Compact Undersampled Digital Predistortion for Flexible Single-chain Multi-band RF Transmitter

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***Abstract*— Compact multi-band RF transmitter solution will play a unique role in the forthcoming 4G-beyond and 5G wireless networks. The emerging RF class data convertor, i.e., RFDAC enables a promising single-chain multi-band RF transmitter solution. To combat the imperfections of practical nonlinear power amplifiers in the single-chain multi-band RF solution, we need multi-band RF signal conditioning unit. This paper presents a very compact single-chain multi-band digital predistortion (DPD) solution using only one under-sampling ADC and a low band-pass filter to replace the conventional DPD feedback paths. The experimental results verified the proposed compact multi-band DPD architecture. Preliminarily, the proposed DPD scheme with a single real ADC at 76.8MSPS sampling rate can achieve satisfactory multi-band linearization performance, i.e., -55 dBc adjacent channel power ratio (ACPR) for 1GHz RF bandwidth.**

***Index Terms*—digital predistortion, multi-band transmitter, PA linearization, RFDAC, undersampling ADC**

I. INTRODUCTION

Wireless communication networks are evolving rapidly. Fast expansion of consumer demand for better service experience is calling for 5G higher data-rate wireless access technologies. Given the fact of the frequency regulation in different countries, it is tough for one operator to obtain a continuous wideband frequency spectrum (especially under 6 GHz), leaving frequency fragments situation in general. Besides going for the mmWave choice, two popular transceiver architectures are under consideration globally and have been explored extensively both in the academia and industry, i.e., 1) large-scale antenna system (LSAS) [1] that will significantly increase the spectrum utilization efficiency at the cost of massive digital signal processing horsepower and 2) flexible multi-band carrier aggregation type wireless system that will use multiple frequency bands to create a single visualized and aggregated wider frequency band for the wireless access network.

The emerging RF-class data convertor, e.g., RFDAC, enables an appealing single-chain multi-band transceiver architecture. However, to boost the RF power conversion efficiency delivered by the multi-band power amplifiers (PA) and maintain reasonable signal quality (linearity), we require multi-band RF signal conditioning modules, such as multi-band digital predistortion (DPD) units. As shown in Fig. 1, the DPD-enabled multi-band wireless transmitter requires multiple forward data paths and multiple feedback paths conventionally. In order to provide reasonable linearization performance, the complexity of the conventional DPD estimation algorithm increases dramatically as the number of coefficients for multi-band DPD is generally much larger than that for single-band DPD. For the sake of reducing the complexity of the concurrent multi-band DPD systems, some works were trying to either reduce the sampling rate at each of the feedback paths [2] or decrease the number of the feedback paths [3].

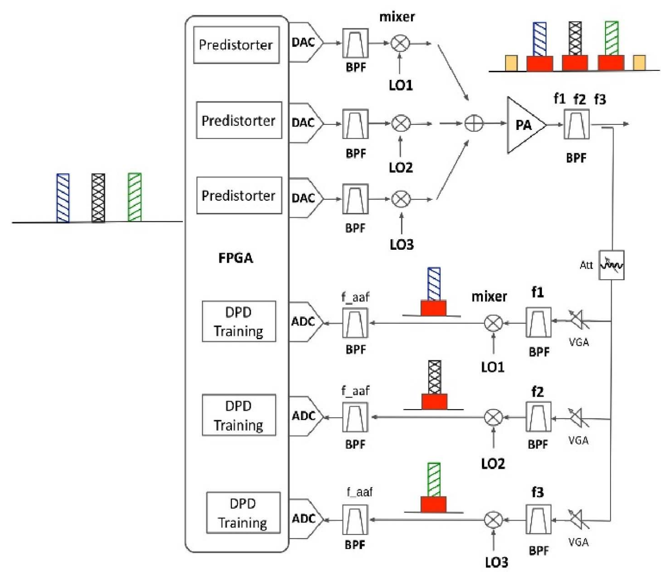

Fig. 1. Simplified diagram of a conventional DPD-enabled concurrent multiband wireless transmitter

