Real-Time Single Channel Over-the-Air Data Acquisition for Digital Predistortion of 5G Massive MIMO Wireless Transmitters

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***Abstract* — In this paper, a single channel over-the-air (OTA) data acquisition approach for real-time calibration of digital predistorter in multiple-input multiple-output transmitters is proposed. By using the data acquired from the far-field OTA tests, the output of each power amplifier (PA) can be virtually reconstructed and thus the linearization reference at the main beam direction can be accurately estimated. Digital predistortion (DPD) can therefore be effectively constructed without direct measurement at PA output. Experimental results demonstrate that the proposed scheme can accurately estimate far-field main beam data and the proposed DPD can achieve excellent linearization performance.**

***Index Terms* — 5G, beam-forming, over-the-air, digital predistortion, multiple-input multiple-output, millimeter wave, power amplifier**

I. Introduction

Massive multiple-input multiple-output (MIMO) transmitters, featuring wide bandwidth and a large number of antennas, is expected to be adopted in 5G communication systems, especially at millimeter wave frequencies [1]. Designing such transmitters at high frequencies with large arrays faces severe challenges in ensuring high linearity and high efficiency. At the same time, deploying a large number of RF chains in the massive MIMO system puts huge constraints on the hardware complexity and the related power consumption. Thus, effective yet realistic linearization techniques must be employed.

Digital predistortion (DPD) is one of the most popular linearization techniques in modern communication systems. With application to MIMO systems, a straightforward architecture is to use a multiple-DPD scheme [2], where each power amplifier (PA) output is captured individually with a coupler before antenna and then linearized by using a separate DPD. This configuration is inherently inefficient and impractical for large arrays. The concept of beam-oriented linearization was proposed in [3], [4]. The target of linearization is changed to the main beam signal, rather than the output of each PA. The shared observation path feeds back different PA outputs in a time-division manner using switches. However, similar to other existing architectures, e.g., the combined feedback proposed by Choi and Jeong [5], it still relies on the use of couplers. Unfortunately, it is not practical to connect a coupler to every PA in massive MIMO transmitters because couplers are usually bulky and it is difficult to fit them into the limited space in the transmitter. In addition, couplers also introduce high insertion loss at millimeter wave frequencies. An architecture in [6] avoids directly acquiring signals from PA output by measuring feedback signals using multiple observation receivers over the air (OTA). The proposed method however requires fully uncorrelated signals to be transmitted in different RF paths and thus it is not suitable for real-time calibration in MIMO systems.

In this paper, we propose a single channel data acquisition scheme for calibrating DPD in real-time using OTA measurements. As shown in Fig. 1, an external observation path is equipped to receive the feedback signal at a fixed location near the main transmitter. In real-time operation, the phase of the signals radiated from the multiple antennas changes according to the location of the user equipment (UE) and thus multiple sets of data with different phase combinations of the PA outputs can be received by the DPD antenna. These data can be used to reconstruct the signals from the PA output and to calibrate the DPD to linearize the signal at the main beam direction. Compared with the existing methods, this proposed solution avoids the use of couplers or switches in the transmitter, thereby alleviates insertion loss and greatly decreases hardware implementation cost.

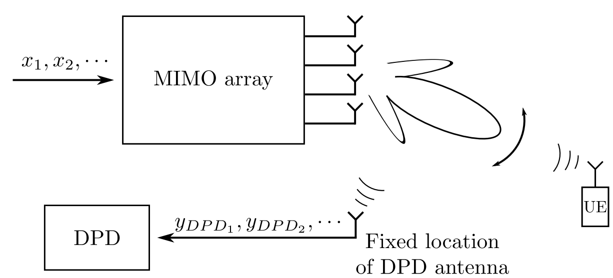

Fig. 1. Illustration of OTA-based data acquisition.

II. The Proposed System

The proposed scheme can be used in both fully digital and hybrid MIMO systems. In this section, we will discuss the DPD scheme in a hybrid beamforming system as an example.

A. OTA Data Acquisition

In Fig. 2, the system model of the proposed MIMO DPD architecture is depicted. An external antenna, namely DPD antenna, is set beside the transmitter antenna array to acquire the transmitted data from a fixed direction. The core idea of the OTA data acquisition is to retrieve the combined outputs of PAs over the air and model every PA output rather than acquire each PA output directly by using couplers.

For simplicity, we consider an uniform linear array (ULA) and only one user in the following analysis. The ULA consists of N antenna elements with equal spacing d and each succeeding RF chain has an β progressive phase increase relative to the preceding one.

