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

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Agenda

- Background
- RF Time-domain Behavioral Modeling
- Modeling Methods
- Simulation Results
- Conclusion

Background

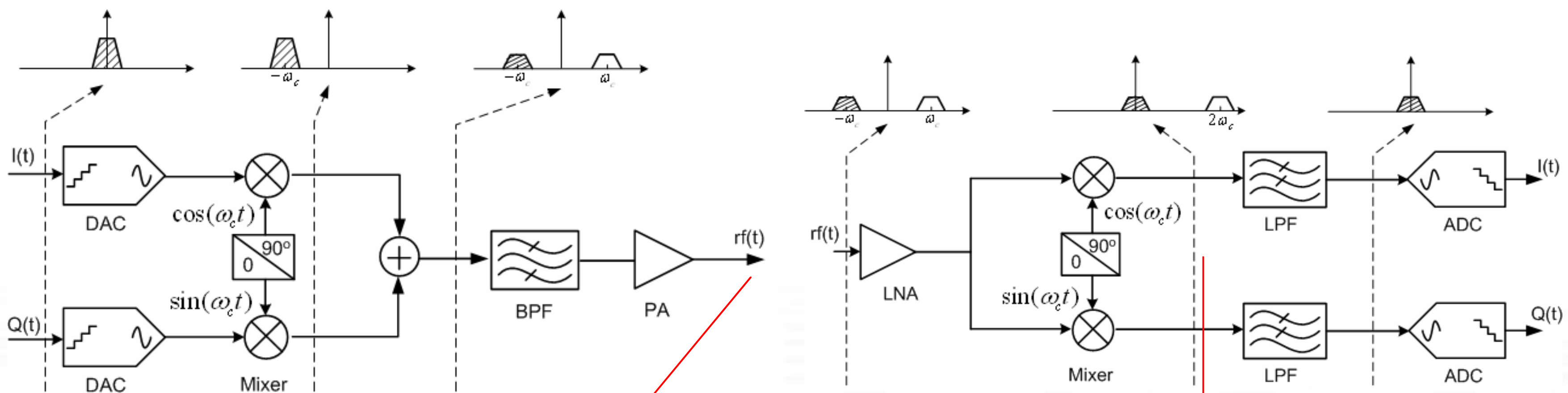
- Industry Trend - Highly Integrated SoC/SiP
  - RF Ckt, ADC/DAC & Digital baseband
- Design Methodology
  - *Top-down* vs. *Bottom-up*
  - *Top-down* methodology becomes necessary for SoC/SiP
- Simulation & Verification
  - *System-level* vs. *Transistor-level*
  - *System-level* simulation & verification play a key role in *Top-down* methodology

Background

- 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



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

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

RF Time-domain Behavioral Modeling

- 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

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

- the polynomial coefficients changed in baseband model

RF Time-domain Behavioral Modeling

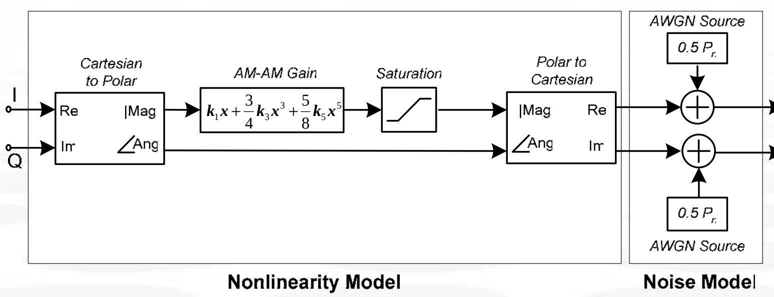
- Noise
  - Noise figure (NF) – Frequency-domain
  - RMS noise power (P_n) – Time-domain