Previously in [4], authors illustrated that the statistical properties mismatching between a small number of training samples and actual running samples leads to considerable errors in the standard least squares (LS) based DPD coefficients extraction, and in [5], authors approved that the accuracy of LS-based DPD coefficients extraction is only determined by the accuracy of the captured data samples and their carried information, which is only related to the statistical properties of the signals. Furthermore, as [6] introduced that DPD could be achieved using modulated feedback signal with the cyclo-stationary property at "any" data-rate. On top of the previous work, in this paper, we will present a very compact multi-band DPD solution for the single-chain RFDAC multi-band wireless transmitter using only one under-sampled ADC to replace the multiple feedback paths that required in the conventional concurrent multi-band wireless transmitters.

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II. Proposed Compact Multi-band DPD solution

A. Compact System Hardware Architecture

The simplified diagram of the proposed compact multi-band DPD system is shown in Fig. 2. It includes the following essential modules: 1) a RFDAC, which is employed in the data forward path to replace the conventional up-convertor unit and high-speed intermediate frequency (IF) DACs, 2) a wideband or multi-band PA, for boosting the transmission power, 3) some passive low pass filters, 4) a coupler for obtaining feedback signal at small amount of power and 5) a low-speed IF-ADC for capturing the analog signals at the feedback path. To guarantee the accuracy of the analog input of ADC, the bandwidth of the anti-aliasing filter and the sample-and-hold circuits of the ADC stay the same as the interested forward path system bandwidth. And the sampling rate of ADC fs_{ADC} is fractional times lower than the data forward path RFDAC sampling rate fs_{DAC}.

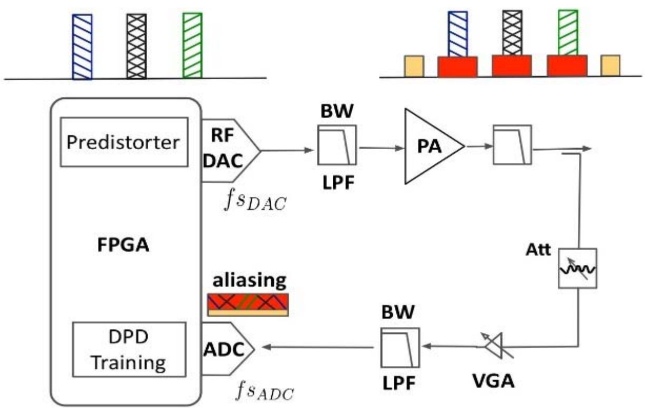

Fig. 2. Simplified diagram of the proposed compact DPD-enabled concurrent multi-band wireless transmitter.

In this proposed compact architecture, we intentionally remove the mixers and corresponding local oscillators (LOs) in both the forward path (by using RFDAC) and the feedback path. Multiple concurrent complex baseband signals are aggregated in the digital domain and "up-converted" to the RF analog domain by RFDAC. Moreover, at the DPD feedback path, a real undersampled ADC is employed to capture the PA output analog signal (with aliasing) and we perform digital down conversion to the complex baseband. In the next section, we will explain the corresponding compact DPD solution from essential algorithm point view.

B. Compact Multi-rate DPD Coefficient Extraction

Conventionally, the DPD coefficients are estimated by time aligned PA input and output signals at the same sampling rate, while in our proposed DPD solution, we will introduce multi-rate time alignment scheme to align PA input and undersampled output signals. Without the loss of generalities, let's assume that the sampling rate of RFDAC is r times the sampling rate of ADC at the feedback path. x_n and y_n represent the high-rate input signal and the feedback signal, respectively. Then the captured feedback signal by the undersampled ADC can be represented as y_{rn}. The original high-rate input signal can be down-sampled to produce a low-rate input signal with the same time resolution as the low-rate feedback signal. By introducing different phase shift (0 to r-1) in the down-sampling processing, we will have r low-rate input signals that can be utilized to perform cross-correlation-based time alignment. The ith ($i \in [0, r\text{-}1]$) correlation result that has the largest peak value indicates that the input downsampled subset x_{in}. will be used for time alignment. Then the time alignment was carried out by cross-correction between x_{in} and y_{rn}. The time-aligned high-rate input and low-rate feedback is illustrated in Fig. 3.

