RadiSim – A Fast Digital RF Behavioral Simulator

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Abstract
RadiSim – A Fast Digital RF Behavioral Simulator including Bit Error Rate Assessment for System Exploration, Validation, and Tuning

RadiSim was created in collaboration with Mark Gehring.
Our Radio Receiver Architecture

- mixed signal TX
- pure analog RX

Figure 1: System model of chip receive path.
Basic Definitions

- Bluetooth wireless standard
  - transmits binary data at 1 Mb/s using GFSK with deviation of 160 KHz
  - uses 79 channels starting at 2.402 GHz spaced 1 MHz apart

- GFSK: Gaussian Frequency Shift Keying
  - Gaussian filter data to soften square waves
  - FM using carrier + deviation, carrier – deviation

- $E_b/N_0$: Modulation Independent Signal/Noise
  - $E_b$ energy per bit
  - $N_0$ noise power spectral density

- BER: Bit Error Rate
  - fraction of bits received in error
  - 1 in a 1000 (1e-3) OK for our application
Figure 2: BER vs. $E_b/N_0$ in dB for our Bluetooth receiver, based on simulating 9 trials of 20K bits at each $E_b/N_0$ value; error bars are one sample standard deviation around the mean.
Problem: Will the Radio Work?

- Must determine BER
- Must determine $E_b/N_0$ margin
- Must determine circuit settings
Solution: System Design Tool

• RadiSim
  – Fast
  – Functional
  – Accurate
Fast

- How fast? Using 500 MHz CPU,
  280 system bits/second end-to-end

- Use baseband models: avoid simulating the carrier
  \[ v(t) = I(t) \cos(\omega t) - Q(t) \sin(\omega t) \]

- Use DSP techniques: oversample analog signal; model with FIR filters, via FFT

- Process entire history in memory, block by block

- Use mixed-level behavioral models
  - modulator is complex exponential \( e^{j\phi(t)} \)
  - hard limiter is \( \tanh(\text{Gain} \times v) \)
  - intermediate frequency (IF) noise filter is one of
    * ideal band pass filter
    * circuit-based band pass filter
Functional

- Simulate system end-to-end
- Given $E_b/N_0$, estimate BER
- Given max BER, solve for min $E_b/N_0$
- Select and mix abstract and circuit-based models
- Select model parameters
- Sweep parameter spaces
- Visually display intermediate and final results
- Create audit trail for software and simulation runs
Figure 3: BER versus $E_b/N_0$ curve, overlayed with initial linear fit; directed trials are indicated by isolated points, labeled by order of prediction.
Figure 4: Estimated $E_b/N_0$ in dB at BER=1e-3 versus trial number; first trial (not shown) at $E_b/N_0=13.70$ dB. Bounds are 1% above and below final trial’s mean value of 15.84 dB.
Figure 5: Frequency response of complex 5th order inverse Chebyshev polyphase bandpass filter taken directly from SPICE simulation.
Figure 6: Tx versus Rx, showing bit error at bit 5.
Figure 7: Oversampling with $16 \times$ and $32 \times$, showing mismatched (bit 4) and common (bit 6) bit errors.
Figure 8: Simulated Eye Diagram at BER=1e-3.
Accurate

- **Simulations match silicon**
  - Prediction: 16.5 dB
  - Measured: 16.4 and 16.5 dB

- Vary oversampling to confirm $16 \times$ sufficient – NOT!

- Compare with theory for various detectors
  - coherent and non-coherent matched filters
  - demodulator with hard-limiter

- Simulate at both baseband and on-carrier

- Compare with SPICE

- Almost every aspect challenged, confirmed

- Still, had 3 dB modeling error for very long time
  - missed signal power translated to 4.8 GHz
Figure 9: Lower line is simulated BER vs. $E_b/N_0$ in dB for chip design; upper lines are noncoherent matched filter simulation results and noncoherent theory prediction.
Cost

• Development
  – 500+ hours, mostly learning and validation
  – 20K lines of MATLAB code in over 100 files

• Deployment

  runs in Octave, a free MATLAB clone, on
  – Linux
  – Solaris
  – Windows
Benefit: Simplify System Design

- In an hour, confirm can discard centering circuit for initial noise filter
  - reduce chip area and power
  - reduce design and avoid layout time
  - improve filter linearity
  - improve adjacent channel rejection

- In an afternoon, determine can replace slow $I(t) + Q(t)$ AGC circuit with independent hard limiters
  - system impact is only 0.62 dB
  - AGC feedback circuit taking too long to stabilize

- Overnight, determine can replace 3 pole Bessel filter with 3 pole Cauer (elliptic) filter to meet adjacent channel interference spec
  - easy to redesign: filter equation from textbook
  - easy to implement: new layout fits in old space
Figure 10: Estimated $E_b/N_0$ yielding BER=1e-3 versus carrier offset, for nominal deviation of 160 KHz.
[Note: Figure from earlier detector simulated with 3 dB modeling error; low $E_b/N_0$ should be about 15.6 dB.]
Conclusion

• A good system design tool is essential when exploring and optimizing non-trivial systems

• Behavioral and baseband simulation models can be fast and accurate

• Simulations using DSP techniques can be fast and accurate

• Guided sampling can be used to efficiently invert a noisy functional relationship

• Validating system simulators and models is difficult

• Techniques used by RadiSim are transferable to many simulators, models, and systems

• RadiSim is a system design tool for digital communications which is fast, functional, accurate, and validated
RadiSim Hits the Mark