FRACTIONAL DELAY COMPENSATION IN DIGITAL PREDISTORTION SYSTEM*

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ABSTRACT

Delay mismatch between the input and output signals of power amplifiers (PAs) may lead to an erroneous assumption of memory effects. In adaptive digital predistortion (DPD) system, the delay mismatch affects the accuracy of coefficients estimation and degrades performance of the DPD system. In this paper, we reveal the impact of fractional delay mismatch, and analyze the relationship between delay mismatch and memory effects. The fractional delay compensation helps to reduce or eliminate the delay mismatch. Benefits of fractional delay compensation are provided through numerical analysis and experimental results.

Index Terms— power amplifier, digital predistortion, nonlinear system, fractional delay, memory effects

1. INTRODUCTION

The evolution of wireless communication systems has been driven by the demand for high data rates, requiring wide signal bandwidth and spectral efficient modulations. On the other hand, these systems are sensitive to nonlinear distortions introduced by the radio chain, especially power amplifiers (PAs) [1]. Distortions cause increase in error vector magnitude (EVM) and generate spectral regrowth, which aggravates adjacent channel interference. To improve the linearity of the PA without sacrificing the efficiency, a number of linearization techniques such as feed-forward, feedback and predistortion methods were studied [1]. Among all linearization techniques, Digital predistortion (DPD) provides a good trade-off between cost and performance.

Fig. 1 shows an adaptive DPD system. In this system, the PA is the device under test (DUT). The DPD block is inserted in the signal data path providing the inverse characteristics of the PA. To adaptively estimate model coefficients of the DPD,

a feedback path is introduced at the PA output. After delay compensation, the input and output of the PA are sent to the DPD estimation block for model coefficients estimation. In this architecture, the propagation delay along the transmitter path and the receiver path cannot be ignored. To accurately estimate PA characteristics, it is critical to synchronize the input and output of the PA [2][3].



Fig. 1. Block diagram of adaptive DPD system.

Cross-correlation between the input and the output is a widely used algorithm for data synchronization. In [4], the authors proved that the cross-correlation algorithm could also be extended to the synchronization of mild nonlinear systems. To improve the synchronization accuracy, a direct method is to increase the sampling rate of the system [5]. This approach, however, is limited to available technologies and the costs. For instance, the LTE system can occupy 20MHz bandwidth; a high oversampling rate for LTE is not practical. Fractional delay compensation [2][3] is an alternative approach to improve the accuracy of synchronization.

The structure of this paper is organized as follows: Section 2 presents the impact of the fractional delay mismatch. Section 3 describes the fractional delay compensation. We also discuss the relationship between the fractional delay mismatch and memory effects of the PA. Fractional delay estimation and compensation algorithms with Farrow structure filter are also provided. Section 4 shows simulation results and experimental results on the benefits using the fractional delay compensation. Section 5 concludes this paper.

2. FRACTIONAL DELAY MISMATCH

In the DPD system, if we directly apply cross-correlation algorithm to input/output samples of PA, the estimation accuracy is limited to integer delays and the fractional delay mismatch is inevitable.

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In the next example, we show the impact of fractional delay mismatch. A memoryless PA model with a 5th-order nonlinearity [6] is presented, which can be expressed by

$$z(n) = \sum_{k=0}^{K-1} a_{2k+1} |y(n)|^{2k} y(n),$$
(1)

where y(n) is the baseband equivalent signal of the PA input and z(n) is the baseband equivalent signal of the PA output. The model coefficients are K = 3, $a_1 = 1.051 + 0.090j$, $a_3 = -0.054 - 0.290j$ and $a_5 = -0.965 - 0.702j$.

We also present a PA with memory effects, which can be expressed by a 5th-order memory polynomial model [6]:

$$z(n) = \sum_{k=0}^{K-1} \sum_{l=0}^{L-1} a_{2k+1,l} |y(n-l)|^{2k} y(n-l).$$
(2)

The model coefficients are K = 3, L = 3, $a_{1,0} = 1.051 + 0.090j$, $a_{3,0} = -0.054 - 0.290j$, $a_{5,0} = -0.965 - 0.702j$, $a_{1,1} = -0.068 - 0.002j$, $a_{3,1} = 0.223 + 0.231j$, $a_{5,1} = -0.245 - 0.373j$, $a_{1,2} = 0.028 - 0.005j$, $a_{3,2} = -0.062 - 0.093j$ and $a_{5,2} = 0.122 + 0.150j$.

As shown in Fig. 1, a delay $\tau = 151.125T_s$ is inserted into the receiver path to model the lumped path delay. The delay mismatch contains an integer delay $NT_s = 151T_s$ as well as a fractional delay $\psi T_s = 0.125T_s$.