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

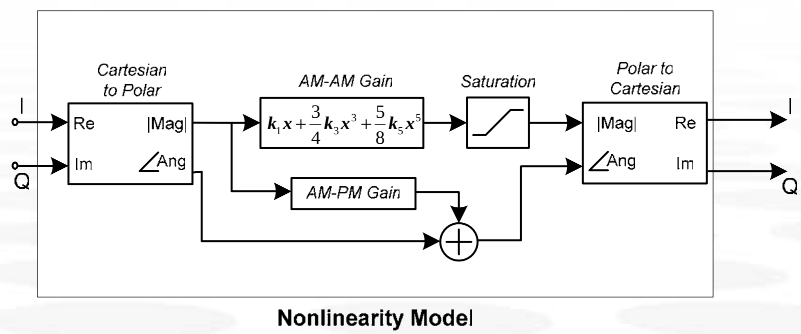
    - Where k is the Boltzmann constant, T is the noise temperature, R is the source impedance and f_s is the sampling frequency.
  - Other Noise source
    - Flicker noise
    - Phase noise
    - Quantization noise

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



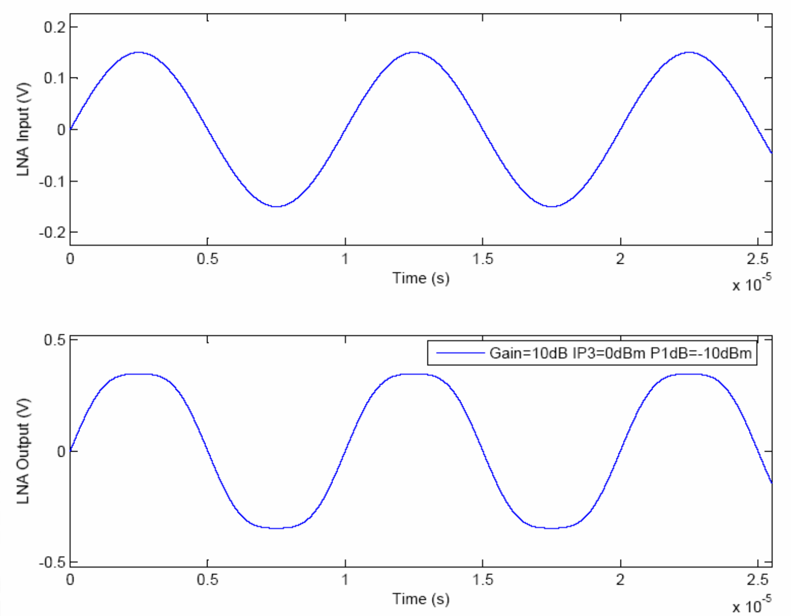
LNA



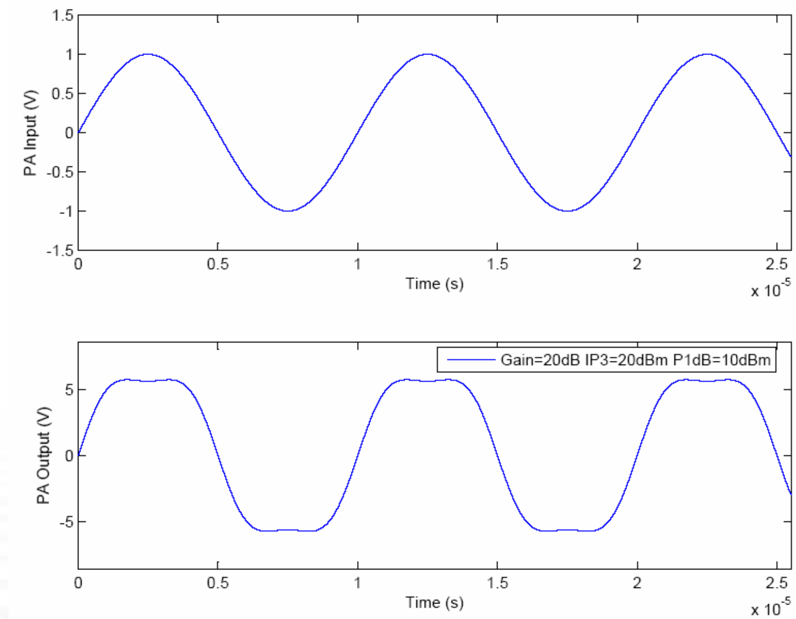
PA

Modeling Methods

- Amplifier Model Verification



LNA

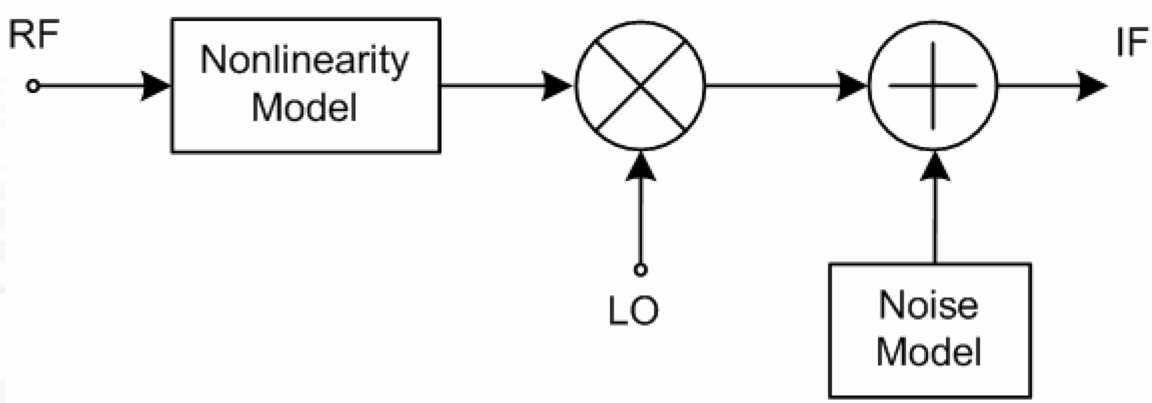


PA

More Nonlinearity is in PA

Modeling Methods

