Performance Modeling and Shaping Function Extraction for Dual-input Load Modulated Power Amplifiers

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***Abstract*— This paper proposes the method of extracting a shaping function for operating a family of Dual Input Power Amplifiers operating with modulated signals such as OFDM-based 5G new radio (NR) signals. The shaping function describing the drive profile for each input was implemented using a Look-Up Table (LUT) approach. This table can be constructed from the previously measured PA data to target various objectives, such as linearity or efficiency. The paper focuses on performance modelling to have a smooth mathematical equation to predict performance. Based on the prediction, we can extract the shaping function targeting the maximization of linearity or efficiency. Experimental results were conducted with a 100 MHz bandwidth 5G NR signal with a 30 kHz subcarrier spacing. The linearize ability of different objectives is evaluated with digital predistortion.**

***Keywords*— power efficiency, outphasing, linearization, performance modelling, shaping function, power amplifiers.**

I. Introduction

The benefits of power amplifiers (PA), where two or more active devices (branch PAs) are allowed to interact with each other, such as Doherty or Chireix outphasing, have been widely exploited and adopted in the telecommunication industry [1]. Historically, these PAs have been designed to operate with a single input where additional components ensure the correct signal conditioning for each of the branch PA. The proliferation of modern DSP capabilities opens the possibility of generating individual drive profiles for each device and creates a space where each branch PA can be driven independently. Several recent publications were dedicated to investigating PAs with such drive conditions. [2]–[4]. The papers implicate that some form of LUT is employed in the solution for signal generation. However, the LUT extraction or optimisation method was not described in great detail. This work focuses on deriving a system-level PA characterisation method, which allows to create a suitable drive profile targetting and maximising specific goals such as efficiency, constant gain or linearity. The method was demonstrated for an outphasing PA, where different drive strategies, here referred to as *shaping functions*, were evaluated with emphasises on the subsequent linearisation using DPD.

The prevalence of the term "mixed-mode" is used in the literature to describe signal conditioning for outphasing PAs where both the relative phase and amplitude of these signals are controlled during the excitation of a PA. Typically only a partial Output Back-Off (OBO) is realised through the control of the relative phase while maintaining a constant amplitude of input signals. The remainder of OBO is achieved by reducing the amplitude of the input signal while maintaining a fixed phase. The threshold or a switchover point is somewhat arbitrary and can vary depending on the PA [5], [6]. In this paper, the Mixed-Mode approach was expanded into a piece-wise shaping function constructed using the LUT obtained during the PA characterisation stage. Although the process was demonstrated using an outphasing PA, it can be applied on a system level to any dual-input PA topology, such as Doherty or LMBA. Several strategies for creating the shaping function were evaluated, maximising either efficiency or linearity. The corresponding drive profiles were created and used to excite the PA while the key performance parameters were recorded and compared with the performance of the same PA driven using Mixed-Mode or Fixed-Phase signals.

The remainder of this paper is organized as follows. Section II describes shaping functions for Fixed-Phase and Mixed-Mode operations. The proposed shaping function using a piece-wise linear operation was also described in that Section. The characterisation process was described in Section III, where the demonstrator PA was excited using CW initially, in a similar fashion to work presented in [7], and later using the two-tone stimulus to extract key metrics used to construct the shaping function. Section IV shows the experimental results considering a 5G new radio (NR) signal with 11 dB of PAPR with and without linearisation. Discussion and conclusions were provided in Section V.