In practice, the phase of transmitted signal changes according to the movement of the UE. Therefore, since the DPD antenna is located at the fixed location, it will receive different data blocks with different gains and phase shifts over the operation time.

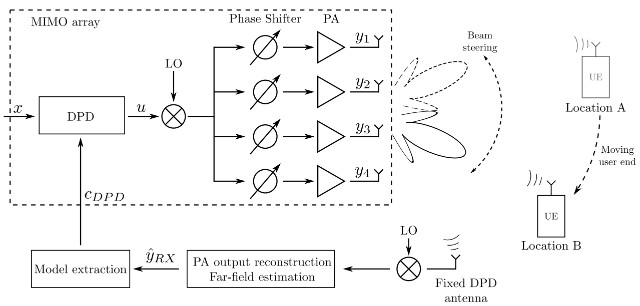

Fig. 2. Architecture of proposed MIMO DPD system.

1) Signal analysis at location A

To transmit main beam signal to location A, assume phase shift in phase shifter of n^{th} RF chain to be $(n-1)\beta_A$ and corresponding phase shift in channel to be $(n-1)\theta_A$. The output of n^{th} RF chain is

$$y_n = H_n[xe^{j(n-1)\beta_A}] = H_n[x]e^{j(n-1)\beta_A}.$$

where x is the input signal and H_n represents the transfer functions for the n^{th} PA. The far-field transmitted signal in the direction of location A is

$$y_{RX_A} = \sum_{n=1}^{N} H_n[x]e^{j(n-1)\beta_A}e^{j(n-1)\theta_A}.$$

The far-field transmitted signal is maximized when the phase shifts in phase shifter compensate for that caused by the channel, i.e. $\beta_A + \theta_A = 0$. Therefore, ideally, in main beam direction θ_A, we have

$$y_{RX_A} = \sum_{n=1}^{N} H_n[x].$$

Correspondingly, when the signal is received from a different direction, θ_{DPD}, which can be assumed to be the direction of DPD antenna, the received signal is expressed as

$$y_{DPD_A} = \sum_{n=1}^{N} H_n[x]e^{j(n-1)\beta_A}e^{j(n-1)\theta_{DPD}}. \tag{1}$$

2) Signal analysis at location B

When the user moves to location B, the main beam signal will be transmitted to location B. Phase shift in phase shifters will change accordingly. The far-field received signal in the direction of location B keeps the same as

$$y_{RX_B} = \sum_{n=1}^{N} H_n[x],$$

while the received signal at DPD antenna is changed to

$$y_{DPD_B} = \sum_{n=1}^{N} H_n[x]e^{j(n-1)\beta_B}e^{j(n-1)\theta_{DPD}}. \tag{2}$$

B. PA Output Reconstruction

After gathering sufficient data blocks, the output of the PAs can be virtually reconstructed via forward modelling. Assuming the m^{th} input data is x_m and β_m represents the corresponding progressive phase shift. The received signal at DPD antenna is

$$y_{DPD_m} = \sum_{n=1}^{N} H_n[x_m]e^{j(n-1)\beta_m}e^{j(n-1)\theta_{DPD}}$$

Assuming the nonlinear behavior of each PA in the array is modelled by a PA model, its output can be expressed by $H_n[x_m] = X_m c_{PA_n}$, where X_m includes all basis functions of the model and c_{PA_n} is the coefficients of PA model in n^{th} RF chain. The received signal at DPD antenna is:

$$y_{DPD_m} = \sum_{n=1}^{N} X_m c_{PA_n} e^{j(n-1)\beta_m}e^{j(n-1)\theta_{DPD}} \tag{3}$$

If we can observe M input data with different β, (3) can be written into matrix format:

$$\boldsymbol{y_{DPD}} = \boldsymbol{X_{\beta} c_{PA} \theta_{DPD}},$$

where

$$\boldsymbol{X_{\beta}} = \begin{bmatrix} X_1 & X_1 e^{j\beta_1} & X_1 e^{j2\beta_1} & \dots & X_1 e^{j(N-1)\beta_1} \\ X_2 & X_2 e^{j\beta_2} & X_2 e^{j2\beta_2} & \dots & X_2 e^{j(N-1)\beta_2} \\ \vdots & & & & \\ X_M & X_M e^{j\beta_M} & X_M e^{j2\beta_M} & \dots & X_M e^{j(N-1)\beta_M} \end{bmatrix}.$$

The PA coefficients can be solved using least squares as:

$$\boldsymbol{c_{PA}} = (\boldsymbol{X_{\beta}^H X_{\beta}})^{-1}\boldsymbol{X_{\beta}^H y_{DPD} \theta_{DPD}^{-1}}.$$

Output of n^{th} PA can be estimated with the PA model:

$$H_n[x] = X c_{PA_n}.$$

C. DPD Construction

The proposed MIMO DPD scheme consists of two main elements, namely far-field estimation and DPD coefficients extraction, as shown in Fig. 2. Far-field received signals at any direction, including both main beam and side lobe, can be estimated based on the output of PAs and channel information.