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



Modeling Methods

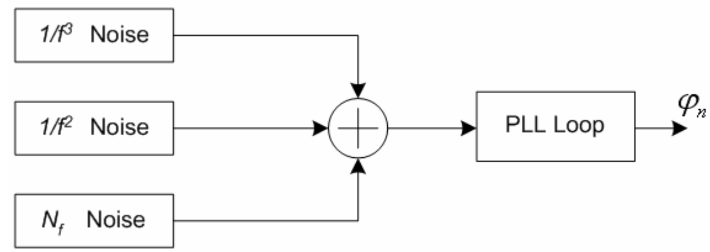
- LO
  - Phase noise
    - $1/f^3$, $1/f^2$, and Noise floor
      - Noise floor is modeled as AWGN
      - $1/f^2$ is modeled as AWGN with transfer function

$$H(z)_{1/f^2} = \frac{1}{1-z^{-1}}$$

      - $1/f^3$ is modeled as AWGN with transfer function

$$H(z)_{1/f^3} = \frac{1}{(1-z^{-1})^{3/2}} \xrightarrow{\textbf{IIR}} H(z)_{1/f^3} = \frac{1}{a_0 + a_1 z^{-1} + a_2 z^{-2} + \ldots}$$

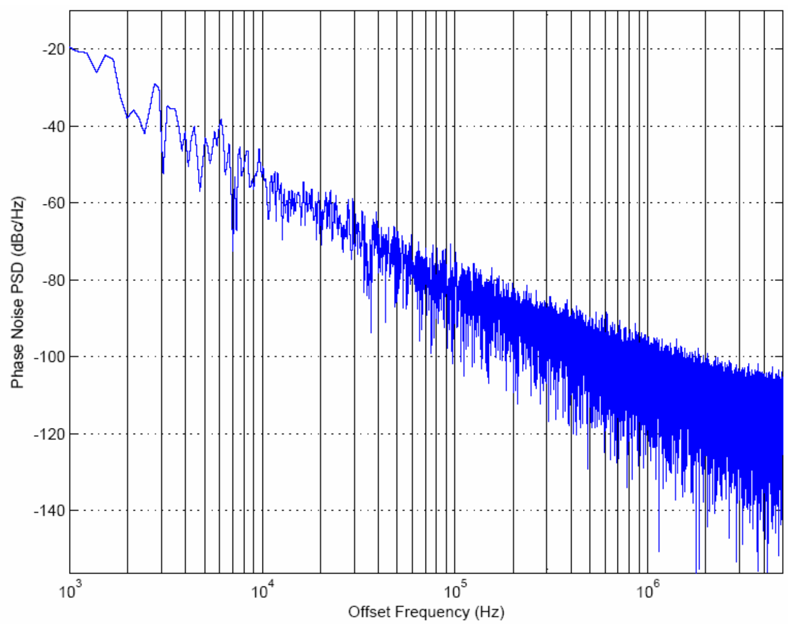
    - PLL loop
      - Second -order high pass filter



