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A Computationally Efficient Predistortion and Segment Thresholding for Distributed PA Arrays

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***Abstract*—Multipath MIMO systems have emerged, providing faster and more reliable wireless communications. These systems require distributed arrays of nonlinear power amplifiers, which in turn require novel digital predistortion solutions. In this paper the authors propose a novel technique called, *variation in the slope*, to reduce the computational overhead of multipath segmented DPD for distributed arrays of power amplifiers. Additionally the approach to calculate the threshold for the segments requires only the second derivative calculation of gain versus input power and thus avoids computationally expensive clustering techniques. This approach was validated using a 100MHz 5G NR signal and a hybrid beam former module, resulting in an achieved -50dB ACLR on average. This value meets the spectral mask requirement for 5G FR2 standards. This method requires fewer training samples and DPD parameters compared to state-of-the-art techniques for multipath systems.**

***Index Terms*—Power Amplifier, Modeling, Digital Predistortion, mmWave**

I. Introduction

In today's modern world, wireless communication is the key to developing various technologies such as IoT. Designing a wireless architecture that provides a good quality of service is essential. The major aspect for improving wireless communications are efficiency, Bit error rate(BER), higher data rate, better spectrum usage, and less interference. This is the key enabler for the development of Multiple In Multiple Out (MIMO) systems [1]. This MIMO system consists of multiple RF paths which consist of Power Amplifiers (PAs), analog mixers, analog-to-digital and digital-to-analog converters. Hybrid MIMO systems are considered which consist of a hybrid beamformer (HBF) and a digital MIMO processor at the baseband for reducing the cost of implementation [2].

In MIMO systems, each antenna patch has a dedicated PA which is prone to produce a spectral regrowth which can be defined as the emission of the signal component outside the band of interest. This lead to interference of the adjacent channel which doesn't comply with the regulatory agency [3]. One of the ways for rectifying the spurious emission due to the PA is by Digital Pre-Distortion (DPD) [2], [3]. By implementing DPD in the RF system also improves the efficiency of the PAs. In the case of HBF, implementing individual DPD block for each PA are not viable since a single RF analog path is split into multiple PAs. This RF architecture thus demands a single DPD block for linearizing multiple PAs. In [4]–[6], research has been done for developing a single DPD block for linearizing an array of PAs. In [4], the DPD actuator was updated using a single PA within an array whereas in [5], the technique used was based on the assumption that the PAs have identical behavior. In [6], shows the linearization technique by minimizing the maximum residual error among the PAs array. Many works have been done for reducing the complexity and one such method is by creating multiple models as shown in [7]–[9]. In [7], shows switched behavioral modeling for different regions of the signal. However, the partition of the region doesn't consider the PA behavior, and time discontinuity between the models was not shown. Authors in [8], presented piece-wise modeling techniques using a spline-based model and the signal separation are done based on prior information of the PAs. In [9], authors show a vector threshold decomposition technique where the threshold was determined using the input power level. The time discontinuity was addressed but it increases the complexity since it decomposes each signal sample into several samples depending on the number of thresholds. In this paper, we propose a novel DPD methodology for linearizing multiple PAs within HBF using a single pre-distorter block. This technique generates sub-models for the HBF by intellectually selecting the sub-sample of the signal and obtaining a pre-distorted signal for HBF. The DPD actuator is segmented for different regions of the signal. The segmentation is done by deriving the rate of change of slope within PA AMAM characteristics. This method reduces the computational burden while maintaining the diverse characteristics of the PAs within HBF. The rest of the paper is described as follows. Section II explains the theory of the proposed method. Section III and section IV show the testbench setup and results & analysis respectively. section V is the final conclusion.

