Experimental Demonstration of Digital Pre-Distortion for Millimeter Wave Power Amplifiers with GHz Bandwidth

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***Abstract*—This paper presents an experimental demonstration of digital pre-distortion (DPD) on E-band power amplifiers (PA) with GHz channel bandwidth. An empirical optimization approach is used to quickly build up the look-up table of DPD coefficients, instead of the conventional behavior modeling technique. The digital pre-distorter is implemented by a simple 5th order memoryless polynomial function. The DAC sampling rate is 4.8 GSps. Based on our approach and system setup, the result shows DPD can push 2 to 3 dB more output power at the same in-band distortion level, which is equivalent to 58% to 100% efficiency improvement.**

***Index Terms*—digital pre-distortion, E-band, in-band distortion, mm-wave, power amplifiers, power added efficiency.**

I. Introduction

The millimeter wave (MMW) wireless system is becoming a viable choice as fiber replacement for use in high capacity, long range, and energy efficient backhaul link, owing to the recent advancement in technology. With light licensing restrictions and high spectrum availability, E-band (71-76 and 81-86 GHz) is one of the most favorable choices for providing backhaul to wireless access point.

However, E-band power amplifiers (PA) are power and efficiency-limited (below 30% at saturation) [1]. Furthermore, the high peak-to-average power ratio (PAPR) of the complex modulation signals makes PAs backed off a few dB to ensure the linear operation and leads to a precipitous drop of efficiency.

Current PA efficiency improvement techniques such as envelop tracking, out-phasing, and Doherty amplifiers [2-4] are not suitable for broad bandwidth and high date rate MMW applications, due to the limitation of current fabrication process and other factors, e.g. frequency regrowth and signal alignment issues. Digital Pre-Distortion (DPD) technique introduces predistortion in digital baseband to cancel the amplitude compression and phase distortion at analog PA front-end, thus increase PA linearity range and improve power and efficiency. Compared to other types of linearization techniques, DPD is a straightforward, high-performance, and cost-effective approach to increase PA efficiency [5-6].

DPD at MMW frequencies with GHz channel bandwidth has many practical difficulties in the implementations. Signal impairments in MMW, such as in-band flatness, I/Q imbalance, and LO leakage, are usually worse than cellular frequency bands due to the degradation of device performance. These impairments degrade the accuracy of the modeling of the PA behavior and the extraction of model parameters. The large channel bandwidth requires high sampling rate, high resolution data acquisition and high-speed DSP units [5,6]. The data processing bandwidth for DPD signals is required to be 3 to 5 times the baseband signal bandwidth as a rule of thumb, which is unavailable in most baseband chips with 2 GHz signal bandwidth.

To our knowledge, this paper is the first attempt to demonstrate the DPD's improving the PA efficiency and in-band distortion at E-band with GHz signal bandwidth. A simple memoryless odd 5th-order polynomial model is adopted in this paper. Memory effect and complex models are not considered because the limitation of the practical implementation for the high data rate (10 Gbps maximally). We adopt different approaches to find the look-up table of the predistorter coefficients. An initial DPD solution is found using PA behavioral modeling technique, however, shows inconsistent result. A constrained optimization problem is solved to find the optimal DPD coefficients by applying an exhaustive search method, and then speed up by a Powell's conjugate direction optimization method.

II. Experimental Setup

Figure 1 gives the block diagram of the experimental setup of our DPD system. It consists of a baseband modem with DSP, DAC and ADC units, a direct conversion up-converter, a driving PA, a commercial GaAs PA, a down-converter, programmable tunable attenuators to control the input power level of the PA and the power at the receiver input, and a hot/cold plate for controlling the ambient temperature. The baseband modem can generate modulated signals with a symbol rate up to 1.6 Giga-Symbols-per-second (GSps) and support different modulation schemes from BPSK to 128 QAM signals. The DAC sampling rate is 4.8 GSps. A direct conversion up-converter is used to up convert the I/Q baseband signal to E-band at 72 GHz. A driving amplifier is connected before the PA under test to make sure the input signal power is linear and large enough. The PA under test is a commercial available GaAs PA with P_{1dB} and P_{sat} about 25.5 and 29 dBm respectively. In the test bench, all the devices are linear except from the PA under test.