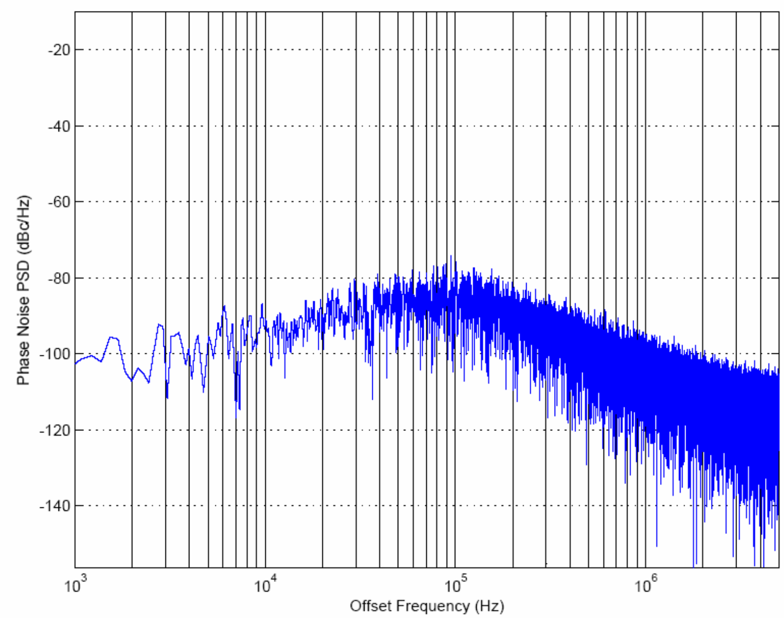
Modeling Methods

- LO Model Verification
  - Phase noise: -50dBc/Hz @10kHz, -80dBc/Hz @100kHz ,&

    -120 dBc/Hz @Noise Floor.
  - Loop bandwidth: 100kHz



PLL Disabled



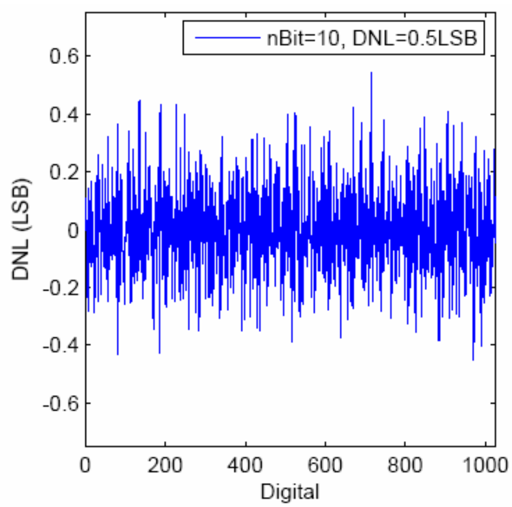
PLL Enabled

