Predistortion and Postdistortion Linearization of RF Amplifiers

Patrick Roblin  
Dominique Chaillot  
Sukkuen Myoung  
Xian Cui  
Mamta Debnath

March 18, 2004

Department of Electrical and Computer Engineering  
The Ohio State University  
Columbus, OH 43210
Introduction: Design Trends

- Pull for more power efficient amplifiers
  - Class B, C, D and E amplifiers are more efficient than class A but exhibit poorer linearity
  - Call for improved linearization performance
- Push for lower cost linearization systems
  - Adaptive predistortion linearization replacing feedforward
  - Alternative novel baseband linearization possible
- Increasing signal bandwidth (e.g. from 2.5G to 3G)
  - Need to deal with both slow (thermal drift) and fast (electrical) memory effects
  - Electrical memory effects degrade the ACPR for wide-bandwidth signals

<table>
<thead>
<tr>
<th>Technique</th>
<th>Correction</th>
<th>Bandwidth</th>
<th>Efficiency</th>
<th>Flexibility</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analog Predistortion</td>
<td>3-5 dB</td>
<td>15-25 MHz</td>
<td>5-8 %</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Cross Modulation</td>
<td>15-20 dB</td>
<td>10-20 MHz</td>
<td>10-12 %</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Feed Forward</td>
<td>30 dB</td>
<td>25-60 MHz</td>
<td>6-10 %</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Digital Predistortion</td>
<td>15-20 dB</td>
<td>15-20 MHz</td>
<td>12-14 %</td>
<td>High</td>
<td>Medium</td>
</tr>
</tbody>
</table>
Memory Effects and Volterra Modeling

A memoryless SISO system can be modeled by:

\[ y(t) = g_m x(t) + g_{m3} x^3(t) \]

The most rigorous theory for including memory effects is the Volterra formalism. In that formalism the system is described by Volterra kernels of various orders. For example a SISO system with a 3rd order kernel is of the form:

\[ y(t) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h(\tau_1, \tau_2, \tau_3) x(t - \tau_1) x(t - \tau_2) x(t - \tau_3) d\tau_1 d\tau_2 d\tau_3 \]
Volterra in Frequency Domain

Consider the frequency response for a two-tone excitation $a$ and $b$ of frequency $f_a$ and $f_b$ in a 3rd order system. The intermodulation terms of interest are the in-band terms which are:

\[
\begin{align*}
    i_{\text{out}}(2\omega_a - \omega_b) &= A_0 a_1^2 b_1^* \\
    i_{\text{out}}(2\omega_b - \omega_a) &= B_0 a_1^* b_1^2 
\end{align*}
\]

where $A_0$ and $B_0$ are the coefficients for the LSB and USB IMD3 respectively.

The two desired tones at the output of the PA are themselves given by:

\[
\begin{align*}
    i_{\text{out}}(\omega_a) &= D_0 a_1 + D_3 a_1^2 a_1^* + D_4 a_1 b_1 b_1^* \\
    i_{\text{out}}(\omega_b) &= E_0 b_1 + E_3 b_1^2 b_1^* + E_4 b_1 a_1 a_1^* 
\end{align*}
\]

where $D_0 \sim D_4$ and $E_0 \sim E_4$ are coefficients which can be derived from the Volterra Kernel.
Memory Effects

A PA system is memoryless if all coefficients are real, e.g. (LSB & USB IMD):

\[ A_0 = B_0 = \frac{3}{4}g_{m3} \]

A PA system is quasi-memoryless if the coefficients are complex and frequency independent, e.g. (LSB & USB IMD):

\[ A_0 = B_0 = \frac{3}{4}y_{m3} = |y_{m3}|\exp(j\theta_m) \]

A PA system exhibits memory effects if its coefficients are frequency dependent, e.g. (LSB & USB IMD):

\[ A_0 \neq B_0 \quad \text{or} \quad y_{m3}(-) \neq y_{m3}(+) \]
ACPR Degradation

Up to 17 dB degradation of ACPR at low and high bandwidth
RF predistortion (quasi-memoryless algorithm)

Polynomial functions

\[ \alpha = 1 + \alpha_3 V_E^1 + \alpha_5 V_E^2 \]
\[ \beta = 1 + \beta_3 V_E^1 + \beta_5 V_E^2 \]
Adaptive baseband digital predistortion (quasi-memoryless algorithm)

- The adaptation can only take care of slow memory effects
- The linearization algorithm cannot handle fast memory effects
RF Predistortion for Quasi-Memoryless Systems

For Two-tone Excitations:

- Volterra analysis assumption: \( A_4 = B_4 = 0 \) (5th order noise)
- \( \alpha_3 \) and \( \beta_3 \) are real coefficients for Quasi-memoryless systems

\[
\alpha_3 = -3\text{Re} \left[ (1 + j) \frac{y_{m3}}{y_m} \right] \quad \text{and} \quad \beta_3 = -3\text{Im} \left[ (1 + j) \frac{y_{m3}}{y_m} \right]
\]
Vectorial Predistortion for Systems with Memory