II. Shaping Functions

In this section, several shaping functions are introduced. Fig. 1 shows the block diagram of the outphasing PA. The outphasing shaping function uses as input the baseband I-Q signal $u[n]$ and generates a pair of signals $x_{\pm}[n]$ with modified amplitudes and relative phases, according to the amplitude of the I-Q input $|u[n]|$. In general, the shaping function is described as follows,

$$\begin{aligned} r[n] &= |u[n]|, \theta[n] = \angle u[n] \\ \varphi[n] &= f_{\varphi}(r[n]) \\ v[n] &= f_{v}(r[n]) \\ x_{\pm}[n] &= v[n]\, e^{j(\theta[n] \pm \varphi[n]/2)} \end{aligned} \tag{1}$$

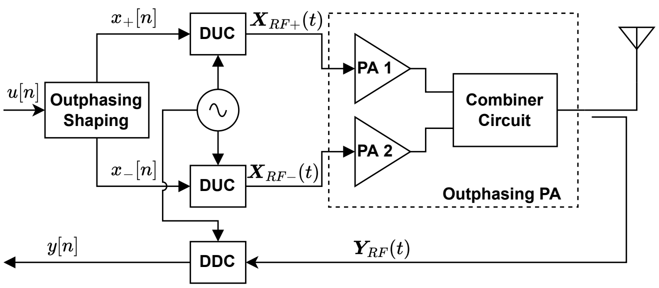

Fig. 1. Block diagram of outphasing PA.

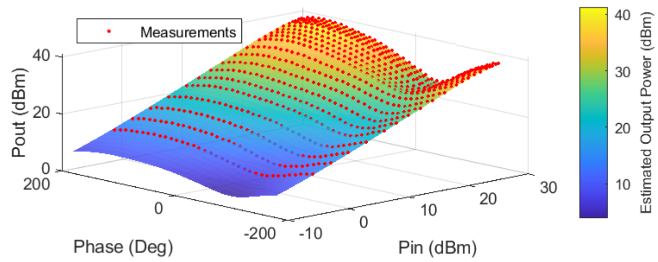

Fig. 2. Outphasing PA output power modeling using $Q = 5, M = 4$.

where $\boldsymbol{r}$ and $\boldsymbol{\theta}$ is the amplitude and phase vector of the baseband input, $\boldsymbol{\varphi}$ is the vector of relative phase, $\boldsymbol{v}$ is the vector of the shaping amplitude. f_φ and f_v are the shaping functions to be determined for generating the relative phase and amplitude. In the following subsections, we introduce Fixed-Phase shaping, Mixed-Mode shaping and the proposed shaping functions.

A. Fixed-Phase Shaping

The Fixed-Phase shaping function operates each branch of the outphasing PA as a class-AB amplifier. Both branches are driven with signals of equal amplitude and a relative phase offset which is fixed. The equation is straightforward, shortly given as follows,

$$\begin{aligned} f_\varphi(r) &= \psi \\ f_v(r) &= r \end{aligned} \tag{2}$$

where ψ is the constant phase, r is the shorthand for $r[n]$ for simplicity. The Fixed-Phase shaping function is provided for comparison with other shaping functions.

B. Mixed-Mode Shaping

The idea of Mixed-Mode shaping in [5] is to define a phase threshold ϕ_{thr} and operate the PA either in outphasing mode or class-B mode. In this paper, the two RF signals are aligned at the PA's input, we introduce a phase offset parameter ϕ_o to compensate for the internal phase mismatch. Therefore, the Mixed-Mode shaping function for the phase is written as,

$$f_\varphi(r) = \begin{cases} \arccos(r) + \phi_o, & \cos(\phi_{thr}) < r \leq 1 \\ \phi_{thr} + \phi_o, & r \leq \cos(\phi_{thr}) \\ \phi_o, & r > 1 \end{cases} \tag{3}$$

where the input amplitude r is normalized to the peak input amplitude of the PA, in which the amplitude has the maximum power efficiency. However, considering the amplitude expansion caused by the predistorter, the amplitude can go beyond 1; in this situation, we use the fixed phase. The amplitude part of the Mixed-Mode shaping function in this paper is defined as,

$$f_v(r) = \begin{cases} 1, & \cos(\phi_{thr}) < r \leq 1 \\ \frac{r}{\cos(\phi_{thr})}, & r \leq \cos(\phi_{thr}) \\ r, & r > 1 \end{cases} \tag{4}$$