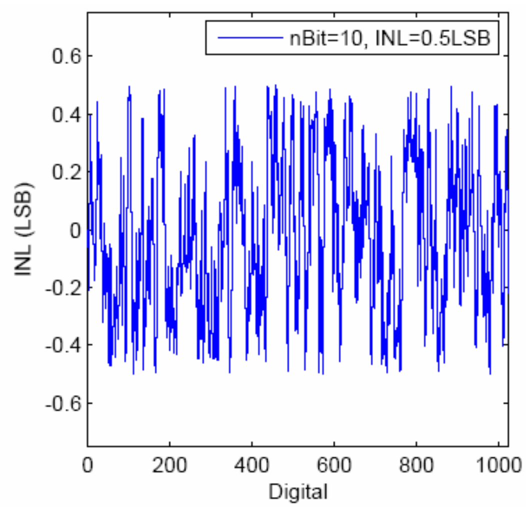
Modeling Methods

- 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

Non−uniform Quantization leve l

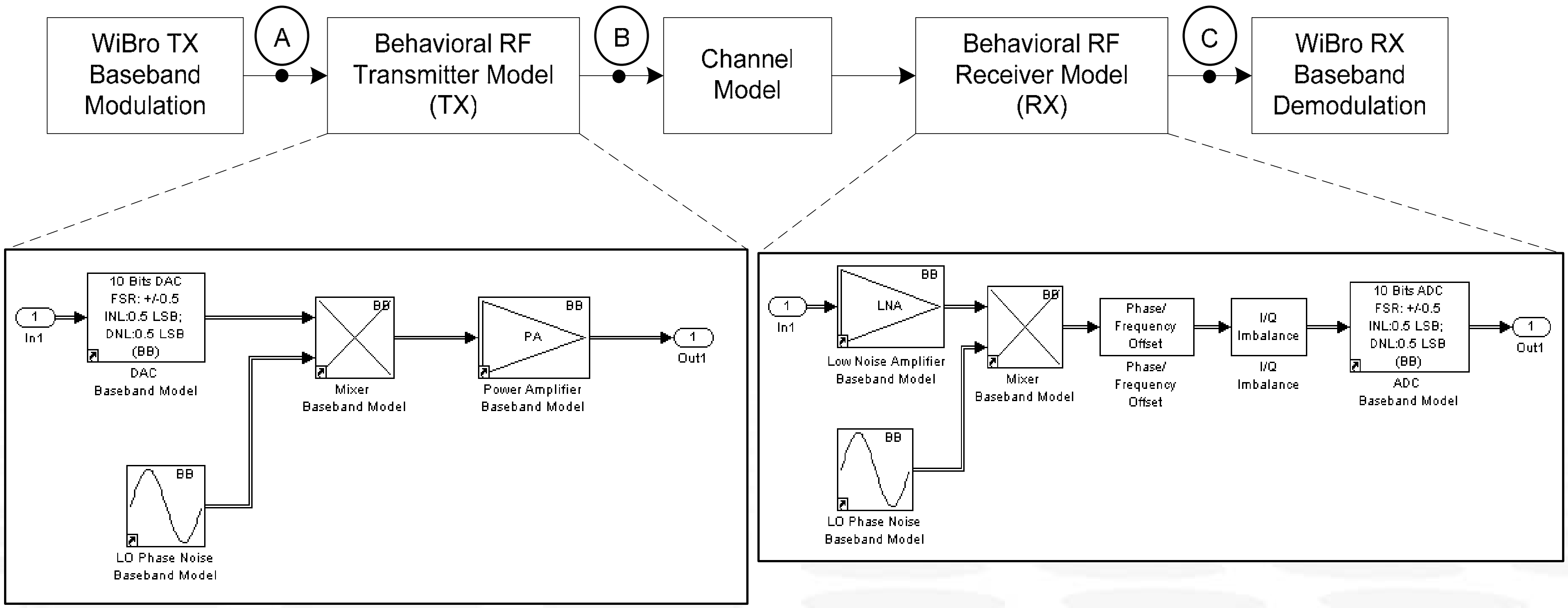
$$v_{INL,k} = \sum_{i=1}^{k} v_{DNL,i} \longrightarrow v_{q,k} = v_{INL,k} + \frac{k}{2^n} v_{ref} + v_{offset}$$



