

OFDM-Based Beam-Oriented Digital Predistortion for Massive MIMO

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Abstract—Linearization of massive MIMO arrays is a significant computational challenge that typically scales with the number of antennas. In this work, we introduce a beam-oriented digital predistortion (DPD) scheme for OFDM-based massive MIMO systems that applies predistortion before the precoder in the OFDM guard-band subcarriers. Using simulation results, we show that, for a 64 antenna massive MIMO array, our proposed method can achieve the same DPD performance as a conventional DPD method while requiring an order of magnitude fewer multiplications.

I. INTRODUCTION

In the last ten years, massive multiple-input multiple-output (MIMO) has gone from initial conception to commercial deployment [1]. While deployments are underway, there are still practical challenges that have not been fully considered. Of note, the linearization of large antenna arrays poses a significant computational burden for base stations [2]. This topic has received recent interest in the literature with discussions of the effects [3, 4], possible technologies [2], and some possible digital predistortion (DPD) solutions [5–7]. A detailed analysis on the effect of nonlinearities is studied in [3]. However, it is assumed that each antenna uses exactly the same power amplifier (PA), which is not realistic due to process variations during the manufacturing of the PAs. The work of [4] considers a more general case with unique PA models for each antenna. However, throughout the analysis, memory effects are not fully considered, which are certainly present in practical scenarios [8]. This neglect of memory effects is especially problematic for the wide bandwidths considered in beyond-5G technologies.

Energy efficiency is a key design goal for MIMO arrays. PAs typically consume the most power in transmitters, so their efficiency is critical. In [2], Doherty PAs are considered a good candidate for large antenna arrays due to their energy efficiency. They are also known for being highly nonlinear, meaning that DPD will be necessary [8]. However, the common DPD approach of using an inverse model of a PA scales poorly to large antenna arrays, as one inverse model is required for each antenna, and few works offer solutions to reduce the computational burden for the linearization of massive MIMO arrays. In [5], complexity is reduced for linearizing a MIMO

array by using a lower-complexity decorrelation-based DPD method. However, the complexity of this method still scales with the number of antennas. When performing DPD, it is clear that high-complexity solutions result in additional power consumption in the form of additional digital signal processing (DSP) blocks on field programmable gate array (FPGA) implementations or additional area on application-specific integrated circuit (ASIC) implementations. This complexity threatens the energy efficiency goals of massive MIMO.

One significant finding throughout the recent literature is that, in beamformed massive MIMO, the majority of the adjacent channel power (ACP) due to PA nonlinearities follows the main beams [3, 4]. Based on this, multiple works have presented a beam-oriented DPD [6, 7]. In these works, the main objective is to linearize along the main beam by only considering the nonlinearity experienced by the intended user. However, these works do not consider the case of orthogonal frequency-division multiplexing (OFDM) modulation found in 5G, which poses a new challenge to these previous methods in that the modulation and precoding are done in the frequency domain whereas the DPD methods are developed for time domain.

In this work, we expand the beam-oriented DPD concept, and we show how to exploit the structure of OFDM-based massive MIMO systems to derive an efficient DPD algorithm. In particular, we apply DPD in the frequency domain and before the precoder so that the DPD application complexity does not scale with the number of antennas. This method is performed by injecting cancellation tones in the normally empty guard-band subcarriers to reduce the nonlinearity experienced by the user.

II. SYSTEM MODEL AND ALGORITHM

A. System Model

We consider a single-user massive MIMO system with one receive antenna at the user and N transmit antennas at the base station (BS). Without loss of generality, we restrict the presentation below to one OFDM symbol. The data to the user is represented by the signal vector $\mathbf{s} \in \mathcal{O}^W$, where W indicates the total number of tones in the OFDM symbol and $\mathcal{O}$ represents the set of complex-valued constellation points. Pulse shaping is applied via the inclusion of guard-band subcarriers that are normally empty. We denote the set of guard subcarriers as $\mathcal{Z}$ and set $s_w = 0 \forall w \in \mathcal{Z}$.