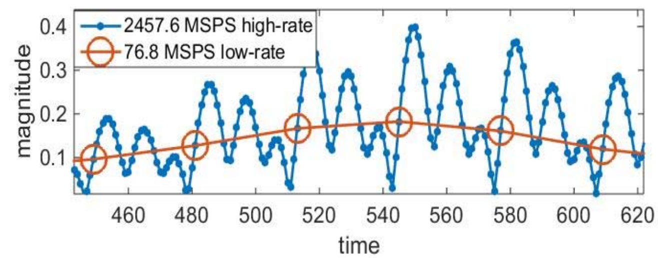

Fig.3. An example of time-aligned multi-rate training samples.

Next, we build DPD coefficients estimation over-determined equation in a multi-rate identification manner. For example, given a nonlinear polynomial type DPD behavioral model f with m terms, the coefficients estimation equation can be achieved by selecting rows from original over-determined equations (at high-rate). The selected rows are corresponding to the available low-rate feedback samples y_{rn} as shown in the Fig. 4, where we assume that 2-tap memory terms are used in the DPD model. Then we perform LS-based global estimation approach to derive DPD coefficients, minimizing the cost functions associated with multi-rate over-determined equation.

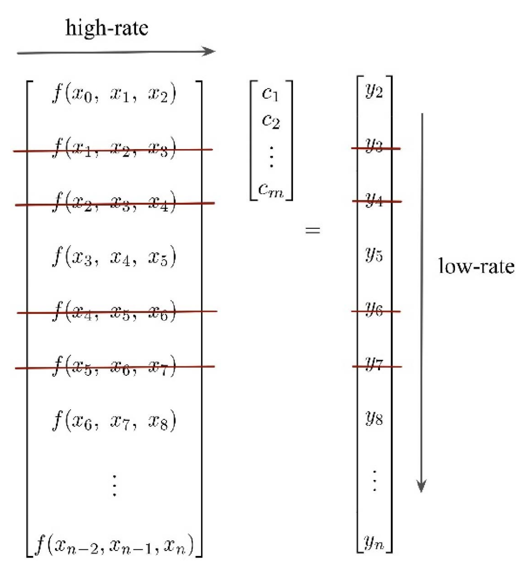

Fig.4. An example of generating multi-rate over-determined equation from referenced high-rate over-determined equation

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As analyzed in [4-5], the performance of the LS-based DPD coefficients extraction approach is largely determined by the probability information of the training samples, and for the modulate signals with cyclo-stationary properties (e.g., 4G LTE signals), the probability information is determined by the number of uniform-sampled data, rather than the sampling-rate. Therefore, to properly carry out DPD coefficient estimation, we need a period of the training samples, the probability of which is close to statistical properties of actual transmitting signal. Fig.5 illustrates an example of probability function of a tri-band LTE signal, and 16K (16384) low-rate training samples can be selected to extract the DPD coefficients robustly due to the statistical similarity (probability matching between training samples and transmitting samples)

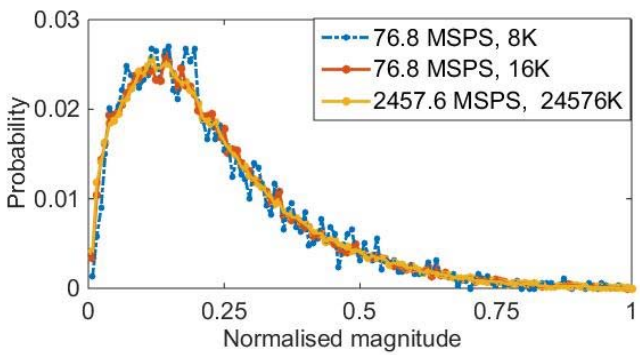

Fig.5. Probability distribution with different numbers of training samples.