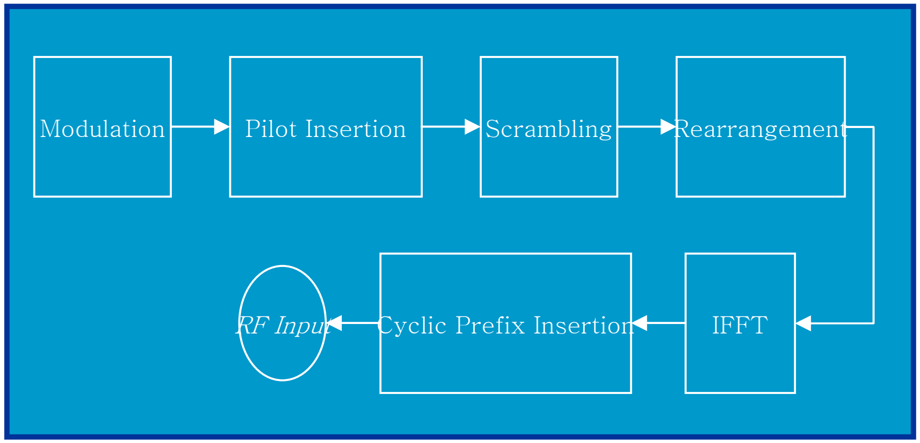


Simulation Results

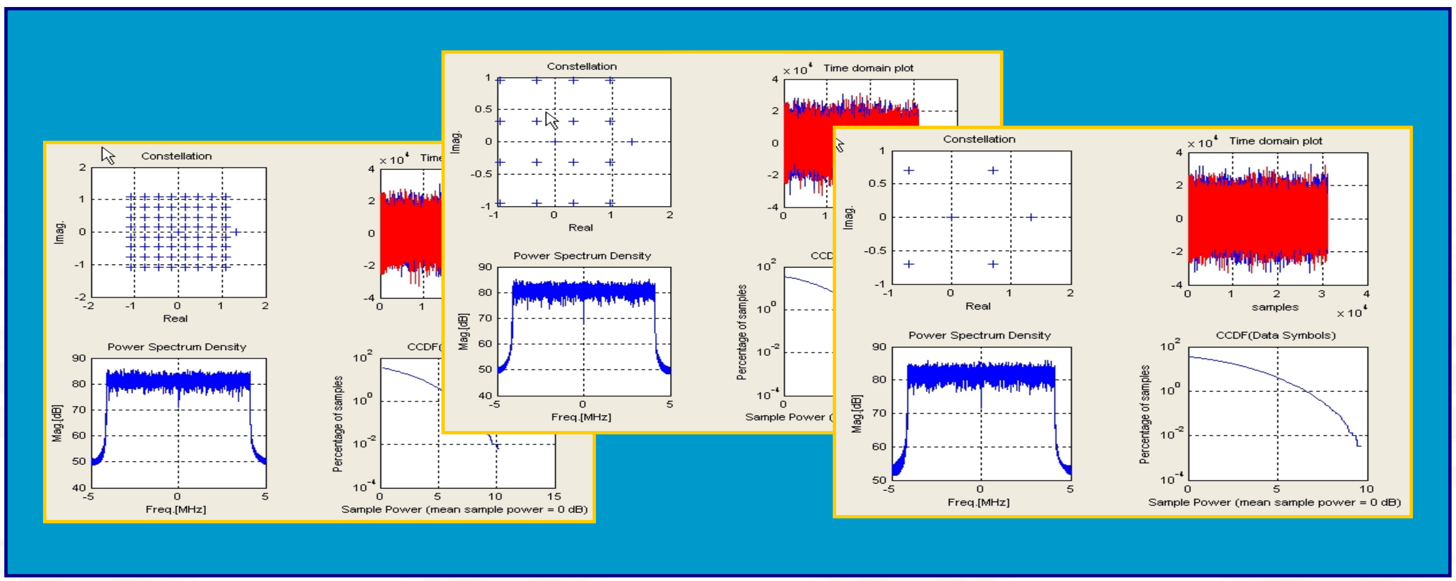
- System Simulation in MATLAB Simulink
- System-level Diagram



