Complexity Analysis of Wideband Power Amplifiers Linearization in Multi-band Signal Transmission for Massive MIMO systems

Siqi Wang, Wenhui Cao, Thomas Eriksson
Chalmers University of Technology, Gothenburg, Sweden

Abstract — Massive multi-input and multi-output (MIMO) systems request wideband power amplifiers (PA) for multi-band signal transmission. In this paper, we present different digital predistortion (DPD) techniques to linearize wideband PA with multi-band stimulus. We firstly propose a general form for pruned multi-band DPD models with low complexity. A study on the implementation complexities of different linearization methods is then analyzed. This paper provides a critical view on the metric of implementation complexity in function of the DPD model complexity and the sampling frequency of the signal processing. We finally propose a sampling frequency threshold to determine the best DPD solution according to the measurement results.

Keywords — Digital predistortion, massive MIMO system, multi-band transmission, nonlinear distortion, wideband power amplifiers

I. INTRODUCTION

Modern wireless telecommunication systems demand wideband power amplifiers (PA) for the compatibility of different standards which occupy different frequency bands. Massive multi-input and multi-output (MIMO) systems need to be able to meet multiple users’ requirements simultaneously [1]. In order to linearize the PAs for higher efficiency, Volterra-based mathematical models have been proposed for digital predistortion (DPD) techniques, such as generalized memory polynomial [2] models.

The implementation complexity of a DPD depends on its model complexity [3] and the sampling frequency of its signal processing [4]. Since wideband signals need very high sampling frequency which is difficult to implement [5], some recent studies are focusing on processing the DPD with a reduced sampling frequency [6]–[9].

An alternative to wideband processing is to process the signal in different bands separately with lower sampling frequencies [10]. However in-band and cross-band distortions caused by the different signals interaction make the PA linearization more difficult. The multiband structure makes multi-input DPD necessary, which increases the model complexity of the DPD [11]–[14] compared with the conventional single band DPD model, which may reduce the benefit of using the multi-band DPD.

In this paper we will study a wideband DPD solution, using high sampling rate, and a multiband DPD solution, with multiple narrowband DPDs with multiple inputs. The two techniques has different advantages and disadvantages:

1) A wideband DPD must be run at a high sampling rate.

Further, the memory effects over the wideband signal can be expected to be more severe than for narrowband DPD.

2) By using multiple narrowband DPDs we have the immediate advantage of a lower sampling rate. Further, the memory effects should be less severe. However, for the multiband case we must use multi-input DPD techniques, which may lead to a high complexity.

In the following, we first propose a pruned form for 3-band DPD and then compare the wideband and multiband cases with respect to the implementation complexity and performance. The implementation complexities of these two DPDs are estimated through a proposed metric and their comparison is discussed. We therefore propose a threshold of sampling frequency to give a clearer baseline of choosing the DPD strategy. The model structures of the DPD are determined according to the trade-off between its modeling accuracy and model complexity [15] and are tested a testbench with a tri-band signal of 20 MHz long term evolution (LTE).

This paper is organized as follows. Section II presents the structure of DPDs in massive MIMO systems. A metric to estimate the DPD implementation complexity is proposed in Section III. In Section IV and V, the simulation and experimental results are presented and discussed respectively. Finally, we make a discussion on the threshold of sampling frequency for wideband DPD in Section VI and the conclusion is given in Section VII.

II. STRUCTURE OF DPD FOR MASSIVE MIMO

The massive MIMO system is depicted in Fig. 1. The signals $u_1(n)$, $u_2(n)$ and $u_3(n)$ are transmitted simultaneously through the antenna array. The signal $u_1(n)$ and $u_3(n)$ are firstly modulated to different frequencies to be combined...
For a given maximum nonlinearity order $m$ and nonlinearity orders $k$, a model can be easily selected by pruning the arrays of different DPDs. We propose a new form of the model of the 3-D memory polynomial (MP) model [16] for the multiband DPD. We have developed to decrease the sampling frequency. This increases the implementation difficulties as well as the power consumption. Therefore different multi-band DPD models have been developed to decrease the sampling frequency.