C. System Level Comparison with Conventional Architecture

In the traditional DPD-enable multi-band RF transmitter architecture, the overall system noise performance of both forward and feedback paths is typically dominated by the noise introduced by the RF-IF conversion path. And the IF should be selected in a proper range that is suitable for the band-pass filter to reject the modulation image so that the DAC and ADC will maintain good output performance simultaneously. The proposed compact structure eliminates the IF stages to provide greater flexibility and higher performance on frequency planning and system noise. It also minimizes the number of analog RF components in both the forward path and the feedback path, as well as the number of feedback paths required in multi-band applications. Since only one undersampled ADC is required, the power consumption of the DPD feedback path can be dramatically reduced for multi-band radio applications. Moreover, the bandwidth limitation of the feedback path is only determined by the sample-and-hold circuits inherent in the ADC. This new structure has the promising capability of extending the bandwidth of DPD feedback path without increasing the requirement for high-speed ADCs.

III. TEST-BENCH SETUP AND EXPERIMENTAL RESULTS

In order to validate the proposed compact DPD solution (Fig. 2), we created a test-bench as shown in Fig.6. It includes three main sections: 1) RFDAC section including a Xilinx ML605 FPGA evaluation board and AD9129 evaluation board (more details is available in [7]), 2) power amplifier section including three 1GHz low-pass filters, a wideband pre-PA ZX60-3018G and a main PA PHA-1+, and 3) DPD sampling receiver section including an ADC evaluation board ADS5463 and a TSW1400 data capture evaluation board. The AD9129 RFDAC was running at 2.4576 GSPS and transmitting concurrent tri-band LTE signals (with PAPR 11.7 dB, each of component carrier has 20MHz instantaneous baseband bandwidth) at center frequencies of 710.4MHz, 787.2MHz and 940.8MHz, respectively. The attenuated PA output signal was directly sampled by a ADC at the low sampling rate (76.8MSPS) with a 1GHz inherent sample-and-hold circuit.

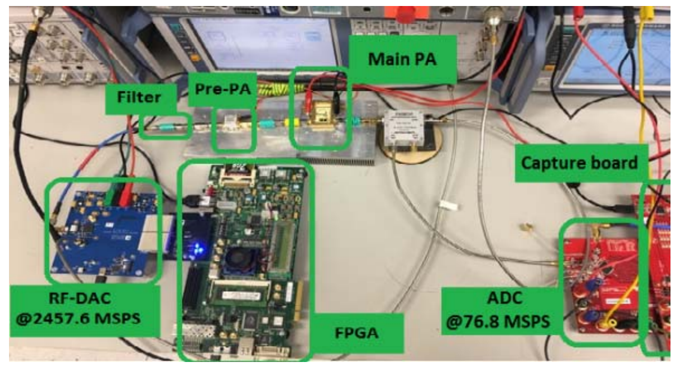

Fig. 6. Experimental measurement setup photograph.

Then real samples were captured and down converted to baseband I/Q signal in the Matlab. After time alignment using multi-rate delay estimation procedure introduced in section II, 8K and 16K training samples were utilized to derive DPD coefficients. We implemented a Memory Polynomial (MP) model with the nonlinear order = 5 and memory length = 8 (40 coefficients in total) and estimated the DPD model coefficients using multi-rate identification method introduced in Section II.

