On The Sensitivity of RF Transmitters' Memory Polynomial Model Identification to Delay Alignment Resolution

Oualid Hammi, *Student Member, IEEE*, Fadhel M. Ghannouchi, *Fellow, IEEE*, and Bill Vassilakis, *Senior Member, IEEE*

***Abstract*—In this letter, the effects of delay alignment between the input and output baseband waveforms on the performance of a radio frequency transmitters' memory polynomial based model are studied. A 100-W average power transmitter is characterized; various delay values are applied to align the input and output data; and, a model is derived for each delay value. The models' performances, evaluated for these delay values both in time and frequency domains, demonstrate that the memory polynomial model is sensitive to delay overestimation but not to delay underestimation. It is established that a delay underestimation by up to one sampling period does not affect the performance of the identified model. This overcomes the need for the signal oversampling required for high-resolution delay alignment. Consequently, the computational complexity of the digital signal processing algorithm employed for delay estimation and alignment is considerably reduced.**

***Index Terms*—Delay, distortion, memory effects, memory polynomial, model, power amplifier (PA), 3G, transmitter.**

I. Introduction

BEHAVIORAL modeling of radio frequency (RF) transmitters (Tx)/power amplifiers (PAs) is an unavoidable and critical task for successful wireless designs. Indeed, the development of an accurate and robust model is essential for performance prediction in the early design stages. This is also crucial for impairment compensation and linearization purposes. Recently, this research area has received increased interest, due to the strict linearity requirements imposed by emerging wireless communication standards. In addition, the trend toward the use of wideband and multi-carrier signals has increased the need for new models that take into account these memory effects.

Several Tx/PA models that consider memory effects have been proposed in the literature [1]–[6]. Two classes define these models, depending on the device characterization methodology that they involve. The first class is suitable for laboratories and experimental environments, since it calls for the use of specific test signals, such as two-tones, multi-tones, etc. [1]–[4]. These characterization techniques often require specific and expensive test equipment, including power meters, vector network analyzers, and spectrum analyzers. The second class [5], [6], in which the characterization of the device under test (DUT) is performed in realistic operating environments using the input and output baseband waveforms technique introduced by Jeckeln *et al.* in [7], is suitable for base station applications and "on-the-fly" characterizations and modeling.

The above-mentioned modeling approaches, especially those based on the input and output waveforms, are sensitive to the delay alignment between the input and output data streams. In fact, if the delay between the two paths is not cancelled, the residual delay causes additional dispersion in the AM/AM and AM/PM characteristics of the DUT and likely leads to inaccurate modeling.

Practically, the delay to be estimated and compensated for is within or below the conventional sampling rate of the digital baseband waveforms. Accordingly, high resolution is required during the delay estimation process. Since, the sampling rate of the input and output waveforms is limited by the available analog-to-digital converters' speed and cost, an accurate digital signal processing algorithm, based on data oversampling, was proposed in [6]. An oversampling ratio, ranging between 20 and 30, was used to estimate the delay accurately, within 0.5 ns resolution. Such an unavoidable delay estimation process is computationally demanding. In addition, the fine delay alignment value that is not an exact multiple of the sampling rate adds more complexity to the delay estimation and compensation process.

In this letter, the sensitivity of the memory polynomial model to fine delay alignment is studied. The accuracy of the model under a wide range of residual delays is assessed. Section II presents the DUT and experimental procedure used for the Tx characterization and modeling. The performance of the derived model is evaluated and discussed in Section III. The conclusions are presented in Section IV.

II. Experimental Procedure for DUT Characterization and Modeling

The experimental setup used in this work is presented in Fig. 1. The digital baseband waveforms were downloaded into an arbitrary waveform generator (AWG) that performs the digital modulation, digital-to-analog conversion and frequency

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O. Hammi and F. M. Ghannouchi are with the iRadio Laboratory, Department of Electrical and Computer Engineering, Schulich School of Engineering, University of Calgary, Calgary, AB T2N 1N4, Canada (e-mail: ohammi@ucalgary.ca; fadhel.ghannouchi@ucalgary.ca).