III. DPD Model and Extraction of Coefficients

The memoryless odd 5th degree polynomial of the predistorter can be expressed as

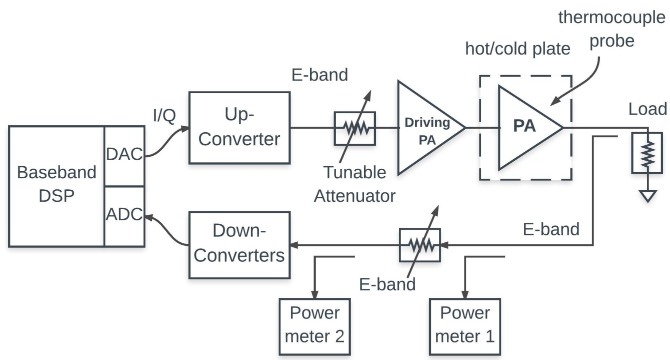

Fig. 1. A diagram of the bench setup for E-band DPD system.

$$y = a_1 x + a_3 x|x^2| + a_5 x|x^4|, \quad (1)$$

where a_1, a_3, and a_5 are complex numbers and thus there are a total of six degrees of freedom, x represents the original data signal and y is the distorted signal after digital processing. The coefficients $\bar{a} = [a_1, a_3, a_5]$ are limited within a certain domain S.

We initially tried the conventional behavior modeling technique by acquiring time-series data of the PA's behavior in the linear and nonlinear operating regime, and the pre-distorter coefficients are extracted by least-squares algorithms. The improvement by DPD in terms of power efficiency is about 0.5 to dB.

One practical problem we found is the extracted coefficients vary a lot on the training data and experimental setups. The performance of the extracted DPD coefficients is also not consistent. The inconsistency issue mostly comes from the signal impairments in the RF channel, the limitation of the memoryless modeling, and may also from the limited sampling rate by digital oscilloscope used in the data acquisition procedure. Common RF impairments at E-band include in-band flatness, the phase noise, LO leakage, etc.

The adjacent channel power ratio (ACPR) is not a big concern in the E-band system, mainly because of the less regulated spectrum at E-band compared to the cellular band and also the easiness of implementing high-out-of-band rejection filters. Therefore, we only consider the improvement of in-band distortion by DPD. The problem can be simplified as an optimization function, i.e. to find the optimal set of coefficients for the highest output power with the EVM below certain threshold (EVM_0)

$$\bar{a} = \arg\max_{\bar{a}\in S}(P_{out}), \text{subject to } EVM \leq EVM_0, \quad (2)$$

or equivalently, to minimize the EVM at certain output power level

$$\bar{a} = \arg\min_{\bar{a}\in S}(EVM), \text{at } P_{\text{out}} = P_0 \quad (2)$$

In any case, we fix $\text{Re}(a_1) = 1$ and search the coefficients nearby the initial values generated from the behavior modeling technique [6]. We adopt an empirical approach to find the optimal solution. An exhaustive search is firstly used to get an intuition what is the behavior of this optimization problem. We measured the EVM of the received signals and PA's output power (P_{out}) for all combinations of the coefficients as plotted in Fig. 2. Each dot represents the test result of a single set of DPD coefficients. Since the overall gain in the system is fixed and the power of the baseband signal is not normalized, the output power of PA changes as the DPD coefficients are different. We clearly see an edge of the mapping exists in Fig. 2, which is labeled with the black dashed curve. The optimal sets of coefficients should lie on the edge which have the minimum EVM at certain power level. The black dashed curve can also represent the look-up-table of the optimal DPD coefficients for PA operating at different output power level.

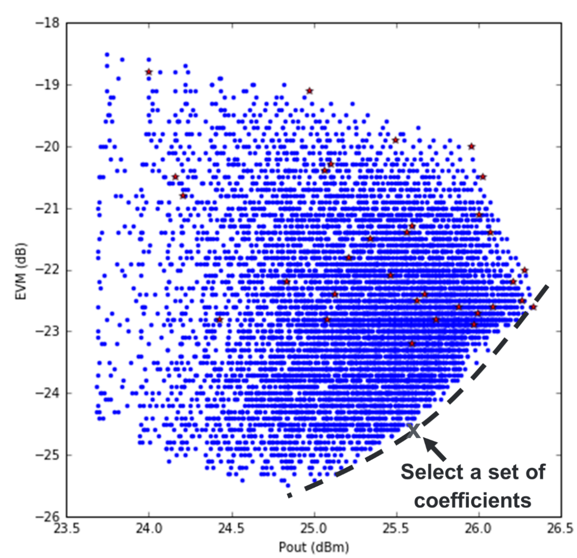

Fig. 2. The output power and EVM mapping for all sets of DPD coefficients within a certain domain; The red star markers label the performance of the parameters at the boundary of the searching domain; The signal under test is 64QAM, 1.6 GSps and the roll-off factor of the square raised-cosine filter is 0.3.

