High-level Behavioral Models With Time-Domain Noise

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Motivation

- Lab-measured noise is usually greater than predicted from small-signal noise simulation
  - Small-signal simulation is appropriate for linear, time-invariant (LTI) systems
  - Switched capacitor (SC) circuits and RF mixers are not LTI
- Discrete-time nature of SC circuits such as sampling mixers aliases wide-band noise into the pass-band.
- This aliased noise does not appear in small-signal noise sims.
- Estimation methods exist:
  - "Design-Oriented Estimation of Thermal Noise in Switched-Capacitor Circuits", R. Schreier

- Transient noise simulation, available in Cadence's Spectre simulator, inserts time-domain noise generators into device models.
  - Noise folding due to sampling occurs naturally due to time-domain nature of simulation
  - Appropriate for circuit simulation of relatively small circuits
  - Run time takes too long for larger systems such as a radio receiver front end.
- **Idea: Add time-domain noise generators to faster-running AMS behavioral models**
  - Noise folding occurs naturally
  - Simulate large, high-speed circuits
  - See the system level effect of thermal noise
- Algorithms for coding of transient noise generators can be found in
  - "Transient analysis of thermal noise on switch cap circuit ", P. Chiu, C. Lee

Wide-Band Noise

- Resistor noise: $N_R = \sqrt{4k_B TR \cdot BW},\ V_{RMS}$
- Resistors inject wide-band noise into a circuit.
- A reasonable definition of wide-band (BW in the above formula) is 10 times the system's bandwidth of interest.
- Since a sampled system can only discriminate frequencies up to half the sampling rate, instead of 10X, we sample the noise generator at 20 times the system bandwidth.
- For a 2 GHz system we sample at 40 GHz, and wide-band noise is defined out to 20 GHz.
- For R = 50 Ohms, T = 300 K and BW = 20 GHz $N_R = \sqrt{4 \cdot 1.38 \times 10^{23} \cdot 300\ 50 \cdot 20 \times 10^{9}} = 129\mu V_{RMS}$

- General Approach:
  - Use a circuit simulator to find the input- or output-referred RMS noise voltage of a wide-band subcircuit
  - Assign RMS noise voltage to a noise generator instantiated in the model

Narrow-Band Noise

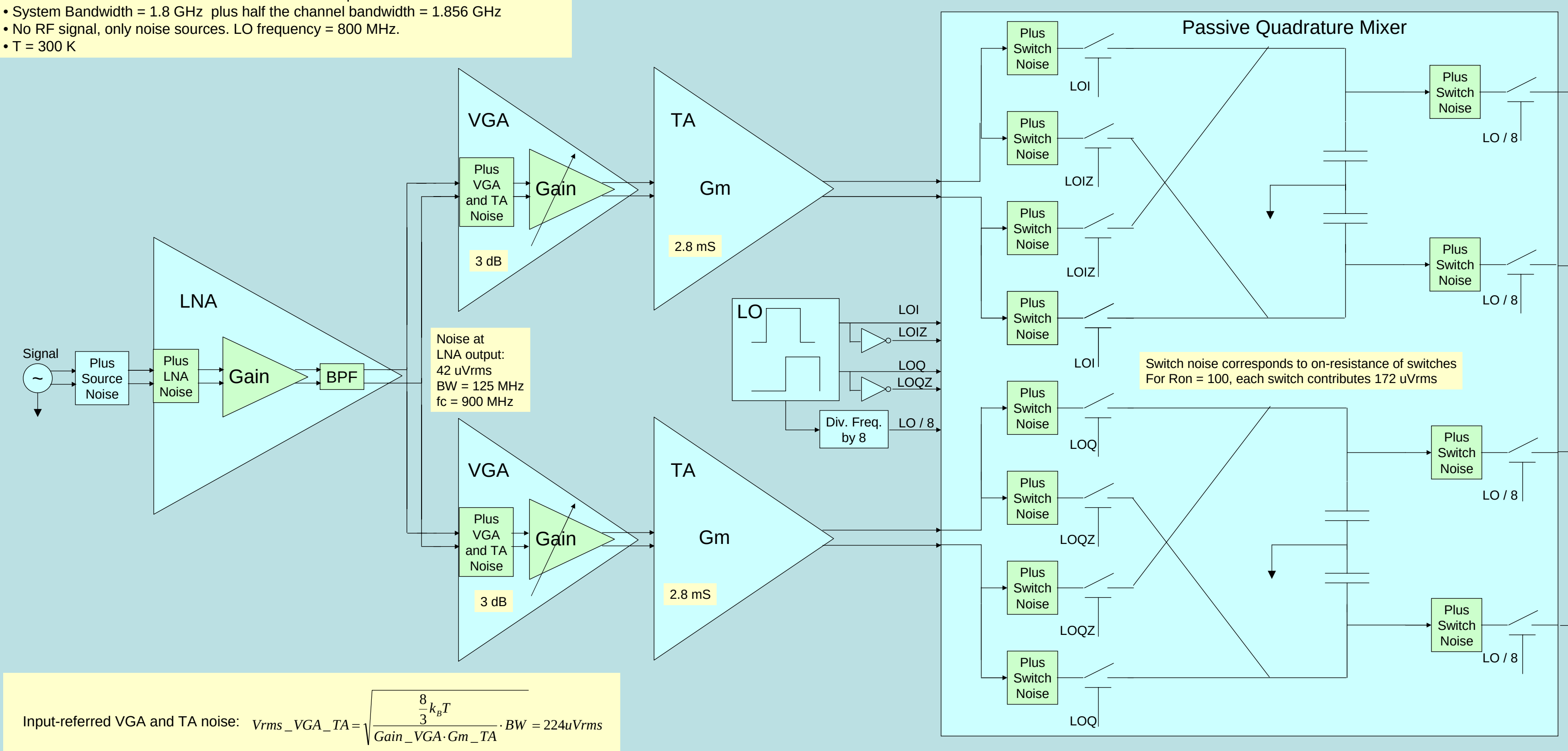
- An LNA has narrow-band noise at its output. Its model:
  - Amplifies its input (including noise) by its gain. (Including parameterized distortion factors.)
  - Adds its own noise (Instantiates a wide-band noise generator.)
  - Bandpass-filters the amplified input noise and its own noise.
- When validating the model, compare its output to the expected output noise level and spectrum, and adjust the BPF gain and filter characteristics accordingly