B. Vassilakis is with Powerwave Technologies, Inc., Santa Ana, CA 92705 USA (e-mail: bvassilakis@pwav.com).

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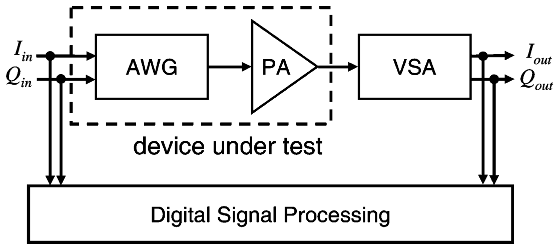

Fig. 1. Experimental setup.

up-conversion. The resulting RF signal was fed to a 100-W average power PA operating around 1960 MHz. The DUT considered in this work included both the arbitrary waveform generator and the power amplification stage. The RF output signal was down-converted, digitized and demodulated using a vector signal analyzer (VSA). The resulting baseband waveform was then used, along with the input baseband waveform, to identify the DUT model. The baseband signal consisted of a four-carrier W-CDMA signal that had a peak-to-average power ratio of 11.22 dB and a total bandwidth of 20 MHz. The sampling rate, used for both the input and output baseband waveforms, was 92.16 MHz.

First, the delay between the input and output baseband waveforms was estimated using the algorithm proposed in [6]. According to this algorithm, the delay between the measured baseband waveforms was 53.5 ns. In order to evaluate the effect of delay misalignment, deliberately inaccurate delay estimation was used to align the input and output baseband waveforms. Accordingly, the output baseband waveform was captured using delay values spanning from 38.5 ns to 68.5 ns, in steps of 0.5 ns. Each set of measurements was then used to identify the DUT memory polynomial model. This model is given by

$$y(n) = \sum_{i=0}^{M}\sum_{j=0}^{N} a_{ij} \cdot x(n-i) \cdot |x(n-i)|^{j} \qquad (1)$$

where $x(n)$ and $y(n)$ are the complex input and output baseband waveforms, respectively. a_{ij} are the model coefficients. N and M are the polynomial function order and the memory depth set to 12 and 2, respectively.

III. Model Sensitivity to Delay Misalignment

The performance of the identified models was evaluated in both the time and frequency domains. First, the mean square error (MSE) between the actual baseband waveform at the DUT output $(y(n))$ and the model's predicted baseband waveform $(\tilde{y}(n))$ was calculated for each value of the estimated delay. The considered MSE is given by

$$MSE = \frac{1}{K}\sum_{n=1}^{K}\left(|y(n) - \tilde{y}(n)|^{2}\right) \qquad (2)$$

where K is the number of the data samples collected.

The variation of the MSE versus the estimated delay is presented in Fig. 2. As shown in this figure, the model performance was not affected by an underestimation of the delay during the characterization step. However, the model performance degraded considerably following a delay overestimation. Moreover, for the sampling rate of 92.16 MHz, the baseband sampling period was 10.85 ns. Accordingly, it appears, from the results reported in Fig. 2, that an underestimation of the delay by up to one sampling period does not affect the performance of the model. Thus, a coarse delay alignment can be used for model identification. This clearly alleviates the need for high resolution delay alignment in the characterization step and circumvents the computational complexity involved for the fine alignment of the input and output waveforms.

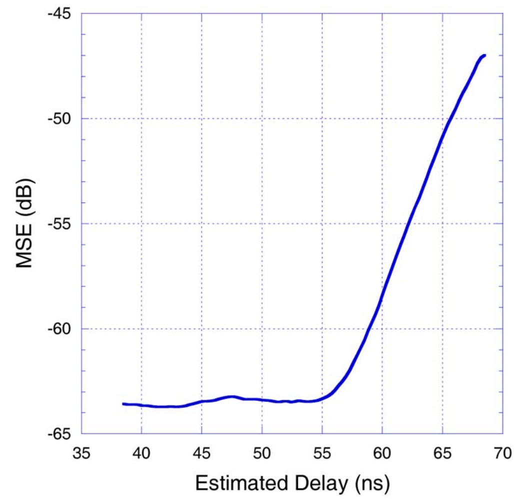

Fig. 2. Mean square error versus delay value.

Consequently, in order to get rid of the fine delay alignment, the following procedure is proposed. First, the memory depth (M) of the DUT is identified (e.g., using auto-mutual information [8]). Then, the model's memory depth is deliberately set to one order higher than the memory depth of the DUT $(M+1)$. The time delay between the time domain input and output waveforms is estimated. Finally, the delay value used to align these data is rounded to the nearest integer multiple of the sampling period that is less than or equal to the computed value of delay.