C. Optimized Piece-wise Shaping Function

The shaping function proposed in this paper is implemented as a piece-wise function composed of several linear functions in the logarithmic scale. Therefore, we first convert the amplitude to power by,

$$p_i = 10\log(v^2/100) \tag{5}$$

where p_i is the instantaneous input power. Denote G as the linear gain we expect from the PA, then the expected instantaneous output power $\hat{p}_o = p_i + G$. The phase part of the piece-wise linear shaping is defined as,

$$f_\varphi(\hat{p}_o) = \begin{cases} \varepsilon_1, & \hat{p}_o \leq \alpha_1 \\ \frac{(\varepsilon_{k+1}-\varepsilon_k)(\hat{p}_o-\alpha_k)}{\alpha_{k+1}-\alpha_k} + \varepsilon_k, & \alpha_k < r \leq \alpha_{k+1} \\ \varepsilon_N, & \hat{p}_o > \alpha_N \end{cases} \tag{6}$$

where $k \in \{1, \cdots, N-1\}$, $\varepsilon_{1,\cdots,N}$ and $\alpha_{1,\cdots,N}$ are the piece-wise coefficients which is defined by the key phase points and the key output power points. Similarly, we defined key input power points $\beta_{1,\cdots,N}$ and map the expected output power to the estimated input power $\hat{p}_i$ by

$$\hat{p}_i = \begin{cases} \hat{p}_o - G, & \hat{p}_o \leq \alpha_1 \text{ or } \hat{p}_o > \alpha_N \\ \frac{(\beta_{k+1}-\beta_k)(\hat{p}_o-\alpha_k)}{\alpha_{k+1}-\alpha_k} + \beta_k, & \alpha_k < r \leq \alpha_{k+1} \end{cases}, \tag{7}$$

and finally, the amplitude part of the shaping function is

$$f_v(\hat{p}_i) = \sqrt{10^{\hat{p}_i/10+2}}. \tag{8}$$

III. PA Characterisation Process

The shaping function described in this paper was constructed using data points obtained during PA characterisation. The measurements were performed with each of the PA inputs excited using signals of equal amplitude, whilst the relative phase between these signals was swept from -180 deg to 180 deg. This process was repeated for a range of input powers. Similar measurements were repeated using a two-tone signal as the stimulus, which allowed for the estimation of the NMSE performance. The measurements were performed using a range of mean input powers and phases, followed by calculating the NMSE of the whole two-tone signal in the baseband. Since we can not test all the points, we need to model the performance using as input both input power and phase. With a fixed phase, the input power to output performance (i.e., output power, efficiency or

NMSE) can be modelled with a very basic polynomial such as follows,

$$\hat{y} = \sum_{q=1}^{Q} w_q p_i^q + b \qquad (9)$$

where $\hat{y}$ is the performance to be modeled, p_i is the input power, $\boldsymbol{w}$ is the coefficient vector, Q is the polynomial order, and b is the offset. Now consider a fixed input power. Apparently, the performance is a periodical function with a relative phase. Therefore, the Fourier series can be used as follows,

$$\hat{y} = \sum_{m=1}^{M} w_{m1} \cos(m\varphi) + w_{m2} \sin(m\varphi) + b \qquad (10)$$

where φ is the relative phase. The tensor product of (9) and (10) gives the dual input performance model as

$$\begin{aligned} \hat{y} = &\sum_{q=1}^{Q} \sum_{m=1}^{M} w_{mq1} \cos(m\varphi)\, p_i^q + \\ &\sum_{q=1}^{Q} \sum_{m=1}^{M} w_{mq2} \sin(m\varphi)\, p_i^q + b. \end{aligned} \qquad (11)$$

