Spatial Digital Predistortion Techniques for Massive MIMO Systems

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***Abstract*—This report summarizes the research outcomes supported in part by the 2021 IEEE MTT-S Graduate Fellowship Program. In the last year, we focused on the linearization problems of massive MIMO systems and proposed several practical digital predistortion (DPD) techniques. The behavioral modeling and DPD schemes for the fully-connected hybrid beamforming (FC-HBF) massive MIMO systems were studied, followed by the preliminary experimental validations on a 4-element array platform. Furthermore, a load-mismatch tracking linearization DPD (LMT-DPD) algorithm is proposed to solve the dynamic linearization problem of a massive MIMO array during beam scanning, which enables automatic and fast adjustments of its coefficients without the re-identification of the DPD model.**

***Index Terms*—Digital predistortion, fully-connected hybrid beamforming, massive MIMO, power amplifier.**

I. Introduction

THE power amplifiers (PAs) are recognized as the most power-hungry components in transmitters. To obtain high efficiency, the PAs are usually operated in the saturation region, resulting in significant nonlinear distortion. In such cases, effective linearization approaches must be adopted to compensate for the distortion while maintaining high efficiency of the PA. The digital predistortion (DPD) is currently the most common PA linearization technique.

In massive multiple input–multiple output (MIMO) systems, state-of-the-art DPD techniques suffer from significant performance loss in terms of linearization effectiveness and power consumption, because of the increase in signal bandwidth, the introduction of phased array and hybrid beamforming (HBF) architecture, strong cross-antenna mutual coupling, etc. Thus, DPD techniques need to be evolved to be adapted to massive MIMO systems.

In previous works, the implementation difficulties of conventional DPD in HBF systems have motivated us to seek creative DPD architectures and solutions, and several prototyping approaches are proposed to linearize the sub-array (SA) HBF system [1]. In this report, we discuss the DPD solutions for the fully-connected (FC) HBF systems, starting with the behavioral modeling of array response to illustrate the nonlinear interactions of different transmit (Tx) signals in the beam steering directions. Then, a multi-stream spatial DPD (MSS-DPD) scheme is proposed to linearize the beam signals. Furthermore, to achieve the dynamic compensation of a massive MIMO array during beam scanning, the time-domain poly-harmonic distortion (TD-PHD) model is studied for PAs under load mismatch conditions. Then, a load-mismatch tracking linearization DPD (LMT-DPD) algorithm is proposed based on the TD-PHD model, which enables fast and automatic update of the coefficients without re-identification.

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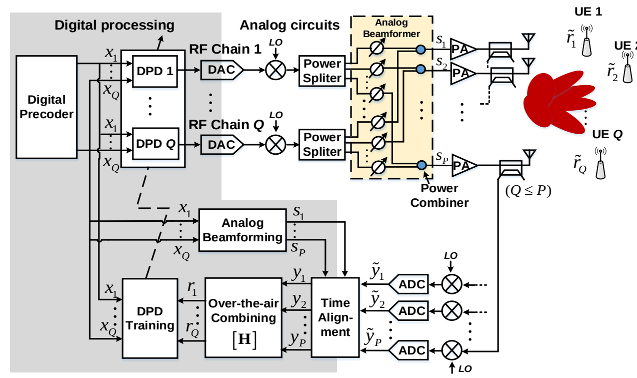

Fig. 1. Block diagram of the proposed multi-stream spatial DPD structure.