For Two-tone Excitations:

- Volterra analysis for: \( A_4 = B_4 = 0 \) (5th order noise)
- \( \alpha_3 \) and \( \beta_3 \) are complex coefficients phase shifted I and Q
- Vectorial predistortion (VPD) doubles the degrees of freedom

\[
\alpha_3 = \frac{1}{2}(Z_1 + Z_2) \quad \beta_3 = \frac{1}{2j}(Z_2 - Z_1)
\]

with

\[
Z_1 = -(1 - j)\frac{A_0^*}{D_0^*} \quad Z_2 = -(1 + j)\frac{B_0}{E_0}
\]
Two Band Implementation

The I and Q signals need to be phase shifted to account for memory effects:

\[ \alpha = 1 + \alpha_3 V_E^1 + \alpha_5 V_E^2 \]
\[ \beta = 1 + \beta_3 V_E^1 + \beta_5 V_E^2 \]

Polynomial functions
Multitone Performance Limitation

Consider a 2 band case (different phase for LSB and USB) with 2-tone and multitone excitations.

- Disadvantage: the number of linearization coefficients increases with the number of frequency bands

- Advantages: no PA modeling required, no band filter required for multi-carrier PAs
Predistortion Using PA Model

PA modeled as multiple 3rd order systems in parallel:
Iterative Predistortion for 8 tone Multisine

- Model is a 3rd order Volterra system
- The correction can be applied iteratively to remove higher order terms generated
Novel BaseBand Linearization Schemes

- Low frequency feedforward linearization (LFFF)
- Input and Output baseband modulation (IBM and OBM)
- Bilateral and Quadratic baseband modulation (BBM and QOBM)
Low frequency feedforward linearization

\[ I_{ds} = g_{m1}v_{gs} + g_{d1}v_{ds} + g_{m2}v_{gs}^2 + g_{m1d1}v_{gs}v_{ds} + g_{d2}v_{ds}^2 + g_{m3}v_{gs}^3 \]
\[ + g_{m2d1}v_{gs}^2v_{ds} + g_{m1d2}v_{gs}v_{ds}^2 + g_{d3}v_{ds}^3 + g_{m4}v_{gs}^4 + g_{m3d1}v_{gs}^3v_{ds} \]
\[ + g_{m2d2}v_{gs}^2v_{ds}^2 + g_{m1d3}v_{gs}v_{ds}^3 + g_{d4}v_{ds}^4 + \cdots, \]

where \( I_{ds} \) = drain-source current, \( v_{gs} \) = gate-source voltage, \( v_{ds} \) = drain-source voltage

\[ f_0 = f_a - f_b \]
Input and Output Baseband Modulation Linearization of PAs

- New proposed baseband linearization schemes (IBM, OBM and BBM)
- Square law operation is performed directly on the baseband
- Filter no longer required
Perfect IM3 and IM5 cancellation using $g_{md}$ for memoryless systems

If the RF signal is given by

$$v_{in}(t) = I(t) \cos(\omega t) + Q(t) \sin(\omega t)$$

the correction for a 5th order system with $g_{m3}$ and $g_{m5}$ terms is

$$v_{LFFF}(t) = -\frac{3}{4} \frac{g_{m3}}{g_{md}} [I^2(t) + Q^2(t)] - \frac{5}{8} \frac{g_{m5}}{g_{md}} [I^2(t) + Q^2(t)]^2$$
Constraints required by Low Frequency Feedforward

\[
|G| = \frac{3 |y_{m3}|}{2 |y_{md}|}
\]
\[
\phi = (2m + n + 1)\pi
\]
\[
\theta_d - \theta_m = n\pi
\]

- Phase shift \( \theta_m \) and \( \theta_d \) associated with \( g_{m3} \) and \( g_{md} \) respectively (cancellation of the 3\(^{rd}\) order intermodulation at RF frequencies)

\[
y_{m3} = |y_{m3}| \exp(j\theta_m)
\]
\[
y_{md} = |y_{md}| \exp(j\theta_d)
\]

- New phase constraint \( \theta_d - \theta_m = n\pi \) required (Yu and Roblin, 2001)
IMD plotted versus phase $\phi$ for different gains $G$ (S. Myoung)
The LO rejection mixer and AWG are controlled by a PC using Labwindow.
Experimental Results for IBL

Phase

IMD power

0 50 100 150 200 250 300 350 400

-70 -65 -60 -55 -50 -45 -40 -35 -30 -25

Microwave Laboratory

The Ohio State University
Limitations of IBM, OBM (LFFF)

- IBM and OBM do not provide enough degrees of freedom to eliminate both LSB and USB intermodulation in two-tone excitations.