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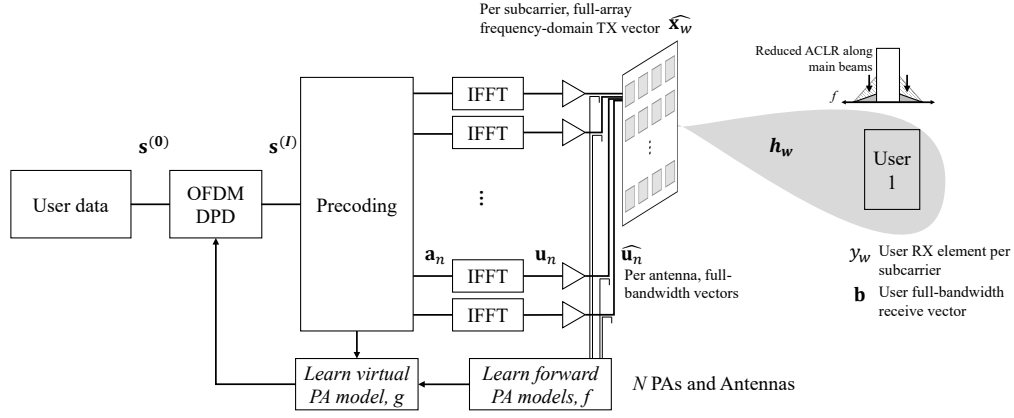


Figure 1. Block diagram for the beamformed OFDM DPD system. User data is updated before the precoder with the goal of sending ACP cancellation tones in the guard-band subcarriers.

Precoding is applied separately to each OFDM tone, generating W vectors $\mathbf{x}_w \in \mathbb{C}^N$. Each vector is remapped to contain all the tones per antenna, $[\mathbf{x}_1, \dots, \mathbf{x}_W] = [\mathbf{a}_1, \dots, \mathbf{a}_N]^T$, where each $\mathbf{a}_n$ is a W -dimensional vector containing all tones for antenna port $n \in \{1, \dots, N\}$. At this point, the data is converted from the frequency domain to the time domain via the inverse discrete Fourier transform (DFT), which is typically calculated via an inverse fast Fourier transform (IFFT). The data is reorganized to be serial instead of parallel, and a cyclic prefix is added. In many systems, windowing is also applied between symbol boundaries to improve the spectral shaping [9]. We express this time-domain representation for each antenna as the vector $\mathbf{u}_n$. This vector is upconverted to an RF frequency where it is transmitted through a PA with nonlinear function $f_n(\cdot)$. The time-domain data for each antenna is given as $\hat{\mathbf{u}}_n = f_n(\mathbf{u}_n)$. The frequency-domain equivalent is given as $\hat{\mathbf{x}}_n$.

In OFDM systems, the channel is usually modeled in the frequency-domain for each tone w as, $y_w = \mathbf{h}_w \hat{\mathbf{x}}_w + n_w$, where y_w denotes the received data for OFDM tone w and $\mathbf{h}_w$ is the $1 \times N$ channel vector, and n_w is a Gaussian random noise term. The user received signal can be remapped to $[y_1, \dots, y_W] = [\mathbf{b}]$ to represent a W dimensional vector of all tones received at the user. The time-domain user-received signal is given as $\mathbf{v}$.

B. Conventional Per-Antenna DPD

Extending the conventional DPD work to apply to multi-antenna systems can be done by applying a DPD block per antenna. In Eq. (1) a memory polynomial (MP) is shown with nonlinearity order P and M memory taps:

$$\hat{x}^{(n)}(i) = \sum_{p=1}^P \sum_{m=0}^M \beta_{p,m}^{(n)} x^{(n)}(i-m) \left| x^{(n)}(i-m) \right|^{p-1}. \quad (1)$$

Here, an indirect learning architecture (ILA) [10] is used to set up a least-squares problem to find the predistorter. An optimal set of coefficients for antenna port n , $\beta^{(n)}$, is found so that the cascade of the predistorter block and the power amplifier is linear [11]. While this method is commonplace and performs

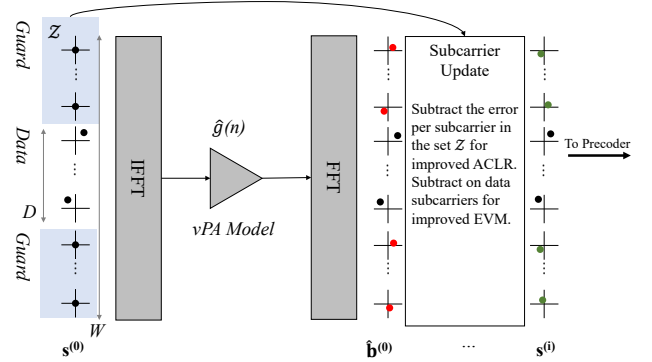


Figure 2. OFDM-based DPD update. A virtual PA modeling the nonlinearities experienced by an end user is used to apply predistortion in the guard-band.

well, it scales poorly in many-antenna scenarios in that it has to be done for every PA. It operates on each time-domain, digital-baseband signal with no knowledge of the full system or the modulation scheme. This is in stark contrast to our proposed method, which we present in the following section.