The coefficients can be extracted by linear least squares with searching test results. Fig. 2 shows the surface that fits the measurement points of output powers. The measurement is the two-tone searching test results with 40 MHz tone separation. The two PA devices were biased with $I_{\mathrm{DQ}} = 50$ mA and operated with a 28 V DC supply. The fitting for output power is quite well, with a mean square error of 0.08. The same performance modelling process was conducted on the efficiency and NMSE. With these performance estimators, it is now possible to find the input power and phase that can optimize the target performance given the expected output power. Fig. 3 shows the shaping trajectories of output power and phase on the efficiency map with different shaping functions and optimization objectives. We can see that the optimal efficiency path always follows the peak efficiency. The optimal NMSE path targeting optimized linearity shifted away from the peak efficiency. Fig. 4 shows the shaping amplitude trajectories, we can see from the optimal efficiency and the Mixed-Mode path that, in order to have better efficiency, the input powers at high values were pushed up. The performance with modulated signals and DPD of these shaping configurations will present in the next section.

IV. Experimental Setup and Results

Fig. 5 shows the Matlab-controlled outphasing PA testbench. AWG M8190 from Keysight was used for waveform generation, and RTP084 from Rohde & Schwarz was used to capture output data. Driver amplifiers ZHL-15W-442-S+ and ZHL-16W-43-S+ from Mini-Circuits were used with circulators at the output ports. The variation of Chireix outphasing, fabricated in 0.25 um GaN MMIC process from WIN Semiconductors, was biased in deep class AB with $I_{\mathrm{DQ}} = 50$ mA and operated with the drain supply of 28V. NR

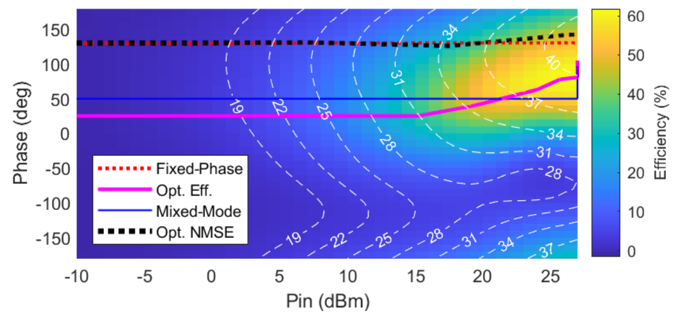

Fig. 3. Input power and phase trajectories of different shaping functions on the efficiency colour map, the contour is the output power.

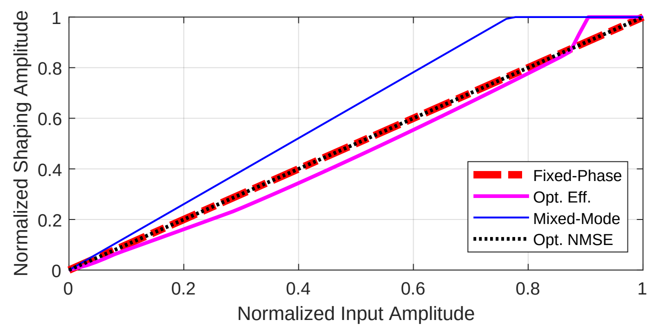

Fig. 4. Normalized input-output amplitude of different shaping functions.

Table 1. Outphasing PA performance with NR 100 MHz OFDM signal

Shaping Function	Performance (Signal PAPR = 11/8 dB) NMSE (dB)	ACPR (dBc)	EVM (%)	Pout (dBm)	Eff. (%)
Fixed-Phase	-24.1/-27.0	-31.6/-33.4	7.3/5.8	29.4/34.4	15.2/25.3
Mixed-Mode	-23.5/-21.3	-31.5/-26.5	4.8/8.6	29.5/34.7	28.1/47.0
Opt.NMSE	-25.4/-28.4	-33.5/-36.1	5.8/4.3	29.6/34.6	17.0/27.8
Opt.Eff.	-22.0/-24.8	-30.9/-31.5	8.1/5.8	29.4/34.8	31.2/50.9
Opt.NMSE*	-37.6/-40.2	-46.5/-48.1	0.9/0.8	29.7/34.6	16.7/27.6
Opt.Eff.*	-37.8/-37.6	-45.3/-45.0	1.1/1.5	29.4/34.8	30.4/50.5

* denotes with DPD Linearization.