Mobile WiMax Signal Source

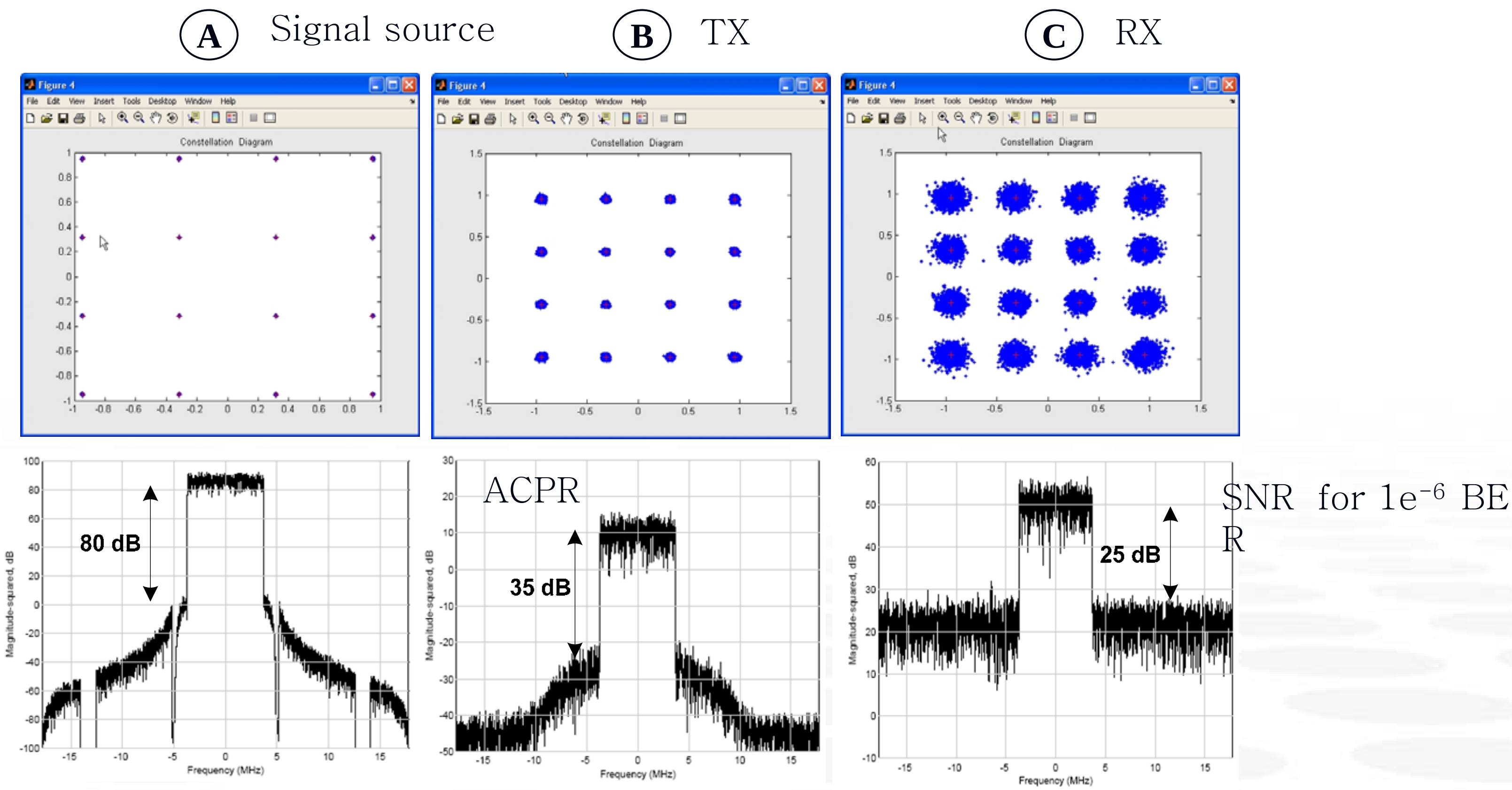


- **Signal Source generation by m-coding**
- **Downlink modulation :**
  64QAM/ 16QAM/ QPSK
- **Uplink modulation : 16QAM/ QPSK**
- **Cell ID : 2**
- **Segment number : 0**
- **DL/ UL ratio : 27/15 symbols**



