM), which are combined at some point in the PA output. It should be noted that most DPAs (including the one originally proposed) have one RF input only and use analog splitting. In this work, we mainly focus on the DPAs with two RF inputs.

Various dedicated digital predistortion techniques have been proposed to linearize ET and VB-DLM PA architectures [7], [8]. Also for DPAs, intensive research has been performed to push the efficiency and linearity to new limits [5], [9], [10]. In some of the works additional measures has been also proposed to control the gate bias of the main and peak amplifiers [11], as well as the optimization of the phase relationships between the two branch PAs [12].

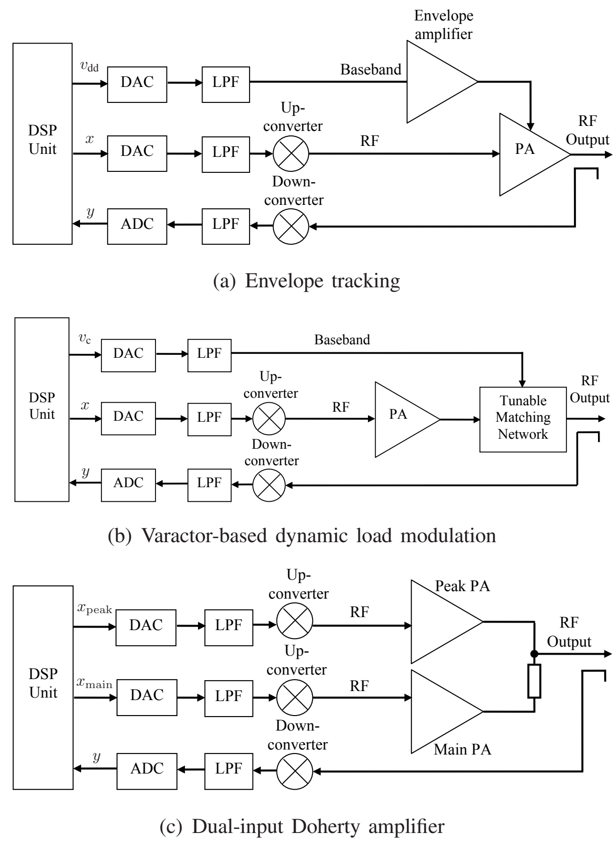


Fig. 1. Simplified block diagrams of high efficiency power amplifier architectures. x_{main} is the RF input signal for the main amplifier, x_{peak} is the RF input signal for the peak amplifier, y is the RF output signal and v_{dd} and v_{c} are envelope signals for ET and DLM, respectively.

However, in previous works the predistortion algorithms for DPAs still consider it as a single-input single-output system. To the best of the authors' knowledge, there is currently no dedicated dual-input digital predistorter (DPD) approach for DPAs reported up to date. In the conventional approach, an analogue/digital input signal

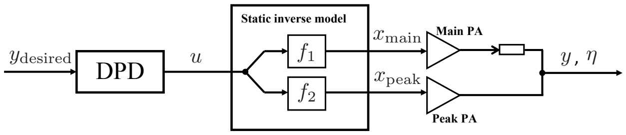


Fig. 2. Conventional linearization method for Doherty power amplifiers. f_1 and f_2 are two static polynomial functions and together acting as a splitter. x is the original RF input signal, u is the predistorted RF input signal, y is the RF output signal, η is the average PAE and x_{main} and x_{peak} are the RF input signals for main and peak amplifiers, respectively.