The input to the PA model is an OFDM-type signal with 1MHz bandwidth. The sampling rate is 6MHz, and the data length is 3×10^4 . In Fig. 2, we plot the amplitude-to-amplitude (AM/AM) response of PAs represented by above models. Referring to Fig. 1, Fig. 2(a) and 2(b) show AM/AM responses of PAs measured with y(n) and z(n). Fig. 2(c) and 2(d) show AM/AM responses measured with y(n) and $z(n - \psi)$.



Fig. 2. AM/AM responses of different PA models.

Fig. 2(a) shows the AM/AM response of the memoryless PA model. The samples converge to a single line, which is an

indication of a memoryless PA. Fig. 2(b) shows the AM/AM response of the memory PA model. The dispersion of input/output samples is typical in the presence of memory effects. Fig. 2(c) shows the AM/AM response of the memoryless PA model with a fractional delay mismatch of $0.125T_s$. The AM/AM response also shows the dispersion behavior, which is similar to that for a PA with memory effects shown in Fig. 2(b). Fig. 2(d) shows the AM/AM response of the memory PA model with a fractional delay mismatch of $0.125T_s$. It is very hard to tell if the dispersion is caused by the delay mismatch or the memory effects.

In literatures, the dispersion of AM/AM response is always considered as a representation of memory effects in PA [7]. The above examples show that the dispersion of AM/AM response may also come from fractional delay mismatch. This phenomenon may lead to a wrong assumption of memory effects. The fractional delay mismatch may also cause the performance degradation in the DPD system [2].

Fractional delay compensation, which follows the Farrow structure, can be applied in DPD system to achieve fine synchronization and improve the performance of predistortion [2][4]. It is worth to note, according to the sampling theorem, the quantity of information is determined by sampling rate. However, integer delay compensation cannot achieve the best accuracy of synchronization.

3. FRACTIONAL DELAY COMPENSATION

As shown in Fig. 1, we model the fractional delay mismatch as a linear-time-invariant (LTI) system. The ideal impulse response of this system is given by [5]:

$$h_{fd}(n) = sinc(n - \psi), 0 < \psi < 1.$$
 (3)

For a causal system, equation (3) can be expanded to a power series with regard to the factor ψ :

$$h_{fd}(n) = \sum_{m=0}^{+\infty} b_m(n)\psi^m, n = 1, 2, \cdots, N.$$
 (4)

Equation (4) can be efficiently implemented by a *Pth*order progression filter with Farrow structure [4][3]. The delayed data sequence $u(n-\psi)$ can be constructed from original sequence u(n) by:

$$u(n-\psi) = \sum_{m=0}^{P-1} \left[\sum_{r=0}^{N-1} b_m(r)u(n-r)\right]\psi^m,$$
 (5)

where N is the length of input/output sequences. From equation (5), we know that $u(n - \psi)$ relates to every preceding points $u(l), l = 1, 2, \dots, n$. Because nearby samples contribute most to the fractional delay, an approximation can be made to (5) with little loss to the model accuracy [2][4]:

$$u(n-\psi) \approx \sum_{m=0}^{P-1} \left[\sum_{r=0}^{R-1} b_m(r)u(n-r)\right]\psi^m,$$
 (6)

where R determines the depth that the fractional delay relates the preceding samples $u(l), l = n - R + 1, n - R + 2, \dots, n$.

Let us revisit the example shown in Fig. 2(c), where fractional delay mismatch occurs. The output $z(n - \psi)$ can be obtained by substituting (1) into (6) :

$$z(n-\psi) = \sum_{m=0}^{P-1} \sum_{r=0}^{R-1} b_m(r) z(n-r) \psi^m$$
$$= \sum_{m=0}^{P-1} \sum_{r=0}^{R-1} \sum_{k=0}^{K-1} \psi^m b_m(r) a_{2k+1} |y(n-r)|^{2k} y(n-r).$$
(7)

Equation (7) shows that with a fractional delay mismatch, the input/output relationship becomes a memory model with memory depth of R. This observation explains the dispersion of the AM/AM response in Fig. 2(c). On the other hand, the delay mismatch is not part of memory effects of the PA, which is introduced by imperfect synchronization. For an accurate DPD model estimation, the delay mismatch should be removed from the loop before the estimation.

Similarly, in the example shown in Fig. 2(d), the delayed output can be obtained by substituting (2) into (6):

$$z(n-\psi) = \sum_{m=0}^{P-1} \sum_{r=0}^{R-1} \sum_{k=0}^{K-1} \sum_{l=0}^{L-1} \psi^m b_m(r) a_{2k+1,l} \\ \times |y(n-l-r)|^{2k} y(n-l-r).$$
(8)

Equation (8) is still a memory model. Comparing to (2), the change exists in the memory depth, which is increased from L to (R + L). The fact also explains the observation that AM/AM responses in Fig. 2(b) and 2(d) are similar.