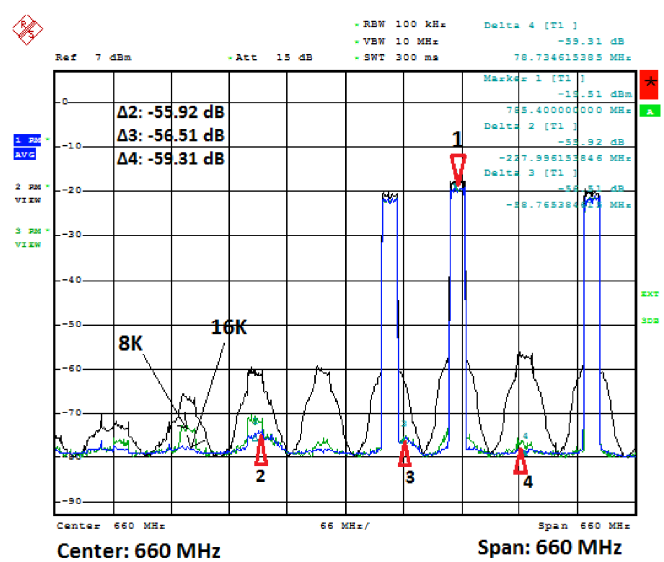

Fig. 7. Measured spectra of PA outputs before and after proposed compact undersampled DPD with 8K and 16K training samples.

As shown in the Fig. 7, the PA output spectra with and without proposed compact multi-band DPD approach were captured by the spectrum analyzer. From the testing result, we can say using only a single real ADC running at low sampling rate can provide sufficient feedback information for DPD coefficients training, and the near band ACPR performance can achieve below -55 dBc, and the cross-band intermodulation terms can be efficiently suppressed to -55 dBc as well. It is worth mentioning that, since the probability information of 8K samples of this tri-band LTE signal fluctuates around the accurate probability function of the long data set, shown in Fig.5, the performance of DPD degraded to some degree comparing to the DPD performance using 16K samples. The AM to AM plot shown in Fig. 8 illustrates the effectiveness of the proposed compact DPD solution, we can see that the nonlinearities and memory effects introduced by the RF analog components are almost removed.

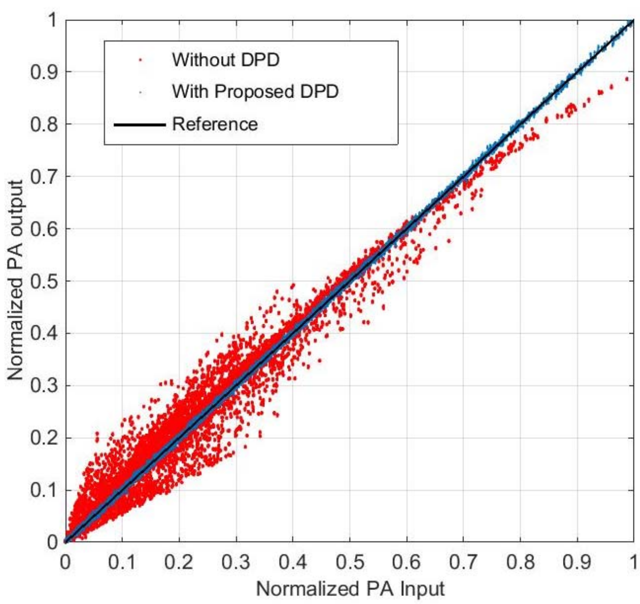

Fig. 8. AM/AM characteristic with and without DPD.

IV. CONCLUSION

This paper presents a very compact DPD-enabled single-chain multi-band RF transmitter solution, in which we intended to minimize the number of analog components. The proposed compact DPD-based multi-band PA linearization solution not only achieved very good linearization performance (below -55 dBc for both near-band ACPR and cross-band intermodulation) for tri-band LTE application but also it can be directly utilized for the linearization of ultra-wideband RF transmitters. Moreover, in this paper, we revealed that the actual achievable DPD feedback bandwidth would be determined by the sample-and-hold circuit on the ADC chip at the feedback path, while the required sampling rate of the ADC is not the critical limitation of the DPD system anymore. The proposed compact multi-band transmitter solution enables a very promising high performance integrated RF solution as an essential physical component in the forthcoming Green 5G wireless network.

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