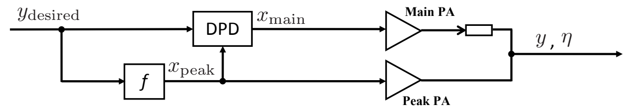


Fig. 3. The dual-input linearization method for Doherty power amplifiers. y_{desired} is the desired RF output signal, y is the RF output signal, η is the average PAE, x_{main} is the predistorted RF input signal for main amplifier and and x_{peak} is an efficiency-optimized RF input signal for peak amplifier.

splitter/conditioner is used to convert the input signal to the individual branch signals. To fill this gap, in this work a dual-input DPD originally proposed for ET and VB-DLM PA architectures [13] has been modified and applied for DPAs with two independent RF inputs. The proposed approach no longer depends on the quality of the input signal splitter which can cause limitations for the linearity and efficiency performance [13]. As such, we can achieve better linearization results and improve the average PAE. The feasibility of this dual-input DPD for Doherty operation will be verified by experiments using a 250 W two-way GaN Doherty PA operating at 2.14 GHz.

II. Dual-input Linearization Technique

As discussed in Section I, today's most popular high-efficiency PA architectures are characterized by the use of dual/multiple input signal paths. However, current linearization techniques do not fully utilize these multiple signal paths and still consider the DPD and PAs as single-input single-output systems, as shown in Fig. 2.

The static functions f_1 and f_2 in Fig. 2 represents the digital signal splitter which converts the input signal to the branch signals optimized for efficiency. In practice, these static functions have polynomial fitting errors in their implementation [13]. Unfortunately, the memory DPD can not compensate for these errors. Therefore, the conventional single-input approach cannot achieve optimal linearity and efficiency performance simultaneously.

However, in this work, a dual-input DPD approach is proposed which controls both input signals simultaneously and can facilitate improved efficiency and linearity of the DPAs. The dual-input DPD idea was originally introduced in [13] and used for ET/VB-DLM PA architectures. Instead of solving a complicated jointly optimization process, it utilized a two-step solution to derive the optimal input signals without loss of generality. With respect to [13], the envelope signal can be replaced by an RF input signal fed to the peak amplifier in the case of the dual-input DPAs studied here. Due to the similarity of the problem definition, we can also apply the same procedures as in [13] to find here the two optimal RF input signals for efficiency and linearity.

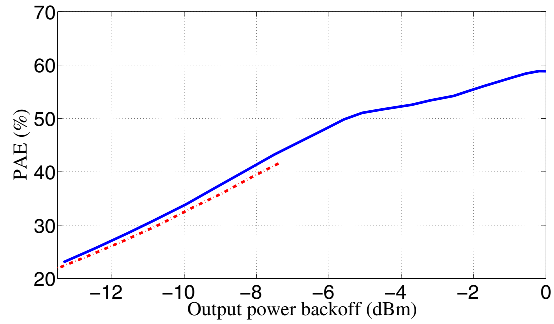
A block diagram of the proposed linearization technique is shown in Fig. 3. The function f is an efficiency-optimized function that is used to derive the RF input signal for the peak amplifier. The dual-input DPD presented in this work is a Volterra-based model, but having two RF inputs x_{main} and x_{peak} which are optimized for linearity and efficiency, respectively. Using a third-order Volterra series as an example and considering only the odd order terms, the dual-input digital predistorter can be written as

$$
\begin{aligned}
&x_{\mathrm{main}}(n) = f_{\mathrm{RF}}^{-1}(y_{\mathrm{desired}}(n), x_{\mathrm{peak}}(n)) = \\
&\sum_{m_1=0}^{M}\sum_{m_p=0}^{M_p} h_{m_1 m_p} y_{\mathrm{desired}_{m_1}} x_{\mathrm{peak,m_p}} \\
&+ \sum_{m_1=0}^{M}\sum_{m_2=m_1}^{M}\sum_{m_3=m_2}^{M}\sum_{m_4=0}^{M_p}\sum_{m_5=m_4}^{M_p}\sum_{m_6=m_5}^{M_p} h_{m_1 m_2 m_3 m_4 m_5 m_6} \\
&\cdot y_{\mathrm{desired}_{m_1}} y_{\mathrm{desired}_{m_2}} y^{*}_{\mathrm{desired}_{m_3}} x_{\mathrm{peak,m_4}} x_{\mathrm{peak,m_5}} x^{*}_{\mathrm{peak,m_6}}
\end{aligned} \tag{1}
$$