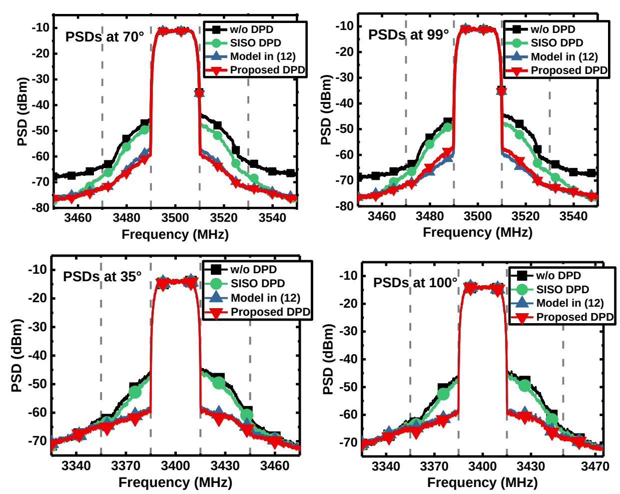

Fig. 2. Measured PSDs of the main beam signals.

II. Multi-Stream Spatial DPD Technique

To resolve the DPD implementation issue in an HBF system, the linearization object of the proposed technique is the beam signals rather than the individual PAs [2]-[3]. Fig. 1 shows the block diagram of the MSS-DPD structure.

The Tx paths of the MSS-DPD technique include Q multi-input predistorters, and each predistorter will linearize the beam signal towards the corresponding user. In the feedback loops, each PA's output signal ($y_1,\ldots,y_P$) is down-converted, sampled and time-aligned with a digital copy of each PA's input signal ($s_1,\ldots,s_P$). According to the beamforming conditions, an "over-the-air combining" module is used to synthesize the "virtual" beam signals transmitted by the FC HBF array simultaneously. Then, the MSS-DPD models for each RF chain are identified with the Tx signals ($x_1,\ldots,x_Q$) and the estimated beam signals

($r_1,\ldots,r_Q$). The MSS-DPD model is consisted of a main branch to describe and compensate for the IMD terms that are always aligned with the linear beam directions, and several auxiliary branches corresponding to the remaining IMD terms. Next, the independent predistorted signals for each RF chain are generated by these DPD models using all of the Tx signals from all RF chains, and, finally, these predistorted signals are converted to the analog domain, up-converted, and passed through the beamforming networks as well as the nonlinear PAs.

To validate the principles of the MSS-DPD, experimental measurements are carried out on a 2-stream 4-antenna element beamforming array. The beam steering directions of the array are adjusted as $(\theta_1 = 70°, \theta_2 = 99°)$ and $(\theta_1 = 35°, \theta_2 = 100°)$, respectively. The MSS-DPD can achieve 13~14 dB ACPR improvements for the beam signals in both tests, as shown in Fig. 2. The superior linearization results indicate the MSS-DPD is fully capable of linearizing an FC HBF array.

III. Load-Mismatch Tracking DPD Technique

Due to mutual coupling and load modulation effect in an active phased array, the load impedance of the PA varies during beam scanning. Fig. 3 shows the signal flows. In such cases, the nonlinearity of PA's output signal is dependent on the beam steering angle, leading to a fast update frequency for DPD blocks. A TD-PHD model is discussed for the behavioral modeling and linearization of PA under mismatch, followed by a practical model construction method, as in (1)-(2):

$$b_2(n) = \sum_{k=1}^{K_1}\sum_{m=0}^{M_1}\alpha_{km} f_{km}^1(a_1) + \sum_{k=1}^{K_2}\sum_{m=0}^{M_2}\sum_{p=0}^{P_2}\beta_{kmp} f_{kmp}^2(a_1, a_2) + \sum_{k=1}^{K_3}\sum_{m=0}^{M_3}\sum_{p=0}^{P_3}\gamma_{kmp} f_{kmp}^3(a_1, a_2^*) \tag{1}$$

$$a_2(n) = \sum_{t=0}^{T}\lambda_t b_2(n-t) \approx \sum_{t=0}^{T} d_t a_1(n-t) \tag{2}$$

It should be noticed that since a_2 is the reflection signal due to load mismatch, its average power is usually far weaker than that of the original input signal a_1. Therefore, a_2 can be recognized as a small perturbation at the same frequency as a_1. In such case, it is reasonable to apply the superposition principle, which assumes that the PA's response induced only by the input signal a_1 will not be affected by the variation of reflection signal a_2. Based on the superposition principle, the load-mismatch tracking DPD technique is derived utilizing the TD-PHD model, and Fig. 4 shows the block diagram of its structure. When the load-mismatch state changes, instead of re-identifying the DPD model, the proposed technique enables fast adaption of the DPD block by simply tuning its coefficients according to the real-time load reflection coefficient. The details of the LMT-DPD are presented in [4].