However, the exhaustive searching is very time-consuming. It takes hours to generate the mapping as given in Fig. 2. Instead, we can apply various optimization methods to reduce the time in Eq. (2). In this case, we fixed the output power of the PA as P_0 by tuning the input attenuation and minimize the receiver EVM. The Powell's conjugate direction optimization method is chosen in this work. Total 5 parameters are optimized in the searching domain, of which the optimization sequence follows $\text{Re}(a_3)$, $\text{Re}(a_5)$, $\text{Im}(a_1)$, $\text{Im}(a_3)$, and $\text{Im}(a_5)$. The initial values are set as zero for all the parameters. Fig. 3 shows an intermediate result of the change of EVM during the Powell's optimization. The spikes come from the initial searching of each new parameter adding into the searching domain. We can see that the EVM actually converges very fast, which is down to near -25 dB in the first 20 iterations. This is due to parameter $\text{Re}(a_3)$ and $\text{Re}(a_5)$ are most influential in DPD performance.

Similar results have been achieved with other commercially available E-band PAs. In this test, the optimal sets of coefficients can be found within 10s of seconds.

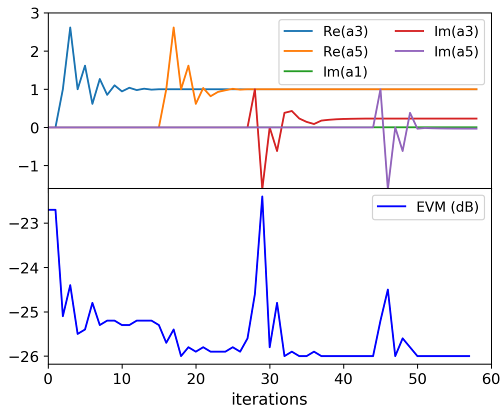

Fig. 3. EVM as a function of number of iterations in the optimization.

IV. Results and Verification

To verify the DPD performance, one set of the optimal coefficients was selected. The EVM threshold is setup based on specific BER requirement and modulation scheme. Fig. 4 shows the DPD performance for 64QAM signal at 25.5 dBm output power. The measured constellation of the received signals with and without DPD are plotted in Fig. 3. Without DPD, the constellation is clearly seen as compressed and the EVM is -20.9 dB, while it is improved to -23.4 dB with DPD.

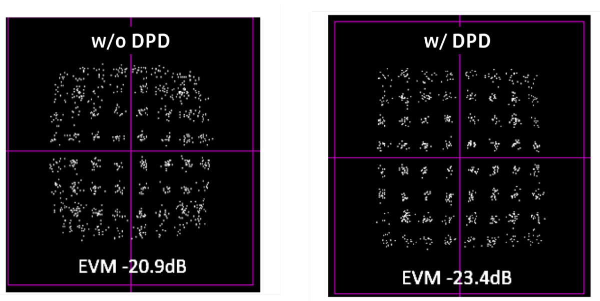

Fig. 3. The constellation diagram of 64 QAM signal at different power levels before and after DPD.

Fig. 4 shows the performance of DPD as a function of output power. The curve with DPD is convex with an optimal operation point at 24 dBm output power. The output power without DPD at the same EVM level is about 21 dBm. For class-A PA (most of the E-band III/V PAs are class-A by nature due to *Ft* limitation), this is about 3dB improvement in power-added efficiency for the same EVM.

V. Summary

Same approach and test setup has been used to other commercial available class-A E-band III/V PAs. All results show that DPD can increase the output power by 2-3 dB at certain EVM threshold, which is equivalent to 58% to 100% efficiency improvement for a linear PA operation. This is a significant amount of power saving at the RF front-end, and especially useful for power-constrained applications, such as the solar-powered gateway on unmanned aircrafts and satellite communications [7]. It is also found conventional behavior model has many difficulties to find the optimal solution at MMW frequencies due to various RF impairments involved with the signal. The empirical approach with optimization method turns out to offer a reasonable improvement in terms of simplicity, time efficiency, and performance. A simple 5th order memoryless polynomial model is considerably good enough at E-band with 2 GHz signal bandwidth. Higher order of polynomial model with memory effect would likely offer even more improvement, however, the added computational requirements on digital signal processing is not readily available and may offset the benefit of power saving on the RF front-end.

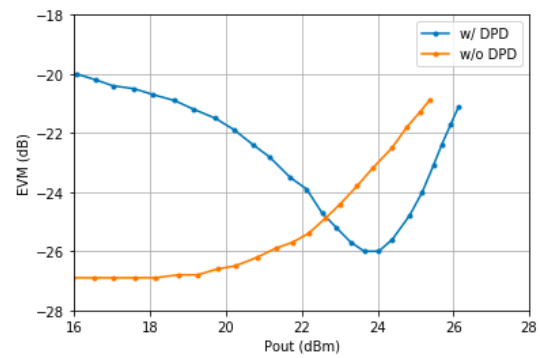

Fig. 4. EVM vs. P_{out} with and without DPD for 64QAM with a baud rate of 1.6 GSps.

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