Novel B-Spline Behavioral Model

Extracted and Verified

Using Vectorial Harmonic and Multitone Data

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Part I: Introduction

Goals and Motivations

• Goal: Develop a Behavioral model for RF power amplifiers accounting for:
  – Non-linearities (harmonics, intermodulation and spectral regrowth)
  – Memory effects (AM-PM)

• Motivations: Behavioral models
  – Provide intellectual property (IP) protection
  – Facilitate the testing and design of communication systems
  – Can assist with the development of linearization systems: (e.g., design of a
    pre-distorder)
Procedure:

- Acquire the targeted measurements on the PA
- Extract the behavioral model in MATLAB
- Implement behavioral model into ADS as a user-compiled-model
- Compare the performance of the behavioral model and the original PA
Modeling Strategy I

Ideal behavioral model requirements:

- fit the time domain and harmonic response
- predict the intermodulation (IMD3, IMD5 ...) and spectral regrowth
- work for a wide range of signal power levels and bandwidth

In practice there is a trade-off process between the number of performance criteria targeted and the accuracy achieved in each of these criteria.
Modeling Strategy II

Our trade-off solution:

- Target a specified range of power and a finite bandwidth
- A finite number of one-tone and two-tone measurements are used for extraction:
  - Components used for fitting: H1, H2, H3, H4; IMD1, IMD3
- An acceptable time-domain performance is achieved by
  - monitoring/bounding and filtering the higher harmonics: H5, H6, H7, H8
- The model predictability is verified with the prediction of
  - Higher order intermodulation: IMD5 and IMD7
  - Multi-tone response (emulation of CDMA)
Example of DataBase

- Verification measurement
  - One-tone tests: 1899, 1900, 1901, 1902 MHz
  - Two-tone tests: 1900 + 1901 MHz
    Note: 3rd order intermodulations (IMD3): 1899, 1902 MHz

- Verification measurement
  - Two-tones IMD5: 1900, 1901 MHz
    Note: 5th order intermodulations (IMD5): 1898, 1903 MHz
  - 8 tone multisine: 1896, 1897, 1898, 1899, 1900, 1901, 1902, 1903, 1904 MHz

- Typical range of input powers:
  - Minimum power: 45 dB below P1dB (e.g., -30 dBm)
  - Maximum power: 15 dB above P1dB (e.g., 30dBm)
Example of PA Circuit in ADS for Data Collection

Virtual Device: Set-up in ADS for Data Collection
Part II: Modeling Methodology

BSpline Model Topology

4 channels are shown but in practice 8 channels are used.
Main Model Components

• 8 Phase-Shift Channels $\phi$ are used to implement memory effects.

• The nonlinear function $A(\phi)$ are implemented using B-Spline representation of order $r$ and knots sequence $k$:

$$A_\phi(x) = \sum_{i=1}^{m} \alpha_i^\phi B_i(x, k, r)$$

  - B-spline representation uses piecewise polynomials
  - B-spline order $r = 4$ (or 5) is selected to enforce the continuity of the 2nd or (3rd order) derivative of $A_\phi(x)$ at the boundaries.

• A filter is used to remove unwanted higher harmonics to improve the time-domain performance at high power levels.
Model is extracted using frequency-domain data (harmonics and intermodulation tones):

\[
\begin{bmatrix}
    B_{\text{OneTone.Hars,1...N}}^n(Re/Im) \\
    B_{T\text{woTone.IMDs,1...M}}^m(Re/Im)
\end{bmatrix}
\begin{bmatrix}
    \alpha
\end{bmatrix} =
\begin{bmatrix}
    H_{\text{OneTone.Hars,1...N}}^n(Re/Im) \\
    H_{T\text{woTone.IMDs,1...M}}^m(Re/Im)
\end{bmatrix}
\]  

(1)

where:

- \( B^k \) are the B-spline functions, \( H^k \) are the real and imaginary component of each harmonics and tones \( \alpha \) are the B-spline coefficients to extract.
- The labels \( Re/Im \) stand for real and imaginary parts.
- The indices \( n \) and \( m \) specify the frequency components, \( N \) and \( M \) specify the range of simulation power levels for one-tone excitation and two-tone excitation respectively.
Extraction of Model Coefficients

- Fitting is done in frequency-domain
  - 8 harmonics are included for fitting
  - An output filter is used to only pass the first 4 harmonics
  - Higher harmonics are included in fitting to bound their values
- Prior-shaping: balance fitting of harmonics as a function of power level
- Optimization:
  - B-spline knots placement
  - Post-shaping (same as prior-shaping but using error feedback mechanism)
Prior Shaping: Weighing as a Function of Power Levels

The original system to solve (for one component):

\[
\mathbf{B} \alpha = \begin{bmatrix} B_{11} & \cdots & B_{1N} \\ \vdots & \ddots & \vdots \\ B_{M1} & \cdots & B_{MN} \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \vdots \\ \alpha_N \end{bmatrix} = \begin{bmatrix} A_1 \\ \vdots \\ A_M \end{bmatrix} = \mathbf{A}
\]

becomes

\[
\begin{bmatrix} w_1 \times B_{11} & \cdots & w_1 \times B_{1N} \\ \vdots & \ddots & \vdots \\ w_M \times B_{M1} & \cdots & w_M \times B_{MN} \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \vdots \\ \alpha_N \end{bmatrix} = \begin{bmatrix} w_1 \times A_1 \\ \vdots \\ w_M \times A_M \end{bmatrix} \quad \text{with} \quad \begin{bmatrix} w_1 \\ \vdots \\ w_M \end{bmatrix} = \begin{bmatrix} \max(A)/A_1 \\ \vdots \\ \max(A)/A_M \end{bmatrix}
\]

