System-Level Time-Domain Behavioral Modeling for a Mobile WiMax Transceiver

2006. 9. 15

Brian Y. Kim, Ph. D.
Telecomm. R&D Centre
Samsung Electronics
Agenda

- Background
- RF Time-domain Behavioral Modeling
- Modeling Methods
- Simulation Results
- Conclusion
Industry Trend - Highly Integrated SoC/SiP
- RF Ckt, ADC/DAC & Digital baseband

Design Methodology
- *Top-down vs. Bottom-up*
- *Top-down* methodology becomes necessary for SoC/SiP

Simulation & Verification
- *System-level vs. Transistor-level*
- *System-level* simulation & verification play a key role in *Top-down* methodology
Time-domain vs. Frequency-domain
- System-level Specification <-> Time-domain
  - Constellation, EVM, BER, FER,…
- RF Performance <-> Frequency-domain
  - Nonlinearity, Noise Figure, Phase noise, …

System-level simulation
- Full signal path and time-consuming simulation
- Time-domain behavioral models are required
- Frequency-domain model -> Time-domain mode

Application Example
- Mobile WiMax IEEE 802.16e (WiBro) in Simulink
**RF Time-domain Behavioral Modeling**

- **Passband vs. Baseband**
  - Real signal processing -> passband model
  - Complex signal processing -> baseband equivalent model

\[
rf(t) = I(t)\cos(\omega_c t) + Q(t)\sin(\omega_c t)
\]

\[
= \frac{1}{2}\{[I(t) + jQ(t)]e^{-j\omega_c t} + [I(t) - jQ(t)]e^{j\omega_c t}\}
\]

\[
= [I(t) + jQ(t)] + [I(t) - jQ(t)]e^{j2\omega_c t}
\]
Nonlinearity

- Polynomial memoryless model
- Passband expression

\[ y(t) = k_1 x(t) + k_2 x^2(t) + k_3 x^3(t) + k_5 x^5(t) \]

- \( x(t) \) is the passband signal, and able to expressed as

\[ x(t) = C(t)e^{j\omega ct} + C^*(t)e^{-j\omega ct}, \]

- \( C(t) \) is the complex baseband equivalent signal.

- Baseband equivalent expression

\[ y_{BB}(t) = \left[ k_1 + \frac{3}{4} k_3 |C(t)|^2 + \frac{5}{8} k_5 |C(t)|^4 \right] \cdot C(t) \]

- the polynomial coefficients changed in baseband model
Noise

- Noise figure (NF) – Frequency-domain
- RMS noise power \( P_n \) – Time-domain

\[
P_n = \sigma_n^2 = 4kRT \cdot f_s \cdot (10^{NF/10} + 1)
\]

Where \( k \) is the Boltzmann constant, \( T \) is the noise temperature, \( R \) is the source impedance and \( f_s \) is the sampling frequency.

Other Noise source

- Flicker noise
- Phase noise
- Quantization noise
Modeling Methods

- Amplifier
  - LNA
    - Polynomial nonlinearity model with hard saturation
    - Noise model
  - Power Amplifier
    - Polynomial nonlinearity model with hard saturation
    - Phase distortion model by AM-PM conversion
Modeling Methods

- Amplifier Model Verification

\[ \text{More Nonlinearity is in PA} \]
Mixer

- Same nonlinearity and noise model as LNA
- Nonlinearity
  - Equivalent to the RF input
- Noise
  - Equivalent to the output port
LO

- Phase noise
  - 1/f^3, 1/f^2, and Noise floor
    - Noise floor is modeled as AWGN
    - 1/f^2 is modeled as AWGN with transfer function
      \[ H(z)_{1/f^2} = \frac{1}{1 - z^{-1}} \]
    - 1/f^3 is modeled as AWGN with transfer function
      \[ H(z)_{1/f^3} = \frac{1}{(1 - z^{-1})^{3/2}} \quad \text{IIR} \quad H(z)_{1/f^3} = \frac{1}{a_0 + a_1 z^{-1} + a_2 z^{-2} + ...} \]
  - PLL loop
    - Second-order high pass filter
LO Model Verification

- Phase noise: -50dBc/Hz @10kHz, -80dBc/Hz @100kHz, & -120 dBc/Hz @Noise Floor.
- Loop bandwidth: 100kHz
ADC/DAC

Nonlinearity:

- INL and DNL: Modeled as non-uniform quantization level
- DNL is generated by Gaussian random noise
- INL is the integration of DNL

\[ v_{INL,k} = \sum_{i=1}^{k} v_{DNL,i} \quad \rightarrow \quad v_{q,k} = v_{INL,k} + \frac{k}{2^n} v_{ref} + v_{offset} \]
Simulation Results

- System Simulation in MATLAB Simulink
- System-level Diagram
Simulation Results

Mobile WiMax Signal Source

- Signal Source generation by m-coding
- Downlink modulation: 64QAM/16QAM/QPSK
- Uplink modulation: 16QAM/QPSK
- Cell ID: 2
- Segment number: 0
- DL/UL ratio: 27/15 symbols

Diagram:

1. Modulation
2. Pilot Insertion
3. Scrambling
4. Rearrangement
5. RF Input
6. Cyclic Prefix Insertion
7. IFFT

Graphs showing constellation, power spectrum density, and time domain plots.
Simulation Results

- System Performance
  - Constellation and Spectrum for 16QAM

A Signal source
B TX
C RX

(a) ACPR
(b) SNR for $10^{-6}$ BER
(c) SNR for $10^{-6}$ BER

- Simulation Results

- System Performance
  - Constellation and Spectrum for 16QAM

A Signal source
B TX
C RX
Simulation Results

- Constellation and Spectrum for 64 QAM

![Simulation Diagram](image)
Simulation Results

- System Performance for Various Cases

Table 1. Simulated system-level constellation performance

<table>
<thead>
<tr>
<th>RF Behavioral Modeling Examples</th>
<th>RMS Constellation Error (dB)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1 16 QAM Ideal TX</td>
<td>-61.032</td>
<td>TX</td>
</tr>
<tr>
<td>Case 2 16 QAM Nonideal TX LO</td>
<td>-45.449</td>
<td>TX</td>
</tr>
<tr>
<td>Case 3 16 QAM Nonideal TX Mixer</td>
<td>-33.672</td>
<td>TX</td>
</tr>
<tr>
<td>Case 4 16 QAM Nonideal PA</td>
<td>-21.311</td>
<td>TX</td>
</tr>
<tr>
<td>Case 5 64 QAM Ideal TX</td>
<td>-50.056</td>
<td>TX</td>
</tr>
<tr>
<td>Case 6 64 QAM Ideal TX and RX</td>
<td>-22.179</td>
<td>RX</td>
</tr>
<tr>
<td>Case 7 64 QAM Nonideal RX LO</td>
<td>-20.766</td>
<td>RX</td>
</tr>
<tr>
<td>Case 8 64 QAM Nonideal RX</td>
<td>-19.722</td>
<td>RX</td>
</tr>
</tbody>
</table>

- Simulation Efficiency

The whole simulation for one frame OFDM signals takes about 4 minutes on a Pentium 4 3.0GHz PC with 1GB memory.
Conclusion

- Behavioral Mobile WiMax Transceiver design has been implemented on Matlab/ Simulink platform.

- Overall Functionality and block specification could be validated based on 802.11e standard.

- The impact of nonlinearity and noise from RF/ Mixed-signal building blocks is addressed by the time-domain system simulation.

- The proposed baseband equivalent model technique is able to be applied by wide range of the system-level simulation covering RF nonlinearity and noise effects.
Thank You!