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OTA-Based Data Acquisition and Signal Separation for Digital Predistortion of Multi-User MIMO Transmitters in 5G

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Abstract— **In this paper, a non-interruptive over-the-air (OTA) data acquisition method is presented to characterize system nonlinearity and calibrate digital predistortion (DPD) in multi-user (MU) multiple-input multiple-output (MIMO) transmitters with low hardware complexity. Based on a unified system model for fully-digital and hybrid MU-MIMO transmitters, the requirements and difficulties of data acquisition for MU-MIMO DPD are outlined first. A versatile OTA data acquisition technique, featuring a multi-observation forward modelling procedure, is thereby developed to obtain power amplifier (PA) output without interrupting the operation of the MIMO transmitters. By using this method, the output of each PA can be reconstructed instead of directly measuring each PA's output, even when the output signals of PAs are correlated. DPD can therefore be effectively constructed to mitigate the distortion. Experimental results demonstrate that the proposed approach can accurately estimate each PA output and linearize all PAs in the array.**

Keywords— **5G, digital predistortion, multiple-input multiple-output, multi-user, over-the-air**

I. INTRODUCTION

Multiple-input multiple-output (MIMO) transceiver has been widely accepted as one of key technologies for 5G communication systems because it can exploit beamforming, diversity and spatial multiplexing techniques to greatly improve spectral efficiency and save energy. Its application to multi-user (MU) scenarios, namely, MU-MIMO, is thus expected to be an important aspect in 5G deployment. Nevertheless, designing MU-MIMO transmitters faces severe challenges as the combination of signals from different users may cause complicated cross-distortion because of the nonlinearity induced by radio frequency (RF) power amplifiers (PAs). Hence, while high linearity and efficiency need to be guaranteed when designing the transmitters, low-cost hardware implementation and low power consumption of linearizers should be ensured as well.

Digital predistortion (DPD) is one of the most widely applied linearization technologies in modern communication systems, but the development of realistic DPD schemes for MU-MIMO systems is still at an early stage. Authors of [1] used uncorrelated signals in each RF chain, which eases DPD model extraction but the system cannot achieve beamforming. DPD for MU-MIMO transmitters sending each user's data via a seperate subarray in hybrid MIMO transmitters was proposed in [2], [3]. Since each subarray can process only one user's signals and signals in different subarrays must be uncorrelated, these solutions are not compatible with common precoding schemes and greatly reduce the flexibility in system design. In addition, because of a large number of RF chains, adopting DPD for large MIMO arrays at millimeter wave (mmWave) faces further hardware challenges. One of the main issues is the design of feedback path for DPD data acquisition. In particular, the conventional approach that acquires PA output signals with bulky couplers will no longer be practical, considering the large number of PAs that need to be monitored. Over-the-air (OTA) data acquisition technique thus becomes a promising alternative in 5G communication systems [4].

In this paper, a non-interruptive OTA data acquisition method is presented for DPD of MU-MIMO transmitters. Without interrupting the normal operation of MIMO transmitters, this OTA data acquisition method can be fit into MU-MIMO systems with both fully-digital and hybrid architectures. After capturing the OTA data, it separates the correlated signals in each RF chain by adopting a multi-observation forward modelling technique. It thus has low hardware cost and does not degrade the performance of the transmitters in MU scenarios where precoding is enabled.

II. UNIFIED SYSTEM MODEL OF MU-MIMO TRANSMITTERS

To correct the nonlinear distortions in MIMO systems, the DPD system needs to capture the output signals of PAs by using proper data acquisition techniques. In this section, we investigate both fully-digital and hybrid MU-MIMO systems and identify the requirements and difficulties in DPD data acquisition based on a unified system model.

A. System Analysis of MU-MIMO Transmitters

Fully-digital MIMO systems are well suited for sub-6 GHz systems because they can fully leverage the power of diversity and spatial multiplexing techniques. In digital beamforming, signals from different users are linearly precoded and distributed to all RF chains. Assume the data for the uth user is $\mathbf{s_u}$, and the precoding matrix is $\mathbf{F}$, the transmitted signals in the RF chains are $\mathbf{X}_{\mathrm{DBF}} = \mathbf{SF}$, where $\mathbf{S} = [\mathbf{s_1}, \mathbf{s_2}, \cdots]$.

