A Reexamination of Nonlinearity Models in Digital Self-Interference Cancellation for Full-Duplex Communication

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***Abstract*—The conventional nonlinearity model used in full-duplex communication is the polynomial Hammerstein model only using odd-ordered terms. This paper reexamines the validity of discarding the even-ordered terms and suggests modification in the conventional designs.**

***Keywords*—nonlinearity, full-duplex, MLS estimation**

I. Introduction

The self-interference cancellation (SIC) is one of the key technologies for full-duplex communication. The self-interference can be suppressed and cancelled in antenna, RF, and digital domains. In antenna domain, direct signal leakage from transmit to receive antennae is electromagnetically suppressed. The RF and digital SIC are basically similar but the former has limited capabilities and is focused on avoiding saturation in analog circuits and ADC. The residual self-interference after the RF SIC is suppressed in digital SIC down to below the noise floor.

The complexity of digital SIC greatly depends on selection of the reference transmit signal. If the power amplifier (PA) outputs are used as the reference and the other nonlinear distortion is negligible, the nonlinearity estimation can be unnecessary. However, the implementation complexity can significantly increase especially for massive MIMO systems. Thus, there have been a lot of literatures using the digital baseband transmit signal as the reference for digital SIC at the cost of additional computational burden for nonlinearity estimation.

The polynomial Hammerstein (PH) model has been widely employed as the standard nonlinearity model in SIC using only odd-order terms [1-2]. In this paper, we review the derivation of the PH model and examine the validity of discarding even-order terms.

II. Polynomial Nonlinearity Models

The Taylor series is one of the most popular models to approximate an arbitrary smooth function $f(x)$ and the general model of nonlinearity characteristic can be $\sum_n c_n x^n$. When x is a real-valued passband signal, only the odd-order terms have meaningful energy in the frequency band of interest so that the model can be reduced to $\sum_n c_n x^{2n-1}$. But, since both the AM-AM and the AM-PM characteristics of PAs are functions of only the PA input amplitude, the widely-used PH model uses $x|x|^{n-1}$ instead of x^n. In most cases, similarly to the Taylor series model, the PH model also uses only odd-order terms, resulting in $\sum_n c_n x|x|^{2(n-1)}$ [1-2].

In this paper, we focus on this final reduction to the PH model with odd-order terms. For simple examples, we use the five memoryless nonlinearity models provided in MATLAB – cubic, Ghorbani, hyperbolic tangent, modified Rapp, and Saleh models – with their default parameters [3] as the target PAs to estimate. Their AM-AM and AM-PM characteristics are shown in Fig. 1. In our simulation, we used a real-valued passband OFDM signal x generated with 256-FFT, which is scaled such that the maximum amplitude is 0.6. This choice of amplitude was intentionally set to enable consistent comparisons across models, rather than for fairness. From Fig. 1, we can observe that the AM-PM characteristics of the cubic and the hyperbolic tangent models are not differentiable at input amplitude 0.1. Due to the non-smoothness at $|x| = 0.1$,

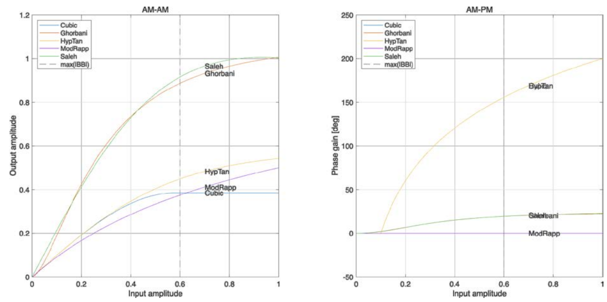

Fig. 1. AM-AM and AM-PM characteristics of the five memoryless nonlinearity models with default parameters provided in MATLAB.

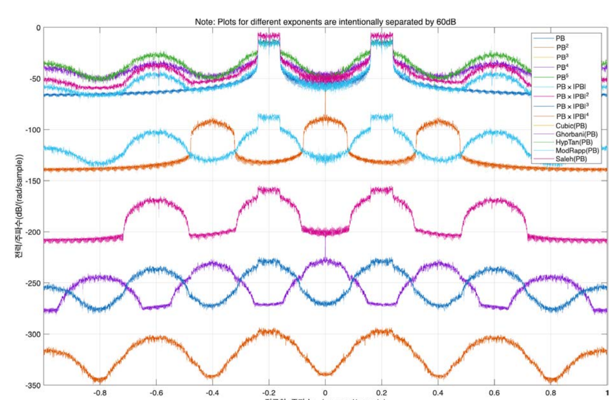

Fig. 2. PSDs of x^n and $x|x|^{n-1}, n = 1,2,\cdots,10$ and PA outputs.