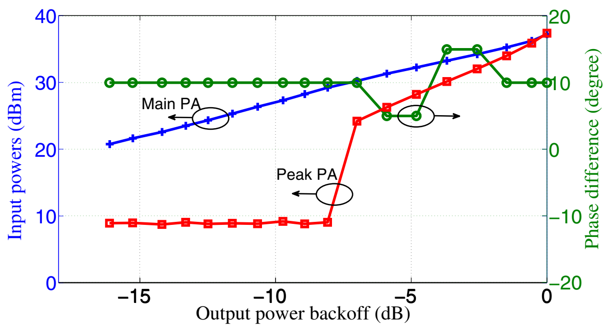
where $*$ denotes the complex conjugate operation, M is the memory depth for the main PA, M_p is the memory depth for the peak PA, y_{desired_m} is the desired RF output signal with delay m samples and $x_{\mathrm{peak,m}}$ is the RF input signal of the peak PA with delay m samples.

Compared to the conventional single-input behavioral modeling approach used for dual-input DPAs, the presented linearization technique does not rely on the static splitter to obtain the input signals to the PA. However, it fully utilizes the extra degree of freedom given by the additional RF input to the amplifier to improve the efficiency and linearity performance, i.e. the RF input signal of the peak amplifier is now used as an additional input to the DPD. This enables the digital predistorter to compensate for the residual errors through iterations in the identification stage, even if the function f used to derive the optimal RF input signals to the peak amplifier has fitting errors. This will be further verified in the experimental results section.

The complexity of the presented dual-input DPD is a bit higher than the conventional single-input model. However, since only very low nonlinear order is used in this work, the complexity is still acceptable.

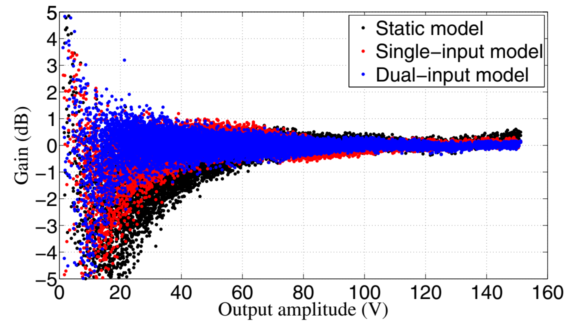


(a)

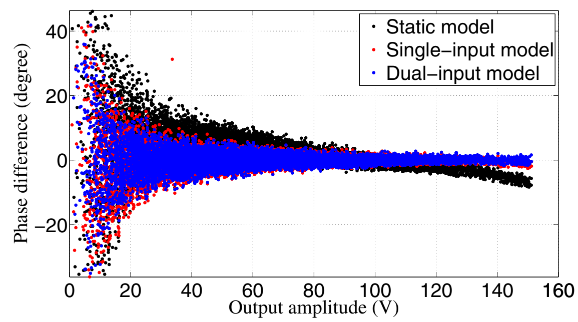


(b)

Fig. 4. (a) Optimal PAE v.s. desired output power. The solid and dashed lines represent the situation when there is very low input power and zero input power to the peak PA when the peak PA is in the ”turn-off” state, respectively. (b) Optimal input powers of the main and peak PAs vs. desired output power.



(a) AM/AM



(b) AM/PM

Fig. 5. AM/AM and AM/PM performance when different linearization methods are applied.

III. Experimental Results

The proposed linearization technique is verified on a two-way GaN DPA operating at 2.14 GHz. The DPA has a saturated power of 250W and 200W P1dB power. The measurement setup used in this work is similar to the one described in [5]. The local oscillators and the PXI chassis are synchronized with a 10 MHz reference signal. The complex baseband signals are generated in the PC and uploaded to the Agilent N6030A arbitrary waveform generators. The measured RF output signals are first down-converted to an IF signal of 15 MHz and captured by the high-speed digitizer cards from National Instruments (NI-PXI5105). The captured IF signal is down-converted to the baseband signal in the PC. System calibrations have been performed using the procedures described in [5] and I/Q imbalance in the up-converting mixers has been compensated for using the method in [14].