Hybrid MIMO transmitters reduce the hardware complexity by splitting beamforming operation into digital and analog parts, so they are suitable for deployment in mmWave systems. As shown in Fig. 1, similar to the fully-digital case, the data of users need to be precoded before transmission [5]. After precoding, each precoded data stream is processed by the corresponding subarray. The final transmitted signals are $\mathbf{X}_{\text{HBF}} = \mathbf{S}\mathbf{F}_{\mathbf{D}}\mathbf{F}_{\mathbf{A}}$, where $\mathbf{F}_{\mathbf{D}}$ and $\mathbf{F}_{\mathbf{A}}$ are the precoding coefficients and the analog beamforming weights, respectively.

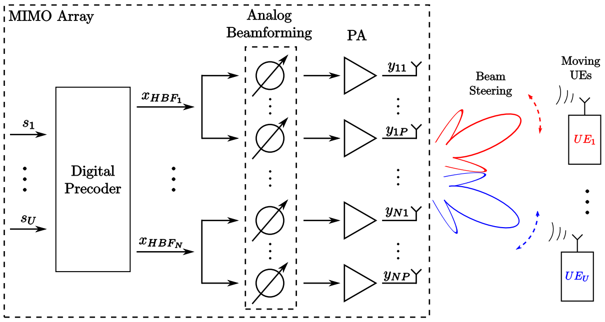


Fig. 1. Architecture of hybrid MU-MIMO transmitter.

B. Signal Correlation and Unified System Model

From the analysis of MU-MIMO transmitters stated above, we can see that there is strong signal correlation between the RF chains or the subarrays. In the fully-digital MU-MIMO transmitters, the data of each user are distributed into all RF chains by the precoder. Since there are usually more RF chains than users, the signals in the RF chains, i.e., different columns of $\mathbf{X}_{\mathbf{DBF}}$, will become correlated. In the hybrid MU-MIMO transmitters, digital precoding is also performed, making the input signals of different subarrays correlated with each other. As the analog beamformer only includes phase shifters, the correlation will remain between the input signals of different PAs.

To better focus on the DPD operation, we describe both fully-digital and hybrid MU-MIMO systems using a simple unified model. Based on the analysis above, it can be seen that the input signals of PAs are different but correlated in both fully-digital and hybrid MU-MIMO arrays. In actual systems, the input signals are distorted by different nonlinear functions because different PAs usually exhibit different nonlinear behaviors. Therefore, the signal to be transmitted by the nth antenna in the array is

$$\mathbf{y}_{\mathbf{n}} = G_n[\mathbf{x}_{\mathbf{n}}], \tag{1}$$

where G_n represents the transfer functions for the nth PA, and $\mathbf{x}_{\mathbf{n}}$ refers to the nth column of $\mathbf{X}_{\text{DBF}}$ or $\mathbf{X}_{\text{HBF}}$, depending on the system architecture. In either case, the $\mathbf{x}_{\mathbf{n}}$'s of different PAs are different but correlated.

C. Data Acquisition Challenges

To facilitate DPD model update, it is important to acquire the full information about system nonlinearity, namely, the output of each PA needs to be captured or estimated. It is a challenging task in a MU-MIMO system.

First of all, DPD data acquisition should not interrupt the normal operation of transmitters. We thus cannot force transmitters to transmit repetitive signals, and we cannot arbitrarily adjust the beamforming and precoding weights during the real time operation. Secondly, it is not feasible to capture the signals directly from PA output using couplers because of the high hardware complexity and integration cost. To avoid this issue, a promising solution is to capture the signal via OTA measurement. The receiver, however, can only obtain the combined signal transmitted from all antenna elements in OTA measurements. To characterize the behavior of every PA in the array, the combined received signal needs to be decomposed to recover the output signal of each PA. Considering the fact that the signal fed into the PAs are correlated, the signal separation process is inherently challenging.