Assuming the input matrix X is built based on the PA models, the estimated main beam signal is

$$\hat{y}_{RX} = \sum_{n=1}^{N} H_n[x] = \sum_{n=1}^{N} X c_{PA_n}$$

To linearize the main beam, the estimated received signal $\hat{y}_{RX}$ is used as the linearization reference. The remaining procedures of linearization are the same as conventional DPD architectures. The proposed method works with any existing DPD models, and both direct learning and indirect learning algorithms can be used to extract the model coefficients. For example, in indirect learning, the regression matrix of post-inverse model, Y, can be built by feeding $\hat{y}_{RX}$ to the DPD model, and the DPD coefficients can be solved by

$$c_{DPD} = \left(Y^H Y\right)^{-1} Y^H u,$$

where u is the output of DPD.

III. Measurement 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). Input signal with bandwidth of 20 MHz and peak-to-average power ratio of 7.27 dB was generated by MATLAB on PC and downloaded to the two signal channels provided by one dual-channel signal generator (R&S SMW200A). Baseband signals can be phase-shifted separately to realize the beam-forming operation. In observation receiver side, one 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. MIMO DPD test bench.

In the experimental test, the main beam was steered to different directions by adjusting the phase shifts of the two signal chains. The DPD antenna was fixed at a specific location while receiving signals of different main beam directions. After capturing a number of data blocks, the forward modelling and DPD model extraction were performed. Afterwards, the extracted coefficients were applied to the input signal for the next iteration. To verify linearization performance, the main beam direction was set to point to the DPD antenna, so that main beam signal can be acquired and evaluated without moving the DPD antenna.

The proposed DPD scheme has been validated by the test setup. As shown in Fig. 4, the modelled far-field main beam signal agrees with the received main beam signal and NMSE between them is -41.77 dB. The performance of proposed DPD is illustrated in Fig. 5. It is shown that the proposed MIMO DPD method achieves an ACPR better than -54 dBc.

IV. Conclusion

In this paper, a novel DPD architecture with real-time OTA data acquisition for massive MIMO transmitter has been proposed. Based on the experimental validation, the proposed method can efficiently realize linearization of far-field signal with only one external antenna, which is very suitable for 5G massive MIMO applications.

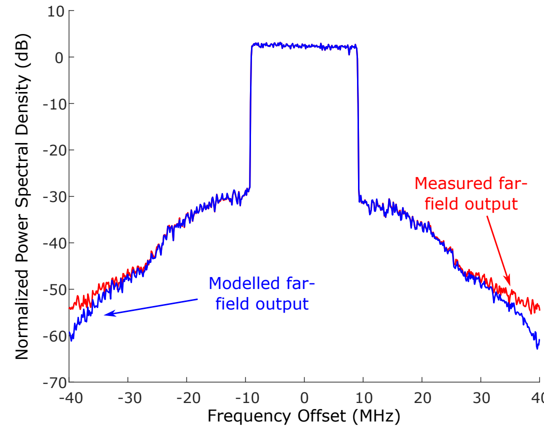

Fig. 4. Modelled far-field output.

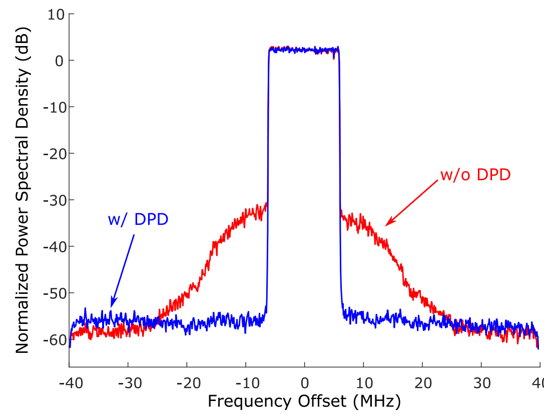

Fig. 5. Far-field output without and with DPD.

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