The model of a multi-band DPD often has hundreds of coefficients in literatures [10]–[14]. In this paper, we propose to prune a 3-D memory polynomial (MP) model [16] for the DPD. We propose a new form of the model of the $i$-th band to facilitate the pruning as

$$x_i(n) = \sum_{k=0}^{K-1} \sum_{j=0}^{K-1} \sum_{m=0}^{K-1} \sum_{l=0}^{L-1} \gamma^{(i)}_{kjm} u_k(n-l) \times |u_1(n-l)|^k |u_2(n-l)|^j |u_3(n-l)|^m,$$

where $k, j, m$ are the indices for nonlinearity of band 1, 2, 3 respectively, $l$ is the indices for memory, and $\gamma^{(i)}_{kjm}$ is the complex coefficient, $\phi(u_i(n))$ represents the phase of signal $u_i(n)$. A hill-climbing algorithm has been proposed in [17] to determine sparse model structures. The basis functions in the model can be easily selected by pruning the arrays of $k, j, m$ and $l$. The array of $k$ is taken as an example in Table 1. For a given maximum nonlinearity order $K$, the sparse array of nonlinearity orders $k$ is a set whose elements are selected from the full array $k = [0 : K]$. The number of selected elements is denoted by the parameter $S$ which represents the sparsity of the array $k$. If we list all possible combinations of the array in increasing order as shown in Table 1, each combination can be located by the parameters $(S, I)$. Thus we need to determine 8 parameters for the 3-D MP model: $(S_k, I_k; S_j, I_j; S_m, I_m; S_l, I_l)$.

The structure of massive MIMO with multi-band DPD is given in Fig. 2. There are the same number of DPD deployed in front of the PA as the number of the signals. Since the cross-band distortion is considered, the DPD has the same number of inputs as the number of signals. The output signals of the DPDs are mixed by different carrier frequencies to RF and are fed to the PA for transmission.

### III. Implementation Complexity

The DPD is usually implemented on a digital signal processor (DSP), such as field programmable gate array (FPGA). The complexity of its implementation is influenced by many factors within whom the number of floating point operations (FLOPs) and sampling frequency are two main factors.

For a Volterra-based DPD model, e.g. the GMP, its number of FLOPs $F_{\text{gmp}}$ depends strongly on its number of coefficients $N_{\text{coeff}}$ [3]:

$$F_{\text{gmp}} = 8N_{\text{coeff}} + 2. \quad (2)$$

The power consumption of an FPGA is proportional to its sampling frequency according to [4]:

$$P = V_{dc}^2 \cdot f \cdot C_l \cdot \alpha \quad (3)$$

where $\alpha$ is the switching activity of bits, $C_l$ the load capacitance, $V_{dc}$ the supply voltage and $f$ is the system frequency directly related to the sampling frequency $f_s$.

Viewing that in (2) the constant 2 can be neglected in front of $8N_{\text{coeff}}$, we carefully propose a metric to estimate the implementation complexity of the DPD:

$$M = Q \cdot f_s \cdot N_{\text{coeff}}. \quad (4)$$

where $Q$ is a constant quality factor which mainly depends on the quality of the DSP hardware.

In case of a multi-band DPD, its implementation complexity is the sum of the complexities of each band:

$$M_{\text{multiband}} = \sum_{i=1}^{K} f^i_s \cdot N^i_{\text{coeff}}. \quad (5)$$

<table>
<thead>
<tr>
<th>$S$</th>
<th>$I_1$</th>
<th>$I_2$</th>
<th>$I_3$</th>
<th>$I_4$</th>
<th>$I_5$</th>
<th>$I_6$</th>
<th>$I_7$</th>
<th>$I_8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td></td>
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<tr>
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<tr>
<td>3</td>
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<td>3</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S = K$</td>
<td>k=[0 1 2 3 4]</td>
<td></td>
<td></td>
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</tbody>
</table>
Fig. 3. Spectra of Wiener model PA output linearized by wideband DPD and 3-D MP DPD.

Table 2. Simulation results comparison between wideband (WB) DPD and 3-D DPD

<table>
<thead>
<tr>
<th>DPD Type</th>
<th>Band 1 (dBc)</th>
<th>Band 2 (dBc)</th>
<th>Band 3 (dBc)</th>
<th>Nb of Coeff</th>
<th>Fs (MHz)</th>
<th>M (×Q)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WB</td>
<td>-70/-70</td>
<td>-72/-72</td>
<td>-70/-70</td>
<td>25</td>
<td>600</td>
<td>15000</td>
</tr>
<tr>
<td>3-D</td>
<td>-68/-64</td>
<td>-68/-66</td>
<td>-65/-69</td>
<td>20/135/60</td>
<td>120</td>
<td>25800</td>
</tr>
</tbody>
</table>

where \( K \) is the number of bands.

Thus in order to make \( M_{\text{wideband}} \) less than \( M_{\text{multiband}} \), we need to reduce the sampling frequency of wideband DPD down to

\[
 f_{s_{\text{wb}}} = \sum_{i=1}^{K} f_{i}^2 \cdot N_{i}^2 \cdot N_{\text{coeff}}^2, \tag{6}
\]

where \( f_{s} \) represents wideband. Since the sampling frequency is proportional to the bandwidth of the predistorted signal, (6) also describes the relation between the narrowband signals in each band, and the wideband combination signal.