With the fractional delay filter, we can provide the procedure of the fractional delay estimation and compensation, which is explained on the memory PA example in Section 2. Given input and output sequences of the PA, y(n) and $z'(n) = z(n - N - \psi)$, cross-correlation synchronization is performed. The amplitudes of the cross-correlation are shown in Fig. 3.



Fig. 3. Cross-correlation amplitudes of synchronizations.

In Fig. 3(a), we observed that for a mild nonlinearity, the cross-correlation output is very similar to a "sinc function".

The integer delay is estimated by searching the delay shift where the maximum amplitude of the cross-correlation output occurs. In this example, the peak of the cross-correlation amplitude is $C_{peak} = 1781.03$, and it occurs at the sampling index $i_{peak} = 151$.

To achieve fine synchronization, we can interpolate the existing sample sequence using the Farrow structure. For instance, we can insert M - 1 equally spaced points between every integer delay indexes. M sequences with fractional delays can be obtained:

$$z'_i(n) = z(n - i/M), i = 0, 1, 2, \cdots, M - 1.$$
 (9)

Cross-correlation synchronization is applied to each pair of input y(n) and output $z'_i(n)$. To simplify the maximum cross-correlation amplitude searching process, we can limit the searching range of indices around the original peak, e.g., $i \in [i_{peak} - 3, i_{peak} + 3]$. When the maximum crosscorrelation amplitude in all M synchronization pairs is found, we can map the index into the fractional delay domain as shown in Fig. 3(b).

In the simulation, we set M = 8. The largest crosscorrelation amplitude $C_{max} = 1786.50$ is achieved at fractional delay index $i_{max} = 151 + 1/8$. The estimated fractional delay mismatch is $\Delta \tau = 0.125T_s$, which equals to the actual delay mismatch. The interpolated data sequence $z'_1(n)$ with proper integer delay compensation is the synchronized PA output for DPD estimation.

4. EXPERIMENTAL RESULTS

Fractional delay compensation improves synchronization accuracy in DPD system. The improvement is also reflected in linearization performance.

In this section, we first examine the DPD performance using simulations. The memoryless and memory polynomial PA models and coefficients provided in Section 2 are applied in simulations. A path delay of $151.125T_s$ is inserted in the system. The input to the PA model is an OFDM-type signal with 1MHz bandwidth. The sampling rate is 6MHz, and the data length is 3×10^4 . For the DPD block, we use a 5th-order memoryless polynomial model as the memoryless predistorter; and a 5th-order memory polynomial model with memory depth of 2 as the memory predistorter [6]. Fig. 4(a) and 4(b) show power spectral densities (PSDs) at the PA output for the memoryless PA model and the memory PA model, respectively. In both cases, from top to bottom, the lines indicate PSDs of (1) the PA output without DPD, (2) the PA output with a memoryless DPD and with fractional delay mismatch, (3) the PA output with a memory DPD model and with fractional delay mismatch, (4) the PA output with a memoryless DPD model and with fractional delay compensation, (5) the PA output with a memory DPD model and with fractional delay compensation, (6) the PA input (normalized to the output power).



Fig. 4. Simulation results of different PA models.

In all cases, if we do not compensate for the fractional delay mismatch, PSDs at the PA output have more out-ofband emission. In both figures, line (3) shows that even with a memory DPD model, the DPD does not fully compensate for memory effects brought by the fractional delay mismatch. The fractional delay estimation and compensation is indispensable in DPD system. Fig. 4(a) and 4(b) show that appropriate DPD models, along with the fractional delay compensation, achieve satisfactory performance in the PA linearization.

The DPD performance is also verified on a physical PA. In this measurement, the PA is a basestation PA with part no. FiberHome HXPA945-30-80H05A, which has a gain of 50dB and operates at the center frequency of 945MHz. The signal generater (Agilent E4438A) generates the PA input signal, which is the same input used in previous simulations. Vector signal analyzer (Agilent PXA N9030A) is applied to receive and analyze output signal of the PA. The PSD at the PA output is shown in Fig. 5. From top to bottom, the lines have the same definition as those in Fig. 4.



Fig. 5. Measurement results of physical PA.

We find that experiment results in Fig. 5 are consistent to simulation results in Fig. 4(a). Fraction delay compensation provides about 3dB gain on the out-of-band emission suppression. In addition, after the fraction delay compensation, the memory and memoryless DPD models obtain similar performance (line (4) and line (5)) which agrees with the case shown in Fig. 4(a), indicating a memoryless PA. Without fractional delay compensation, a different conclusion may be drawn from line (2) and (3) in Fig. 5.

5. CONCLUSION

Adaptive DPD is an attractive linearization technique to improve the PA linearity without sacrificing the efficiency. In DPD system, the delay mismatch degrades the accuracy of parameter estimation as well as the system performance. In this paper, we analyze the relationship between delay mismatch and memory effects. A fractional delay estimation and compensation algorithm is provided to reduce or compensate the delay mismatch. The benefits are demonstrated with numerical analysis and experimental results.

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