II. Theory

In this section, we propose a novel DPD approach where the different regions of the signal are derived by utilizing the variation in the amplitude characteristic of the highest

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compressed PAs with respect to the input power within HBF. This method utilizes this region of signal to find the semi-average response of the HBF and to derive the sub-model for the DPD actuator. This technique produces a linear response while reducing the computational process. Firstly, the signal is captured from the PA which exhibits the highest compression when provided with the same input signal within HBF. Now, by using the output information from the PA, a memoryless model is created using the equation (1)

$$y_{MLP}(n) = \sum_{p=0}^{P-1} a_p x(n) \left| x(n) \right|^p \tag{1}$$

where P is the order of non-linearity, a_p is the coefficient, n is the number of samples. The memoryless equation (1) approximates the characteristics of the PA.

$$f''(y_{MLP}) = \frac{d^2 y_{MLP}}{dy_{MLP}^2} \tag{2}$$

Finding the second derivative of the approximated signal y_{MLP} using the equation (2) will allow us to find the rate of change of the slope of the line. This information is utilized for the separation of the signal region based on the gain compression as shown in Fig. 1

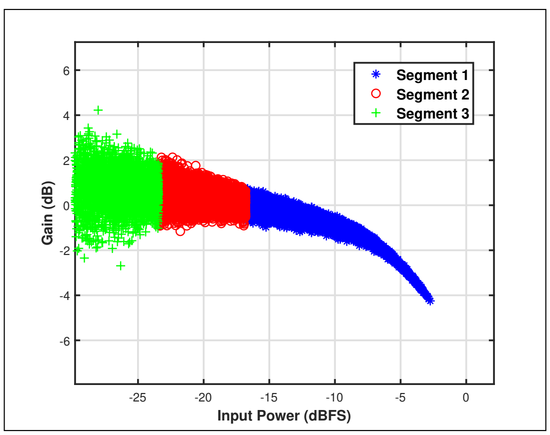

Fig. 1. Signal Segmentation Based on PA Gain Compression Characteristics

Fig. 1 depicts the segmentation of the PA gain characteristics and this segmentation is based on the rate of change of the slope of the line, which was determined by the minimum and maximum rates. In addition, this segmentation helps to identify areas of potential improvement in the PA gain characteristics by deriving sub-DPD actuator models for each segment. Consequently, this segmentation is an integral step in determining an optimized semi-average response of the PAs within HBF. PA shows the highest compression and the characteristics of the PAs within HBF deviate at the higher power region as shown in Fig. 2. Fig. 2 shows the different PA responses when provided with the same input signal within HBF. The semi-average response of HBF is obtained by averaging only the samples of the signal which experience the compression at a higher power level. The selection of the samples for averaging

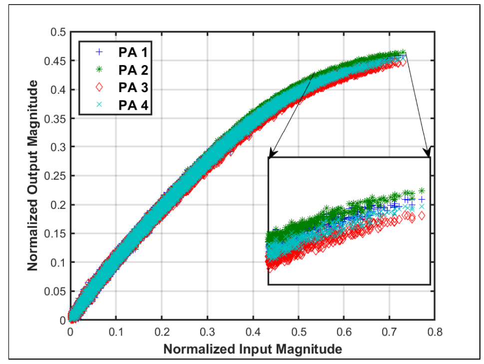

Fig. 2. AMAM plot for different PA within HBF

is done by relating the segment which has the highest gain compression (in this case segment 1 from Fig. 1) to the input power level. In other words, a semi-average signal consists of samples from the highest compressed PA (in this case segment 2 and segment 3 from Fig. 1) and average samples from PAs within HBF which experience the highest compression. One of the major issues with the DPD using a segmented approach is the time discontinuity between each segment. In this work, time discontinuity is tackled by creating copies of the signal using the Generalized Memory Polynomial(GMP) equation (3) [3]. This equation (3), generates numerous duplicates of the signal based on the conjunction of the instantaneous signal and its instantaneous, preceding, and trailing envelopes as shown in Fig. 3.

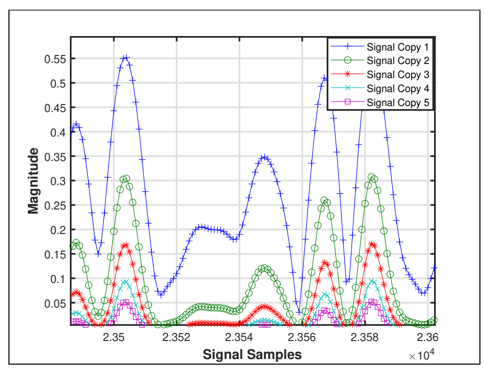

Fig. 3. Signal's Multiple Copies using GMP

$$\begin{aligned} y_{GMP}(n) = & \sum_{k=0}^{K_a-1} \sum_{l=0}^{L_a-1} a_{kl} x(n-l) \left| x(n-l) \right|^k \\ & + \sum_{k=1}^{K_b} \sum_{l=0}^{L_b-1} \sum_{m=1}^{M_b} b_{klm} x(n-l) \left| x(n-l-m) \right|^k \\ & + \sum_{k=1}^{K_c} \sum_{l=0}^{L_c-1} \sum_{m=1}^{M_c} c_{klm} x(n-l) \left| x(n-l+m) \right|^k \end{aligned} \tag{3}$$