III. BEAMFORMED OFDM DPD ALGORITHM

The system architecture of our proposed OFDM-based massive MIMO DPD approach is illustrated in Fig. 1. Our method's main idea is to utilize the normally empty subcarriers to reduce the ACP by injecting tones with the opposite phase of the ACP.

A. Virtual Power Amplifier

To represent the nonlinearity experienced by the user, we aim to learn a single *virtual PA* (vPA) with transfer function $g(\cdot)$. To do this, the transfer function of each PA is modeled with a memory polynomial from Eq. (1). While this is similar to the memory polynomial DPD approach, these are forward models which are shown to be less susceptible to noise [12] and will only be used in this learning phase of our algorithm.

Given data for a user, we can perform each of the modulation steps outlined in Section II-A including transmission through the PAs to estimate the receive vector y at the user. With the

time-domain version of the user's data, $\mathbf{r} = \text{IFFT}(\mathbf{s})$, and their estimated time-domain receive data, $\mathbf{v}$, we learn a memory polynomial, $\hat{g}(\cdot)$ from the TX data to the RX data via a least-squares estimation.

B. DPD Application

After learning a vPA, $\hat{g}(\cdot)$, we can estimate the received error in each subcarrier through this low-complexity proxy for the system's nonlinearities. The user data is converted to the time domain where it goes through $\hat{g}$. The estimated time-domain receive signal is then converted back to the frequency domain to get $\hat{y}$ for all subcarriers, including the guard-band subcarriers $w \in \mathcal{Z}$. The user data vector is then updated as $\mathbf{s}^{(i+1)} = \mathbf{s}^{(i)} - \mu (\hat{\mathbf{b}}^{(i)} - \mathbf{s}_k)$, where i denotes an iteration index, and μ is a learning rate. This concept is illustrated in Fig. 2.

In this work, we assume perfect channel state information (CSI). Practically, it would not be possible to directly measure CSI on the guard-band subcarriers as the users do not transmit pilots on these subcarriers. However, it may be possible to extrapolate these subcarriers by extending known CSI or applying interpolation-based techniques common for OFDM denoising [13].

IV. DPD SIMULATION RESULTS

In this section, we explore massive MIMO simulations under the presence of unique MPs with $P = 7$ and $M = 4$. PA coefficients for each antenna are drawn from a normal distribution with a 10% variance around a PA model collected from the WARP SDR platform [14]. The combination of using a measurement-based PA model with memory effects and variance between all PAs in the array contributes to making this simulation realistic. $D = 1200$ OFDM data subcarriers out of $W = 4096$ total subcarriers are beamformed by a zero-forcing precoder to a user at 70 degrees and 400 meters from the uniform linear array operating at 3.5 GHz. We assume that the base station has full CSI and that there is a line-of-sight channel. The Quadriga channel model [15] software environment is used to create the simulation topology.

We consider the radiated power as a function of angle and subcarrier index in Fig. 3. For this plot, vertical cross-sections are equivalent to a power spectral density (PSD), and horizontal cross-sections are equivalent to a beamforming plot. Fig. 4 shows the PSD in the user's direction for each case. Fig. 5 shows the beampatterns for an in-band and out-of-band subcarrier. In Fig. 3a where no DPD is applied, it is shown that the ACP is dominant in the user's direction while there are minor nonlinearities appearing in other spatial directions. This finding is consistent with other works in the literature [3, 4]. Fig. 3b shows the radiated power after our OFDM DPD. Here, the out-of-band (OOB) emissions in the direction of the user have been reduced. There are still nonlinearities appearing in other directions, but they remain below the OOB in the direction of the user. Fig. 3c shows the radiated power after applying a MP DPD per antenna. This method linearizes each PA so that there is little nonlinearity left in the system. When