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we can expect that the two models would be harder to estimate accurately than the other three.

The PSDs of x^n and $x|x|^{n-1}, n = 1,2,\cdots,10$ are shown in Fig. 2 together with those of the five PA outputs. Note that the PSDs for different n are intentionally separated by 60 dB for easy discrimination. It is obvious that the PSDs of x^n and $x|x|^{n-1}$ are identical when n is odd.

In the case of x^n, as n increases, the PSD of x is duplicated with broader signal spectra at $(2m-n)f_c, m = 0,1,\cdots,n$, where f_c denotes the carrier frequency of the passband signal x. On the other hand, the PA output PSDs are concentrated around the odd multiples of f_c. For this reason, it has been accepted that the odd-order terms dominate in polynomial nonlinearity models. However, this dominance appears in the Taylor series model, but not in the PH model where the PSDs of $x|x|^{n-1}$ for all n have hills at the odd multiples of f_c.

III. Comparison of Least Mean Square Estimates

For verification of the analyses in the previous clause, let us observe the LMS estimates of the PA characteristics [4]. Figs. 3 and 4 show the magnitudes of the estimated polynomial coefficients and terms and the estimated AM-AM characteristics for the PAs. These results confirm that the odd-order terms dominate in Taylor series model but not in PH model.

We can also observe that, for the Taylor series model in Fig. 3, the estimated characteristics split into two curves for large input amplitudes. This split occurs due to the phase ambiguity of 0 and $\pm\pi$ of the PA input for the even-order terms. For the PH model in Fig. 4, to the contrary, such ambiguity does not appear. The PH model including even-order terms is observed to outperform the Taylor series model and shows excellent accuracy up to very large input amplitude.

Finally, the error tends to increase for large input amplitudes since the large amplitude inputs do not appear often and thus the curve-fitting is insufficient for them. However, its effect is not expected to be significant due to the infrequency. Especially, infrequent large error peaks might be clipped off by AGC and ADC before digital SIC.

IV. Conclusions

Nonlinearity estimation is one of the critical problems in digital SIC for full-duplex communication. In this paper, we reviewed the validity of conventional acceptance of the PH model only with odd-order terms. Our analysis shows that the odd-order terms do not dominate in the PH model. Thus, we recommend incorporating even-order terms to improve nonlinearity estimation using the PH model. Furthermore, it was observed that the PH model outperforms the Taylor series model as it is robust against input phase ambiguity.

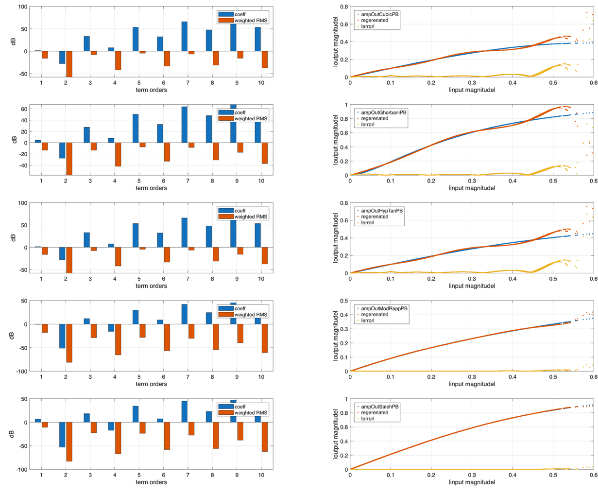

Fig. 3. MLS PA estimates with the Taylor series model, $\sum_{n=1}^{10} c_n x^n$.

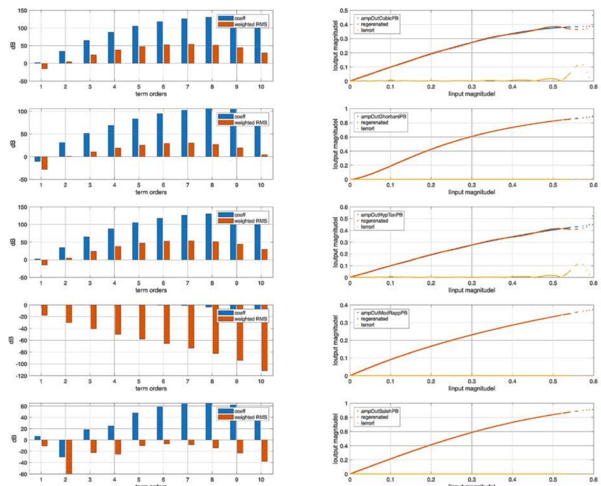

Fig. 4. MLS PA estimates with the PH model, $\sum_{n=1}^{10} c_n x|x|^{n-1}$.

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