QPSK OFDM signals of 100 MHz bandwidth with a duration of 1 subframe (i.e., 1 ms), 30 kHz subcarrier spacing were used.

Table 1 shows the NMSE, ACPR, EVM, output power and efficiency performance with different shaping functions and PAPRs. The PAPR of the generated signal was 11 dB and 8 dB, reduced by applying crest factor reduction (CFR) to challenge the efficiency. Without linearization, the optimal NMSE trajectory can provide the best linearity performance in terms of NMSE and ACPR, however, with low efficiency. On the other hand, the optimal efficiency trajectory can provide better efficiency at around 50% for with the 8 dB PAPR signal while having a worse linearity starting point. Then a generalized memory polynomial DPD model with 30 memory delays and the highest order of 8 was used for linearization. With DPD, the optimal efficiency shaping can meet the linearity spec with ACPR below -45 dBc, keeping the high efficiency advantage. The optimal NMSE shaping can also meet the ACPR spec after linearization. However, the

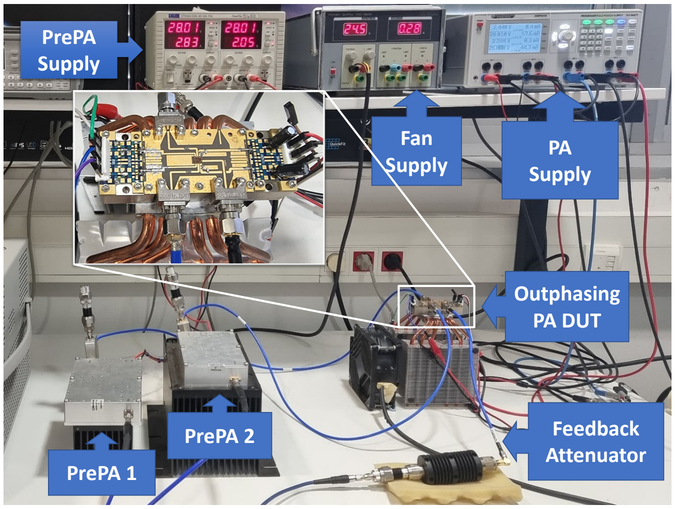

Fig. 5. Picture of the demonstrator PA testbed.

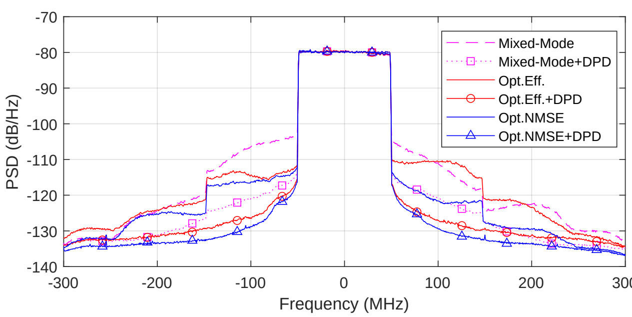

Fig. 6. Power spectra density plot of different shaping functions with and without DPD linearization.

efficiency is low compared to the optimal efficiency shaping. Fig. 6 shows the power spectra density (PSD) plot of the PA output with different shaping functions with and without applying DPD linearization.

V. Conclusion

This paper presented several strategies for constructing drive signals for dual-input PAs. Evaluation of the post-linearization performance with different optimization goals revealed that the shaping parameters extracted with efficiency criterion can provide an efficiency advantage. After linearization, the demonstrator PA achieved above 50% overall efficiency and met the ACPR spec of -45 dBc when operating with 5G NR signals with 100 MHz bandwidth.

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