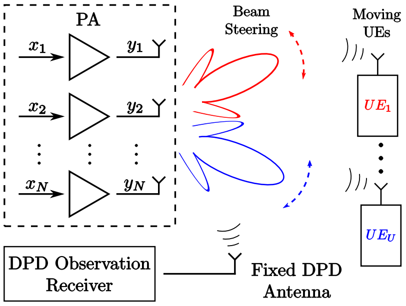


Fig. 2. System model for MU-MIMO transmitters with proposed OTA DPD method.

III. NON-INTERRUPTIVE OTA DATA ACQUISITION

Based on the analysis of MU-MIMO systems in previous section, a non-interruptive OTA data acquisition technique is proposed here. This method meets all the requirements, and can be applied to both fully-digital and hybrid MIMO transmitters. Using OTA-based data acquisition for DPD is not new, and it has been presented in the literature, e.g., [1][4], however, how to utilize this architecture in MU-MIMO systems to seperate correlatd signals has not been presented before, which we will discuss in detail here.

A. OTA Data Acquisition

In Fig. 2, the system architecture of the proposed OTA-based data acquisition is depicted. An external antenna, namely DPD antenna is set besides the transmitter to acquire the transmitted signals from a fixed direction. By using DPD antenna to capture data, the bulky switches and couplers can be avoided, greatly reducing the hardware complexity of the DPD observation path.

For similicity, we consider an uniform linear array (ULA) in the following analysis. The ULA consists of N antenna elements with equal spacing. The received signals at uth user equipment (UE) is

$$\mathbf{y}_{\mathbf{u}} = \mathbf{Y}\mathbf{h}_{\mathbf{u}}, \tag{2}$$

where $\mathbf{Y} = [\mathbf{y}_{\mathbf{1}}, \mathbf{y}_{\mathbf{2}}, \cdots]$, and $\mathbf{h}_{\mathbf{u}} = [h_1^u, h_2^u, \cdots]^T$ is the channel between transmitter and uth user. The far-field received signals at DPD antenna can be expressed as

$$\mathbf{y}_{\mathbf{o}} = \mathbf{Y}\mathbf{h}_{\mathbf{o}}, \tag{3}$$

where $\mathbf{h}_{\mathbf{o}} = [h_1^o, h_2^o, \cdots]^T$ is the channel between transmitter and the DPD antenna. Therefore, the received signals at UE and DPD antenna are different linear combinations of the PA output signals.

B. PA Output Reconstruction

After capturing the OTA data, it is necessary to separate the signal of each PA from the combined OTA signal.

1) PA Output Reconstruction with Uncorrelated Signals

If all PAs have independent input signals, the signal separation can be achieved by a forward modelling procedure. Assuming the nonlinear behavior of each PA in the array is modelled by a PA model, $\mathbf{y_n}$ can be modelled as

$$\hat{\mathbf{y}}_\mathbf{n} = \mathbf{A_n}\mathbf{c}_{\mathbf{PA_n}}, \tag{4}$$

where $\mathbf{A_n}$ includes all basis functions of the model and $\mathbf{c}_{\mathbf{PA_n}}$ is the corresponding model coefficients. Since all input signals are independent, different $\mathbf{A_n}$'s will be uncorrelated, so the forward model coefficients can be directly extracted by least squares (LS) as

$$\mathbf{c_{PA}} = (\mathbf{A}^H\mathbf{A})^{-1}\mathbf{A}^H\mathbf{y_o}, \tag{5}$$

where $\mathbf{A} = [\mathbf{A_1}h_1^o, \mathbf{A_2}h_2^o, \cdots]$ and $\mathbf{c_{PA}} = [\mathbf{c_{PA_1}}^T, \mathbf{c_{PA_2}}^T, \cdots]^T$.

2) PA Output Reconstruction with Correlated Signals

In MU-MIMO, however, the input signals of different RF chains are correlated, (5) is no longer valid, because the linear equation is under-determined. In this part, we propose a new signal reconstruction method that can work with correlated input signals.