In the following of this paper, we make the study of different MIMO system linearization methods while being wary of their implementation complexities.

IV. SIMULATION RESULTS

We create a baseband 3-band signal with 60 MHz frequency separation as the stimulus. The signal in each band is a 20 MHz LTE signal. The signal is fed to a Wiener model PA [18].

The spectra of linearized PA output in simulation results are illustrated in Fig. 3. The detailed values of the adjacent channel power ratio (ACPR) of each band and the estimated DPD complexities are listed in Table 2. The linearization performance of the wideband DPD is slightly better than that of the 3-D DPD but very close. The wideband DPD is implemented at a high sampling frequency \( f_{sh} = 600 \text{MHz} \). Its structure is determined by the algorithm in [15], which has 25 coefficients. The 3-D MP DPDs are implemented at a low sampling frequency \( f_{sl} = 120 \text{MHz} \). Their structures are determined separately, and their number of coefficients are 20, 135 and 60 for the 1st, 2nd and 3rd band respectively.

The implementation complexity of the wideband DPD is then 15000\( Q \) while that of the 3-D DPD is 25800\( Q \). In this case, the wideband DPD outperforms the 3-D DPD in terms of the implementation complexity.

V. EXPERIMENTAL RESULTS

We use test bench of WebLab [19] for measurements. The PA in the test bench is a CGH400006 transistor mounted in the manufacturer demo-board fabricated by CREE. Its nominal gain is 13 dB at 2 GHz and the output power at 1dB gain compression is 40.2 dBm. The AM/AM & AM/PM (Amplitude Modulation/Amplitude Modulation & Amplitude Modulation/Phase Modulation) curves of the PA are illustrated in Fig. 4.

We generate the 3-band LTE signal with 200 MHz sampling frequency and up-convert it to 2 GHz and feed it to the PA. The bandwidth of each band is 5 MHz. The frequency separation is 20 MHz.

The PA output spectra of experimental results are depicted in Fig. 5. The corresponding ACPR values and the estimated implementation complexities are given in Table 3.
Three wideband DPDs are tested with a high sampling frequency \( f_{sh} = 200 \text{MHz} \). Their number of coefficients are 18, 23 and 54 respectively. The 3-D MP DPDs are implemented at a low sampling frequency \( f_{sl} = 25 \text{MHz} \). Their structures are determined separately, and their number of coefficients are 54, 54 and 54 for the 1st, 2nd and 3rd band respectively. Due to the PA characteristics, the powers of two bands aside are lower than that of the middle band. The 3-D DPD considers only the distortion of each sub-band which fails to compensate for the power as shown in Fig.5.

The wideband DPDs with 18 and 23 coefficients have very similar performance in linearization and implementation complexity compared with the 3-D DPD. The one with 54 coefficients achieves better linearization performance but results in a double implementation complexity.

VI. DISCUSSION

According to the simulation and experimental results in Table 2 and 3, we can see that the sampling frequency of the wideband DPD can be only 3 times of the bandwidth of the wideband signal since we focus on reducing its in-band distortion.

The comparison of implementation complexity between wideband DPD and multi-band DPD can be influenced by the DPD model complexity and the frequency locations of the sub-carriers of each signal band. A wideband DPD model is usually less complex than a multi-band DPD. Using our proposed pruned multi-band DPD can largely reduce their difference on complexity so that we can keep \( N^i_{\text{coeff}} \) less than 5 times of \( N^i_{\text{wb}} \).

For \( K \)-band signal with bandwidth \( B \) for each sub-band, if the sampling frequency of each multi-band DPD is \( f_{sl} = 5B \), the wideband DPD can have advantage on implementation complexity when its sampling frequency is as low as

\[
 f_{sh} \text{threshold} = 5 \cdot a \cdot KB,
\]

where \( a \) represents the ratio between average number of coefficients of the multi-band DPD and that of the wideband DPD, and thanks to our proposed pruned multi-band DPD, here we have \( a \leq 3 \).

VII. CONCLUSION

In this paper, we make a study of implementation complexity of different methods for massive MIMO system linearization. The main two impact factors are the DPD model complexity and its sampling frequency. We first introduce a pruned multi-DPD to make its complexity comparable with that of wideband DPD. Finally with analysis on measurement results, we give a threshold value for the sampling frequency of the wideband DPD. In future work we will study more (4 or 5) bands signal transmission with different bandwidths, and study the impact of different frequency separations and different band occupations of the signals.

REFERENCES