A. Pulsed CW Measurements

In order to identify the optimal combinations of both RF input signals for maximum efficiency operation, static characterization of the DPA is first performed. As the two inputs are complex, both the input powers of the main and peak PAs as well as the phase differences are swept in pulsed CW measurements. Based on the pulsed CW measurements, a 3-D search has been performed to identify the maximum efficiency for different instantaneous desired output power levels. The optimum PAE , input powers, and phase difference between the main and peak PAs versus the desired output power are shown in Fig. 4. As the phase difference between the main and peak PAs are designed to be in-phase for the DPA, the optimal phase difference is found to be approximately fixed at 10 degree except for some small changes. It should be noted that even when the peak PA is in the “off” state, a small input power with the same phase to the peak PA can gives a bit higher efficiency compared to an absolute “zero” input, as is shown in Fig. 4. The derived optimal relationship between the RF output signal and the RF input signal of the main amplifier can be considered as a static DPD, while the optimal relationship between the RF output signal and RF input signal of the peak amplifier is considered as the efficiency-optimized function f. The static DPD and function f are used in the first modulated measurement. The measured output signals are then used together with the desired output signals and the RF input of the peak amplifier to identify the parameters of the dual-input DPD.

B. Modulated Measurements

A single-carrier WCDMA signal with 7 dB PAR is used in the measurements. The behavioral model used for the

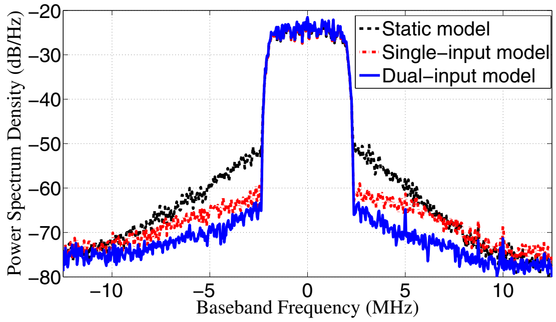


Fig. 6. Output spectra when different linearization methods are applied.

dual-input digital predistorter is a Volterra-based model. The nonlinear orders used for the RF input signals of the main and peak PAs are 5 and 1, respectively. The memory depth used for the main and peak PAs are: $M = 2$ and $M_p = 0$, respectively. In this case, the model coefficients of the dual-input model is only double compared to the conventional single-input model.

The measured AM/AM and AM/PM performance is shown in Fig. 5. It can be seen that the presented dual-input model outperforms the conventional single-input model, as it has the possibility to compensate also for the fitting errors resulting from the static characterizations. The out-of-band performance comparison of different linearization methods can be seen in Fig. 6. The dual-input model can suppress the distortion to lower than -45 dBc which is the requirement of the standard for a single-carrier WCDMA signal. Also, when comparing with the static model and the conventional single-input model, the dual-input model has around 14 and 3 dB improvement, respectively. At the same time, the measured average PAE can be kept as high as 40%. Considering the fact that the model coefficients of the dual-input model has only one time more than the single-input model, the linearization performance improvements of the dual-input model outweigh the complexity of it added.

By fully utilizing both RF inputs of the DPA and relying on an efficiency-optimized dual-input DPD scheme that also ensures minimum distortion, the proposed linearization technique has the ability to achieve optimum efficiency and linearity simultaneously.

IV. Conclusions

This paper presents a dual-input linearization technique for dual-input Doherty PAs. The dual-input digital predistorter has been shown to be more robust and can achieve better linearization results compared to the conventional single-input model generally used for Doherty PAs. The dual-input digital predistorter concept can be easily extended to the multi-input cases for linearization N-way Doherty PAs.

Acknowledgement

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