In experimental validations, the reference DPD and the single-point (SP) DPD are also compared with the LMT-DPD. The reference DPD represents the ideal case where the DPD coefficients are re-extracted when the load impedance changes, and the coefficients of the SP-DPD are fixed during validations. By simply adjusting the coefficients, the proposed DPD

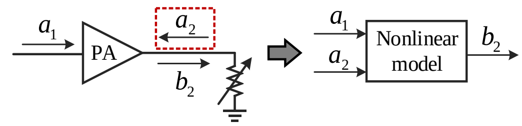

Fig. 3. Behavioral model schematic for PA under load-mismatch.

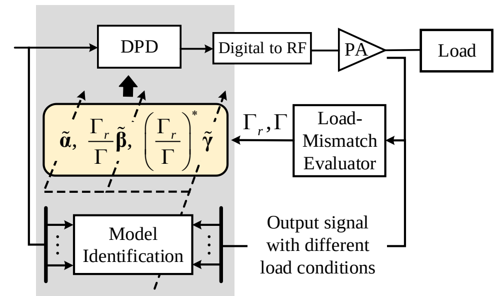

Fig. 4. Block diagram of load-mismatch tracking DPD.

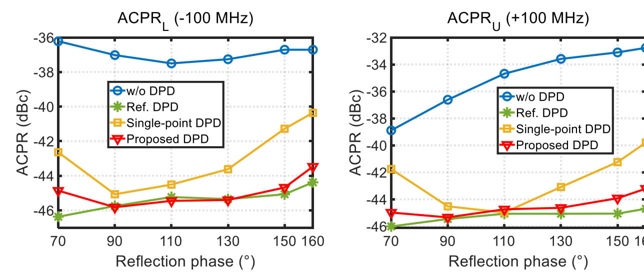

Fig. 5. ACPR values under different load-mismatch conditions.

presents comparable performance with the reference DPD and outperforms the SP-DPD among a wide range of load impedances without coefficients re-calibration, leading to a significant reduction of identification complexity.

IV. Fellowship Impact and Career Plan

I am truly honored to receive the 2021 IEEE MTT-S Graduate Fellowship Award, and I would like to present my gratitude to the IEEE MTT society. This Fellowship helped me a lot to complete my doctoral research projects and encouraged me to continue my research in the design and linearization of power amplifiers. As for my career plan, I intend to pursue an academic career in a university or research institution. I look forward to attending more activities hosted by MTT-S, and presenting more interesting and meaningful works in the future.

References

[1] X. Liu et al., "Beam-Oriented Digital Predistortion for 5G Massive MIMO Hybrid Beamforming Transmitters," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 7, pp. 3419-3432, July 2018.

[2] X. Liu, W. Chen and J. Chu, "Behavioral Modeling and Digital Predistortion for Fully-Connected Hybrid Beamforming Massive MIMO Transmitters," *2020 IEEE Asia-Pacific Microwave Conference (APMC)*, 2020, pp. 463-465. (**Student Paper Prize**)

[3] X. Liu, W. Chen, J. Chu, F. M. Ghannouchi and Z. Feng, "Multi-Stream Spatial Digital Predistortion for Fully-Connected Hybrid Beamforming Massive MIMO Transmitters," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 68, no. 7, pp. 2998-3011, July 2021.

[4] X. Liu, W. Chen, W. Chen, Y. Guo, and Z. Feng, "Load-Mismatch Tracking Digital Predistortion for Mobile-Terminal Power Amplifiers," *2022 IEEE MTT-S International Microwave Symposium (IMS)*, Denver, CO, 2022.