In practical mobile communication systems, the beamforming coefficients will change continuously according to the movement of UEs. Therefore, the transmitter will send out different data sequences with varying precoding and beamforming weights during real time operation. Taking advantage of this feature, by using the fixed DPD antenna, multiple blocks of data with different combinations of the PA outputs can thus be received without interrupting the operation of the MIMO transmitter.

After gathering sufficient data blocks, the output of PAs can be virtually reconstructed via forward modelling because different data with different precoding and beamforming weights can avoid the under-determined equations during signal seperation of correlated signals. Assuming the mth input data for user u are $\mathbf{s_u^{(m)}}$, and the corresponding input and output signal for nth RF chain is $\mathbf{x_n^{(m)}}$ and $\mathbf{y_n^{(m)}}$, respectively. The received signal at DPD antenna is

$$\mathbf{y_o^{(m)}} = \sum_{n=1}^{N} \mathbf{y_n^{(m)}} h_n^o. \tag{6}$$

By applying a similar forward modelling technique, we obtain

$$\mathbf{Y_o} = \mathbf{A}'\mathbf{c_{PA}} \tag{7}$$

where

$$\mathbf{A}' = \begin{bmatrix} \mathbf{A_1^{(1)}}h_1^o & \mathbf{A_2^{(1)}}h_2^o & \cdots \\ \mathbf{A_1^{(2)}}h_1^o & \mathbf{A_2^{(2)}}h_2^o & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix},$$

$\mathbf{Y_o} = [\mathbf{y_o^{(1)}}^T, \mathbf{y_o^{(2)}}^T, \cdots]^T$, and $\mathbf{A_n^{(m)}}$ include basis functions of nth PA model built by mth input signals.

It is worth noting that even though there may be strong correlation between the columns of different $\mathbf{A_n^{(m)}}$'s, the big matrix $\mathbf{A}'$ is still well conditioned because the varying beamforming coefficients break the linear dependencies between different input signals. Therefore, the PA model coefficients can be extracted using LS as

$$\mathbf{c_{PA}} = (\mathbf{A'}^H\mathbf{A}')^{-1}\mathbf{A'}^H\mathbf{Y_o}. \tag{8}$$

Finally, the output of nth PA can be estimated with the corresponding PA model:

$$\hat{\mathbf{y}}_\mathbf{n} = \mathbf{A_n}\mathbf{c}_{\mathbf{PA_n}}. \tag{9}$$

C. DPD Construction

After PA output reconstruction, the DPD coefficients can be conveniently extracted. In fully-digital MIMO transmitters, it is necessary to employ one DPD for each RF chain. The extraction of DPD coefficients can follow the conventional linear optimization methods. For example, in indirect learning architecture, we build a regression matrix $\mathbf{B_n}$ by feeding $\hat{\mathbf{y}}_\mathbf{n}$ into the DPD model and extract coefficients by LS as

$$\mathbf{c_n} = (\mathbf{B_n}^H\mathbf{B_n})^{-1}\mathbf{B_n}^H\mathbf{u_n}, \tag{10}$$

where $\mathbf{u_n}$ is the output signal of the nth DPD.

In hybrid MIMO transmitters, to realize good overall linearization performance, analog predistorters may be employed for each PA to make all PAs in one subarray have similar nonlinear behavior such that a common DPD block can cancel the nonlinear distortions in all spatial directions. To extract the common DPD block, we can use the first PA in the subarray as linearization target. The remaining procedures are the same as the fully-digital case.

IV. MEASURED RESULTS

In order to validate the proposed method, a test bench was set up as shown in Fig. 3, which includes PC, signal generators, spectrum analyzer and a MIMO transmitter covering 5G frequency band (24.75-28.5 GHz). The validation measurement was implemented on a MIMO system serving two users with two RF chains. The input signals for the RF chains with bandwidth of 20 MHz and peak-to-average power ratio of 8.26 dB were generated by matched filter (MF) precoding in MATLAB on PC and downloaded to the two signal channels provided by one dual-channel signal generator (R&S SMW200A). On the observation receiver side, a horn antenna was employed as DPD antenna and a spectrum analyzer (Keysight N9030A) was utilized to capture the OTA outputs. Both the output and the input were sent back to the PC for further DPD processing.