where a_{kl}, b_{klm}, and c_{klm} are the coefficients of instantaneous, lagging, and leading envelope respectively. The matrix consisting of multiple copies of the signal is broken down into sub-matrix based on the number of segments as shown in Fig. 4. These sub-matrices are used for finding the coefficients

	Static Term	Memory Term	Lagging Term	Leading Term
Segment 1	✓			
Segment 2	✓	✓		
Segment 3	✓	✓	✓	✓

Fig. 4. Matrix Breakdown for Signal Samples Based on Segments

for the DPD actuator using the Least Squares (LS) algorithm. The LS estimate for the set of DPD coefficients h is defined as (4).

$$h = (Y^T Y)^{-1} Y^T e. \tag{4}$$

Where Y is a set of basis functions and e is the calculated error. In this paper indirect learning architecture is used hence, the residual error is calculated using pre-distorter and post-distorter signals as stated in [10] whereas the basis function typically relates to Volterra series, in this case, its GMP. The non-average segments (segments 2 and 3 in Fig. 1) are selected from the PA that exhibits the highest error compared to the other PAs within HBF, in order to achieve better convergence. The Mean Square Error (MSE) equation is used to monitor and track the errors.

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \tag{5}$$

where n is the number of signal samples, y_i is the actual input i.e., input signal, $\hat{y}_i$ is the observed/output signal.

III. Experimental Measurements at mmWave

In this experiment, a RFSoC ZCU111 was used to generate and receive wideband signals. The signal was a 100 MHz bandwidth 5G NR signal and was transmitted to hybrid beamforming array PAs at 28 GHz frequency. The output of the PA was monitored at a 30 dB coupled output and shifted back to the baseband. The experiment was controlled and signal processing was performed using MATLAB. The test bench setup is shown in Fig. 5. The HBF used in this work consists of an array of 4 PAs and each PA has a dedicated RF gain and phase-shifter modules. These modules were adjusted such that the output power from each PA generates 8dBm. One should take note that the signals are received individually by alternating between the paths within HBF, using a shared receiver. The proposed DPD approach is compared against the state-of-the-art min-max DPD technique. Adjacent Channel Power Ratio (ACPR) was used for validating the performance.

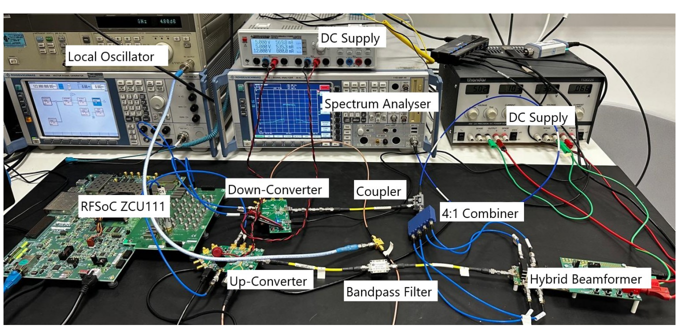

Fig. 5. Experimental Test Bench

IV. Result

TABLE I
ACPR performance for PAs within HBF

PA	PA (dB)	Min-Max (dB)	Segmented (dB)
PA1	-29.4024	-60.243	-50.6832
PA2	-29.6119	-52.5583	-51.8266
PA3	-28.7132	-56.8897	-47.8685
PA4	-29.0908	-56.6115	-50.7054