Fig. 3 presents the estimated spectra at the output of the DUT for three values of the estimated delay: 53.5 ns, 38.5 ns, and 68.5 ns. This corroborates the results reported in Fig. 2, concerning the effects of delay underestimation and overestimation on the accuracy of the DUT model. In fact, for the same value of delay misalignment (15 ns), the spectrum at the output of the DUT model, in the case of delay underestimation, accurately mimicked the spectrum estimated at the output of the DUT using a model derived following accurate delay estimation. However, the spectrum estimated at the output of the DUT model derived under delay overestimation conditions was quite different from the actual spectrum at the output of the ideal DUT model.

The estimated spectrum level at 17.5 MHz offset from the carrier frequency was evaluated as a function of the estimated delay. The results reported in Fig. 4 illustrate a behavior similar to that observed in Fig. 2. Indeed, the estimated spectrum at both frequency offsets was constant for estimated delay values ranging from 38.5 to 54 ns. Conversely, the estimated spectrum

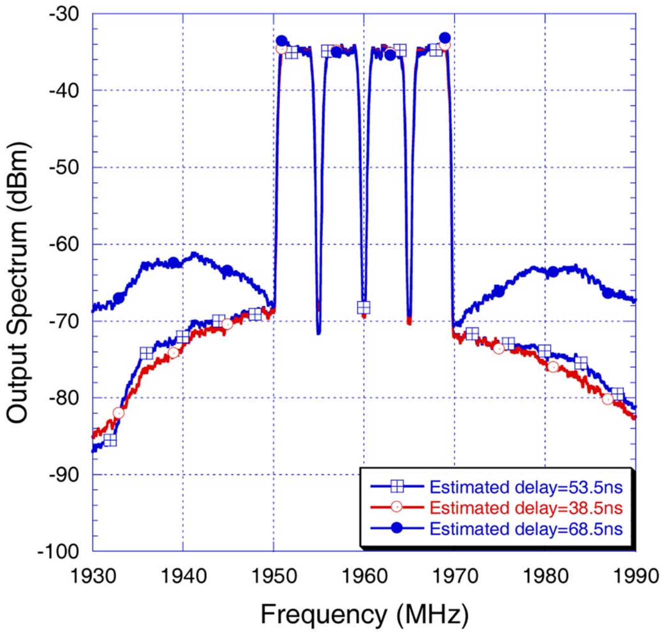

Fig. 3. Model output spectra (delay estimation error = 15 ns).

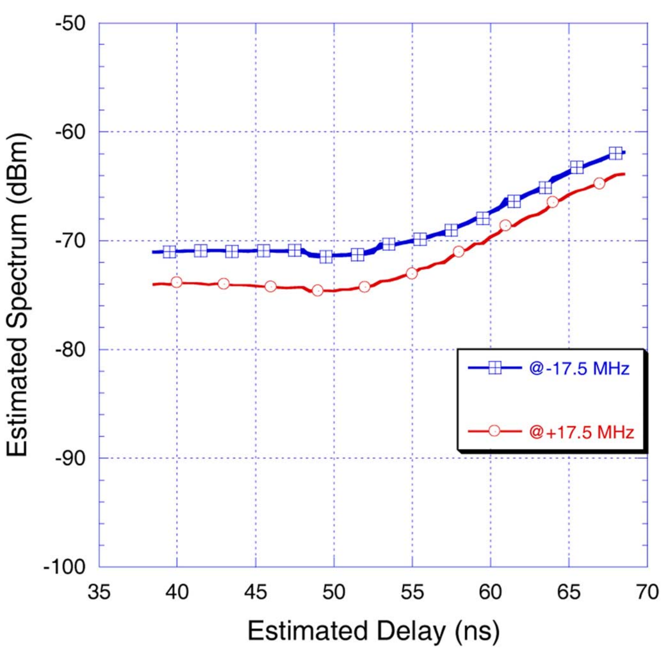

Fig. 4. Estimated spectrum versus delay value.

at both frequency offsets rapidly drifted away for higher values of the estimated delay. This is in agreement with the previously depicted effects of delay underestimation and overestimation.

IV. Conclusion

In this letter, the effects of the delay alignment on the accuracy of the memory polynomial based Tx/PA model are presented. The time and frequency domain modeling errors were derived under a wide range of delay misalignment values. It was shown that the model performance was very sensitive to delay overestimation. Conversely, the memory polynomial model performance was unaffected by delay underestimation. It was also demonstrated that a delay underestimation by up to one sampling period did not degrade the model performance. This alleviates the need for high resolution delay alignment that requires computationally extensive digital signal processing.

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