- Weights depend on the power levels within each component fitted
- The purpose is to balance the extraction of high and low power level data.
- Prior shaping is done at the beginning of the extraction (no error feedback needed)
Before and After Using Prior-Shaping

Figure 1: IMD3 ($2\omega_1 - \omega_2$ and $2\omega_2 - \omega_1$) before and after prior-shaping.
Optimization of B-spline Knot Placement

Integrated error (linear scale) versus knots distribution (dBm scale)

Other parameters such as the number and phase-shift $\phi$ of the memory channel could also be optimized.
Overall Extraction Algorithm including Optimization

Start

Prior Shaping

B-Spline Knots Optimization

Done?

Post Shaping

Done?

End

Final result
Part III: Results

Implementation of Behavioral Model as a User-Compiled-Model in ADS
Demo PCS amplifier: Transistor and Matching Network

Optimized Matching Circuits

Detail of PCS amplifier
Model Fitting and Prediction for PCS circuit

- Fitting
  - one-tone fitting
  - two-tone fitting

- Prediction:
  - IMD5
  - Multi-sine: 4-tone fitting and 8-tone fitting
One-tone fitting: Fundamental, Second, Third harmonics

(a) Real and imaginary components, (b) Power (dBm) for $\omega$, $2\omega$, $3\omega$. 
One-tone fitting: Third, Forth, Fifth Harmonics

(a) Real and imaginary components, (b) Power (dBm) for $3\omega$, $4\omega$ and $5\omega$. 
One-tone fitting: Sixth, Seventh, Eighth harmonics

(a) Real and imaginary components, (b) Power (dBm) for 6\omega, 7\omega and 8\omega.
Two-tone fitting: IMD3

(a) Real and Imaginary components
(b) Power (dBm) for $2\omega_2 - \omega_1$ and $2\omega_1 - \omega_2$;

Note: The circles are the locations of B-Spline knots.
Two-tone fitting: IMD1

(a) Real and imaginary, (b) Power (dBm) for $\omega_1$ and $\omega_2$
Two-tone prediction: IMD5

Predicted (a) Real and imaginary components (b) Power (dBm) for $3\omega_2 - 2\omega_1$ and $3\omega_1 - 2\omega_2$
One-tone fitting: Time-domain performance

Time-domain representation for some power levels; Left: before filtering; Right: after filtering
Multi-sine Excitation

\[ v_{in} = R_F \cos(\omega_{RF}t) \times \sum_{n=0}^{N_{\text{phi}}} \cos(n\omega_{IF}t + \phi_n) \]

\[ \phi_n = \pi \frac{n^2 - 1}{N_{\text{phi}}} \quad \text{or} \quad \phi_n = \pi \frac{(n - 1)^2}{N_{\text{phi}}} \]

Multisine input signal in the time domain
Prediction(1-a): PCS circuit: 4-tone fitting multi-sine
Comparison of Time-domain signal: original PA in ADS and our model in ADS
Four-tone prediction:

Left: amplitude; Right: phase and phase difference
Four-tone prediction: Fundamental

Left: amplitude; Right: phase and phase difference
Four-tone prediction: Second

(a) V-out: Amplitude

(b) V-out: Phase

V-out: Phase difference

Left: amplitude; Right: phase and phase difference
Four-tone prediction: Third

Left: amplitude; Right: phase and phase difference
Four-tone prediction: Forth

Left: amplitude; Right: phase and phase difference
Four-tone prediction: Fifth

Left: amplitude; Right: phase and phase difference
Prediction(1-b): PCS circuit: 8-tone fitting multi-sine
Time-domain signal: original PA in ADS and our model in ADS
Eight-tone prediction: All

Left: amplitude; Right: phase and phase difference
Eight-tone prediction: Fundamental

Left: amplitude; Right: phase and phase difference
Eight-tone prediction: Second

(a) V-out: Amplitude

(b) V-out: Phase

Left: amplitude; Right: phase and phase difference
Eight-tone prediction: Third

(a) V-out: Amplitude
(b) V-out: Phase

Left: amplitude; Right: phase and phase difference
Eight-tone prediction: Forth

V-out: Amplitude

V-out: Phase

V-out: Phase difference

(a) (b)

Left: amplitude; Right: phase and phase difference
Eight-tone prediction: Fifth

(a) V-out: Amplitude

(b) V-out: Phase and phase difference

Left: amplitude; Right: phase and phase difference
Prediction(2): OAT circuit: 4-tone fitting multi-sine
Input Power=12 dbm: Time-domain signal: original PA in ADS and our model in ADS
Four-tone prediction: Fundamental

Input Power=12 dbm: Left: amplitude; Right: phase and phase difference
Input Power=0 dbm: Time-domain signal: original PA in ADS and our model in ADS
Four-tone prediction: Fundamental

Input Power=0 dbm: Left: amplitude; Right: phase and phase difference
Experimental Validation of Model

- The behavioral model developed is now sufficiently mature to be directly extracted from experimental data.
- This requires the availability of vectorial data for both the fundamental and harmonics generated for single and multi-tone input signals.
- The forthcoming acquisition of the LSNA in our laboratory will put us in the position to acquire these data.