Table. I presents a comparison of the ACPR performance achieved by two methods: the proposed segmented DPD approach and the min-max DPD approach. The experiment was conducted fairly with 10 iterations. The results indicate that, on average, the min-max approach achieves an improvement of around 27dB, while the proposed segmented DPD method achieves an improvement of around 21dB, as demonstrated in Table. I. The approach of the proposed DPD is divided into segments, with each segment having different settings for non-linearity order, memory tap, leading, and lagging tap. For segment 1, the non-linearity order used was 8, with a memory tap of 4, and leading & lagging taps of 2 and 1, respectively. In segments 2 and 3, however, the non-linearity order was reduced to 2, with memory taps of 2 and 3 respectively, and no leading or lagging taps were considered. For the min-max approach, the non-linearity order was set to 15 with memory, leading, and lagging taps of 9, 5, and 3, respectively for characterizing the distortion generated by PA using a single polynomial function. In the min-max technique, the total number of coefficients needed was 143, while in contrast, the segmented approach necessitated only 61 coefficients. This signifies that the segmented approach requires significantly fewer computational resources and has the potential to improve the performance of digital pre-distortion systems by reducing the complexity associated with coefficient calculations. Furthermore, the suggested approach provides greater adaptability to signal changes by utilizing distinct pre-distorting coefficients for different signal segments. To segment the signal, an analytical approach is utilized, which utilizes the rate of change of slope to indicate changes in characteristics based on the input power level. This analytical segmentation approach requires less computational resources compared to using a machine learning technique, such as K-mean clustering. Fig. 6 & 7, shows the rectification of the spectral growth using the proposed segmented DPD and min-max DPD method. While the ACPR specification outlined in [11] is satisfied by both techniques, the segmented DPD method suggested requires lower computational resources. The proposed method calculates coefficients with fewer samples by averaging only the samples with higher distortion, unlike most average methods which use the entire signal. Non-average segment samples are taken from PAs with higher distortion on each iteration for DPD convergence on the highest error.

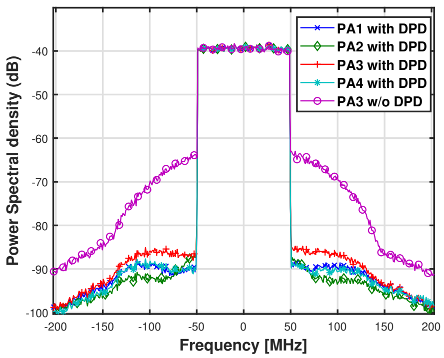

Fig. 6. Proposed Segmented DPD Method

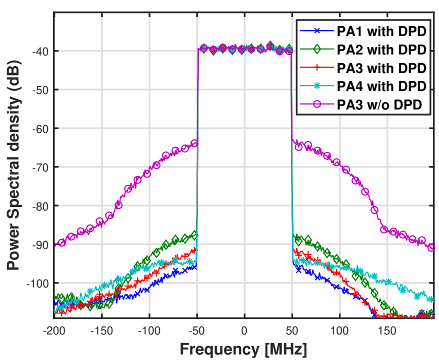

Fig. 7. Min-Max DPD Method

The AMAM characteristics before and after implementing the proposed method are shown in Fig. 8, with signal normalization relative to the input signal's RMS value.

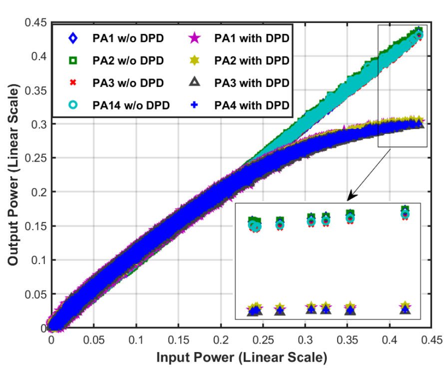

Fig. 8. AMAM Characteristic for Proposed Segmented DPD

V. Conclusion

The paper introduces a novel DPD approach to correct distortion in power amplifiers within Hybrid Beamformer (HBF) systems. The proposed technique not only reduces computational resources but also adapts better to signal changes by using distinct pre-distorting coefficients for different signal segments, determined through a novel analytical approach that characterizes the rate of change of slope of the power amplifier's AMAM characteristics. The paper also proposes a new approach where only a signal's sub-sample facing the highest distortion is used for averaging while the rest of the signal samples are taken from the power amplifier with the highest error with respect to the input signal. This innovative method adapts DPD actuators for the strongest non-linearity and achieves an average of 21dB of ACPR improvement with fewer DPD actuator coefficients.

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