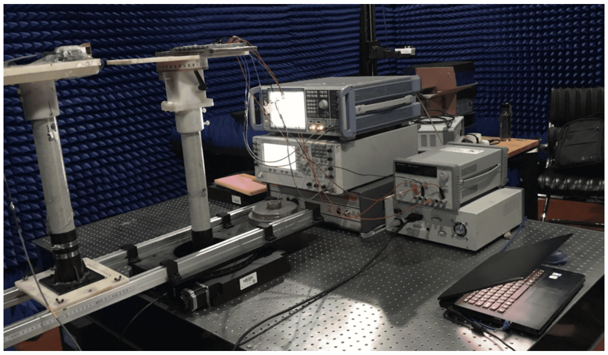


Fig. 3. The experimental test setup.

In the experimental test, the main beams of both users were steered to different directions by changing the digital precoding coefficients for the two users. The DPD antenna was fixed at a specific location while receiving signals with different digital precoding coefficients. After capturing enough data blocks, the forward modelling and DPD model extraction were performed. Afterwards, the extracted coefficients were applied to the precoded signals for the next iteration. For DPD, magnitude-selective affine (MSA) model [6] with M = 4 and K = 6 was considered.

To obtain the actual PA output for comparison with the reconstructed PA output, signals were sent by a single RF chain separately. Phase shifts and loss in the air of received signals by DPD antenna can be excluded by synchronization and normalization, so that the synchronized and normalized signals received at DPD antenna can be seen as actual PA output. To verify the linearization performance, the main beam directions of two users were set to point to the DPD antenna, so that main beam signal can be acquired and evaluated without moving the antenna.

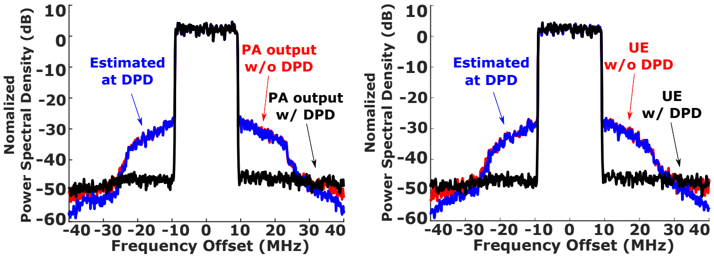
The measurement results of signal reconstruction and linearization are summarized in Table 1 and Table 2. As shown in Fig. 4, the reconstructed PA output and UE's signals agree with the actual PA output and UE's signals, respectively. The proposed DPD scheme for MU-MIMO transmitters was also verified to achieve good linearization performance.

Table 1. Measured NMSE between actual and reconstructed signals

	PA1	PA2	UE1	UE2
NMSE (dB)	-34.98	-38.34	-39.50	-39.64

Table 2. Measured DPD linearization performance

	NMSE (dB)		ACPR (dBc)	
	w/o DPD	w/ DPD	w/o DPD	w/ DPD
PA1	-26.28	-34.49	-35.99/-34.90	-48.88/-48.41
PA2	-27.43	-39.06	-36.44/-34.93	-50.21/-49.09
UE1	-17.64	-34.44	-36.07/-34.80	-49.12/-48.44
UE2	-17.98	-34.47	-36.59/-35.16	-49.15/-48.46



(a) (b)

Fig. 4. Measured results of signals reconstruction and linearization performance in 2 × 2 ULA (a) first PA; (b) first UE

V. CONCLUSION

In this paper, a non-interruptive OTA data acquisition has been proposed for MU-MIMO transmitters. Nonlinearity information for both PA outputs and far-field signals can be reconstructed by using this method with low-cost hardware implementation and without interrupting the normal operation of transmitters. Based on the experimental test, DPD with the proposed OTA data acquisition can effectively linearize both each PA and far-field signals with only one external antenna and a single feedback path, which has potential application for 5G massive MIMO transmitters.

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