Simulation Results

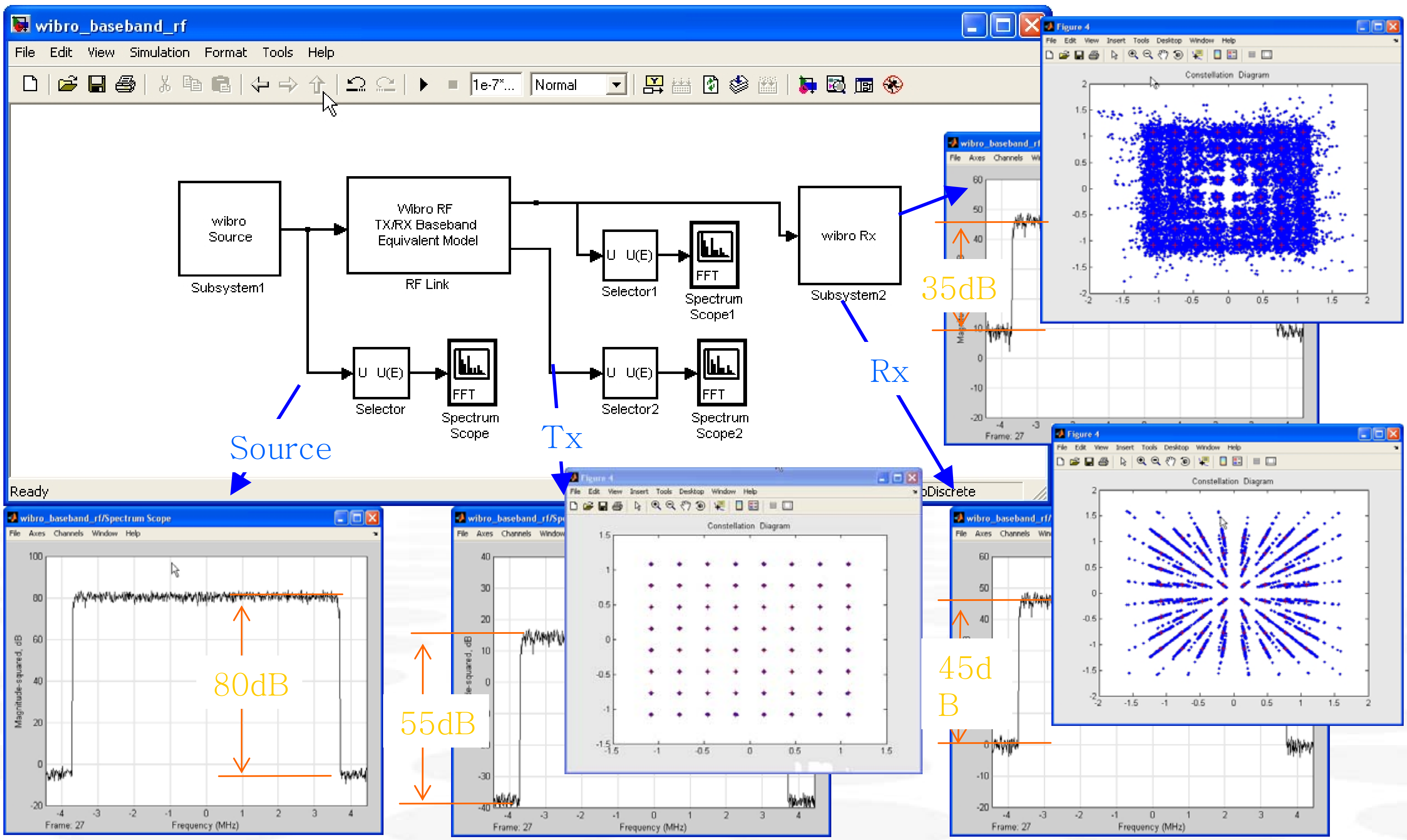
- System Performance
  - Constellation and Spectrum for 16QAM



(a) (b) (c)

Simulation Results

- Constellation and Spectrum for 64 QAM



Simulation Results

- System Performance for Various Cases

Table.1. Simulated system-level constellation performance

RF Behavioral Modeling Examples			RMS_Constellation_Error (dB)	Notes
Case 1	16 QAM	Ideal TX	-51.032	TX
Case 2	16 QAM	Nonideal TX LO	-45.449	TX
Case 3	16 QAM	Nonideal TX Mixer	-33.672	TX
Case 4	16 QAM	Nonideal PA	-21.311	TX
Case 5	64 QAM	Ideal TX	-50.056	TX
Case 6	64 QAM	Ideal TX and RX	-22.179	RX
Case 7	64 QAM	Nonideal RX LO	-20.766	RX
Case 8	64 QAM	Nonideal RX	-19.722	RX

- 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!

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