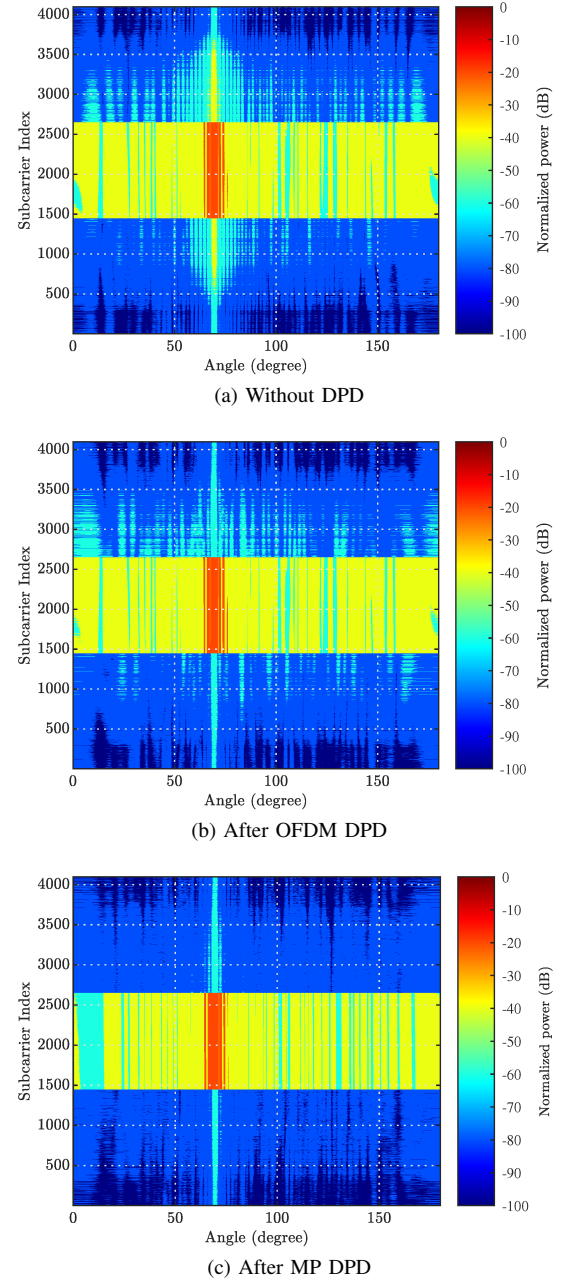


Figure 3. Radiated power as a function of angle and subcarrier for a user placed at 70° from a uniform linear array with $N = 64$ antennas.

compared to the OFDM DPD, we can see that the radiated ACP in all directions has been reduced. However, when examining Fig. 4, we can see that the performance in the direction of the user is similar. The user received PSD without any DPD shows significant spectral regrowth so that the adjacent channel leakage ratio (ACLR) is approximately -34 dBc. The OFDM DPD and MP DPD each linearize so that the ACLR is reduced to -52 dBc.

In Fig. 5, we examine the behavior over all angles. In Fig. 5a, we see the ideal in-band pattern in black. After being broadcast through the PAs, we see in the red curve that the beam pattern's rolloff from its strongest point at 70 degrees has been weakened

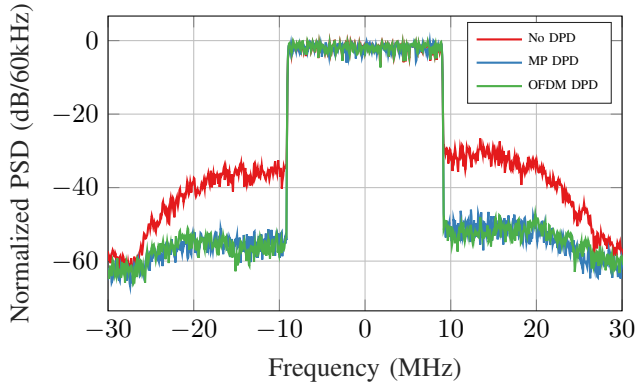


Figure 4. Normalized PSD at the user. The received spectrum with the MP DPD per antenna and the OFDM DPD show similar reductions in ACP.