Time-domain Wide-Band Noise Verilog-AMS Code

```
inout Z1, Z2;                         // Noise generator input, output

parameter real RMS_noise_voltage = 129e-6;                 // Assigned noise voltage
parameter real System_Bandwidth = 2e9;                     // in 2 GHz system
parameter integer SEED = 0;           // Zero results in different noise sequences in
    // each run.  For identical noise each run, use SEED > 0, but if so, each  noise generator instance
   // must have a different SEED value, of course, or each noise generator will output the same waveform.

real ts;                              // Noise generator sample time
integer seedx;                        // The actual seed used by the random number generator
real vn;                              // Random number sample

initial begin
  ts = 1/(20*System_Bandwidth);       // Set the sampling time.  Noise spectrum is 10 * System_Bandwidth
end

analog begin
  @(initial_step("static")) begin
    seedx = (SEED == 0) ? $random:SEED;  // Either a random or fixed seed for random number generator.
    vn = 0.0;                            // Initial noise sample.
  end

  @(timer(0,ts)) begin                                     // Generate a random real number
    vn = RMS_noise_voltage * $rdist_normal(seedx,0,1.0);
  end
  V(Z1,Z2) <+ vn;                                          // Assign it to the voltage across inouts
end
```

Application: GSM Receiver Front End with Switched-Capacitor Passive Mixer

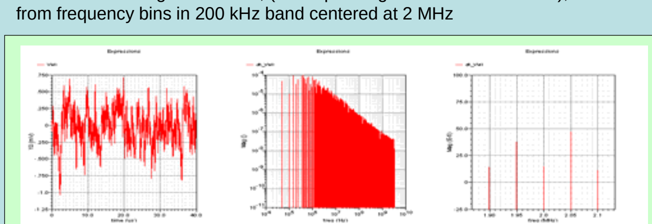
MODEL BLOCK DIAGRAM for noise simulation compared to lab measurement:
- System Bandwidth = 1.8 GHz plus half the channel bandwidth = 1.856 GHz
- No RF signal, only noise sources. LO frequency = 800 MHz.
- T = 300 K



Input-referred VGA and TA noise: $Vrms\_VGA\_TA = \sqrt{\dfrac{\frac{8}{3}k_B T}{Gain\_VGA \cdot Gm\_TA} \cdot BW} = 224uVrms$

Noise Simulation, Measured Results and Conclusions

APPROACH:
- Mixer output VMI = MI – MIN plotted and post-processed
- Discrete Fourier analysis performed with Waveform Calculator and plotted
- 40 us transient simulation yields 50 kHz frequency resolution
  - Simulation run time: 33 minutes, versus several hours for Pnoise.
- RMS noise voltage in IF band, (corresponding to lab measurements), calculated from frequency bins in 200 kHz band centered at 2 MHz



Transient Noise at Mixer Output   Noise Spectrum   Noise Spectrum within IF Band

Comparison of Simulation to Measurement

Signal	PNOISE Simulated Results	Noise Generator Simulated Results	Laboratory Measured Results
Mixer Output	27 uVrms	64.4 uVrms	119 uVrms

CONCLUSIONS:
- Behavioral models can be written to inject transient noise into their inputs or outputs
- Transient noise generator simulation is faster and more accurate than small-signal noise simulation of switched-capacitor systems

LESSONS LEARNED:
- A valuable method for evaluating the system-level effects of thermal noise
- Further investigation is required to find the source of discrepancy between simulated and measured output noise such as
  - Transient noise generator levels may have been based on overly optimistic device level noise models
  - Lab-measurements may include interference as well as thermal noise
  - Possible mistake in de-embedding of device from signal source, matching, buffer, instruments

Contact Robert.Peruzzi@Infineon.com for further behavioral modeling information or access to source code for these models.