- New methods with more degrees of freedom will be investigated next to cancel both LSB and USB:
  - Bilateral Baseband modulation (BBM)
  - Quadratic Output Baseband modulation (QOBM)
  - Quadratic Output Baseband modulation (QIBM)
Bilateral Baseband Modulation (BBM) for PA with Memory

\[ \begin{align*} 
& \text{LO} \\
& \text{Baseband} \\
\end{align*} \]

\[ \begin{align*} 
& \text{IQ} \\
\end{align*} \]

\[ \begin{align*} 
& \text{RF} \\
& \text{RF} \\
\end{align*} \]

\[ \begin{align*} 
& \text{IMN} \quad a_1 \\
& \text{RFC} \quad b_1 \\
& \text{RFC} \\
\end{align*} \]

\[ \begin{align*} 
& \text{PA} \\
& \text{OMN} \quad c_1 \\
& \text{OMN} \quad c_2 \\
\end{align*} \]

\[ \begin{align*} 
& \hat{1} + \hat{Q} \\
& \phi_1 \\
& \phi_2 \\
& \text{BBL} \\
\end{align*} \]
Volterra Analysis of BBM for Systems with Memory

For a two-tone excitation the intermodulation terms of interest are:

\[
\begin{align*}
    i_{\text{out}}(2\omega_1 - \omega_2) & = A_0 a_1 b_1^* + A_1 a_1 c_1^* + A_2 a_1 c_2^* + A_3 b_1 c_1^* c_2^* + A_4 b_1 c_2^* c_2^* + A_5 b_1 c_1^* c_2^* \\
    i_{\text{out}}(2\omega_2 - \omega_1) & = B_0 a_1^* b_1^2 + B_1 b_1 c_1 + B_2 b_1 c_2 + B_3 a_1 c_1^2 + B_4 a_1 c_2^2 + B_5 a_1 c_1 c_2
\end{align*}
\]

where \(A_0 \sim A_5\) and \(B_0 \sim B_5\) are the coefficients for the LSB and USB IMD3 respectively.

The two desired tones at the output of the PA are themselves given by:

\[
\begin{align*}
    i_{\text{out}}(\omega_1) & = D_0 a_1 + D_1 b_1 c_1^* + D_2 b_1 c_2^* + D_3 a_1^2 a_1^* + D_4 a_1 b_1 b_1^* + D_5 c_1 c_1^* a_1 + D_6 c_1^* c_2 a_1 + D_7 c_1 c_2^* a_1 + D_8 c_2 c_2^* a_1 \\
    i_{\text{out}}(\omega_2) & = E_0 b_1 + E_1 a_1 c_1 + E_2 a_1 c_2 + E_3 b_1^2 b_1^* + E_4 b_1 a_1 a_1^* + E_5 c_1 c_1^* b_1 + E_6 c_1^* c_2 b_1 + E_7 c_1 c_2^* b_1 + E_8 c_2 c_2^* b_1
\end{align*}
\]
Under certain operating conditions both the upper and lower IMD3s can be theoretically reduced by 100 dB and 200 dB respectively. Note however that, depending on the Volterra Kernel, the biquadratic system does not always admit a solution for certain power levels.
Volterra Analysis of QOBM for Systems with Memory

Figure 1: Topology of quadratic OBM

Like for predistortion we define $\alpha_3$ and $\beta_3$ from $c_I = \alpha_3 \ b_1 a_1^*/2$ and $c_Q = \beta_3 \ b_1 a_1^*/2$. For a quasi-memoryless system $\alpha_3$ and $\beta_3$ are given by:

$$\alpha_3 = -\frac{3}{2} \Re \left[ (1 + j) \frac{y_{m3}}{y_{md}} \right] \quad \text{and} \quad \beta_3 = -\frac{3}{2} \Im \left[ (1 + j) \frac{y_{m3}}{y_{md}} \right]$$
Multitone Performance Limitation

Consider a 2 band case (different phase for LSB and USB) with 2-tone and multitone excitations.

- Works for 1 tones per frequency band but degrades for multitones
- Disadvantage: the number of linearization constraints increases with the number of frequency bands
- Advantage: no PA modeling required
QOBM Using a PA Model

- Model is a 3rd order Volterra system
- Higher order term in the baseband output modulation are neglected
Testbed for Digital Vectorial Predistortion, BBM and QOBM

Goals:

- Study impact of memory effects for broadband signals
- Compare the performance of the various linearization schemes
- Study potential combination of linearization techniques
Capabilities of the LSNA

- 70 dBc dynamic range
- -80 dBm noise floor
- Calibrated in frequency, time and power
- Measure amplitude and phase of up to 10,000 tones
- Acquire harmonics up to 20 GHz (in OSU system)
- 4 channels, 10 W damage level
- Equipped with a load pull
- Modulated source (E4438C-504) 250 kH to 4 GHz (with WCDMA 3GPP)
Applications of the LSNA in PA Design and Linearization

• PA design:
  – Model verification
  – Design PA using load pull
  – Tune PA (IF and harmonics impedance terminations) by directly inspecting the load-line

• PA Modeling and Linearization:
  – Extract a Volterra Kernels coefficients using multitone excitations
  – Acquire the trajectory of I and Q at the PA output directly from the RF signal