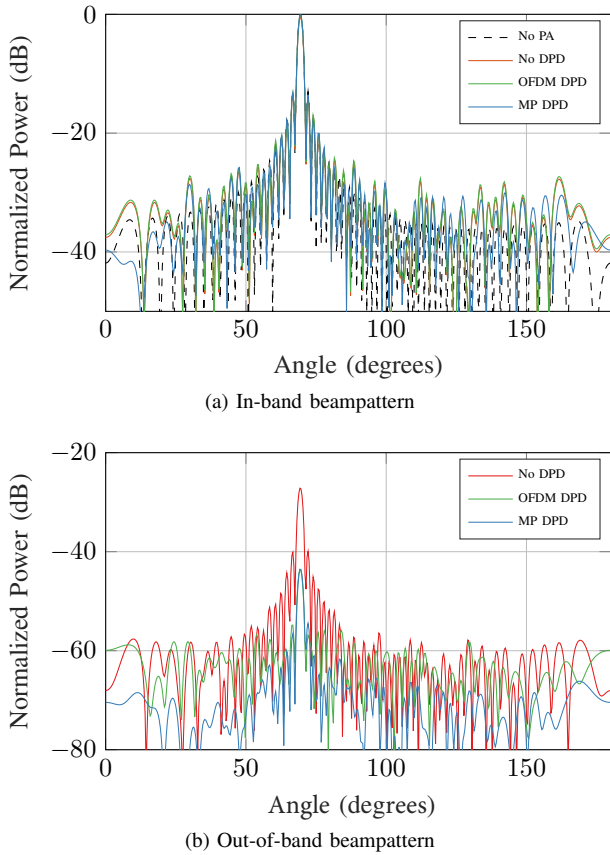


Figure 5. Beampatterns with and without DPDs for a user placed at 70° from a uniform linear array with $N = 64$ antennas.

with a few side-lobes being accentuated by a few dBs. The OFDM DPD method does little to correct this as it operates only in the direction of the user. The MP DPD linearizes each PA and reduces a few of the protruding sidelobes.

In Fig. 5b we examine the OOB beam pattern by plotting the array response for subcarrier 3000 from Fig. 3. Without PAs, there would be no bandwidth expansion to plot. With PAs in the system, we start with the case of no DPD shown in red. The OFDM DPD method reduces the power in the subcarrier

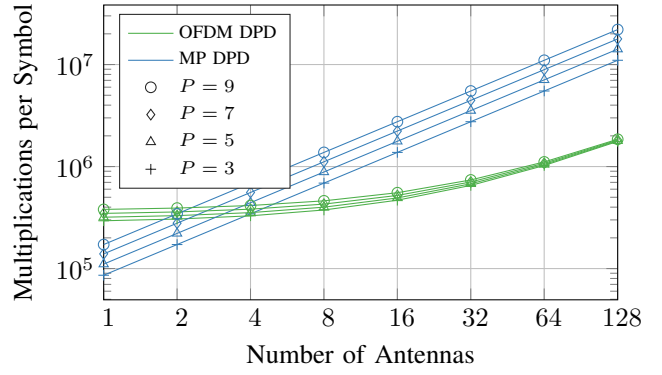


Figure 6. Multiplications per OFDM symbol versus the number of antennas.

at 70 degrees by 20 dB. It does little in other directions, but this is of little consequence in that the power in the direction of the user is the primary concern. The MP DPD reduces the power for the OOB emissions in all directions.

a) Algorithm Complexity: Using commonplace approaches such as the MP or generalized-MP DPD will require linearizing each PA individually as outlined in Section II-B. When considering the large number of antennas considered in 5G and beyond, the complexity can quickly become prohibitive. The main advantage of our proposed approach is that, while the MP-per-PA approach scales with the number of antennas, the OFDM-based DPD uses a single MP. In Fig. 6 we plot the complexity of the MP-per-antenna DPD and the OFDM DPD versus the number of transmit antennas N . Here, we fix the memory to $M = 4$, and we consider the case where there are 1200 data subcarriers. The signal is upsampled to 4096 samples per OFDM symbol for both DPDs to be over 3x upsampling. The MP-per-antenna DPD, shown in blue, increases linearly as each new antenna requires a new MP. The OFDM DPD, shown in green, requires only 1 MP for all cases. While there is only one MP, complexity increases with the number of antennas due to multiplications associated with the additional precoding of guard-band subcarriers. At $N = 1$, the OFDM-based DPD has higher complexity since there is an added IFFT and FFT as well as the extra multiplications for precoding the zero subcarriers. At $N = 8$, the required number of multiplications is clearly below the case of applying a DPD per antenna. In the case of $P = 7$ and $N = 64$, the OFDM-based DPD requires only 12% of the number of multiplications compared to the conventional per-PA MP DPD.

V. CONCLUSIONS

In this work, we introduced a novel DPD scheme targeted at massive MIMO systems using OFDM modulation. By predistorting before the precoding, we effectively linearize the beam to the user. Since most OOB energy follows the main beam, linearizing the beam provides sufficient reduction in ACLR for the whole system. Compared to performing DPD on all antennas, OFDM DPD provides similar performance at a fraction of the complexity, which can translate to more energy-efficient massive MIMO implementations.

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