Demystifying Noise Simulation in RF Circuits
Spectre APS and RF Option

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Many different types of circuits – Many “flavors” of noise

- Linear Time Varying
  - LNAs
  - Mixers
  - Oscillators: Xtal, LC, Ring
  - Switched-Capacitor Filters
  - Digital/divider Circuits
- Linear Time Invariant
  - Linear Filters
- Non-periodic
  - $\Delta\Delta$, ADCs, PLLs
  - SerDes and PHYs

Small-signal
- Periodic
- Non-Linear Time Varying
  - Pnoise
  - HBnoise
  - Phase Noise
  - Jitter
  - Jee, Jcc, Jc
  - Noise Summary
  - Full-spectrum
  - Jitter Noise Figure, Output Noise

Large-signal
- ViVA/Calculator
  - Post Process Functions
- Spectrum
- PSD
- Transient Noise

Rectangular Plots: NF, Output Noise

Smith Chart: Noise Circles

Noise (ac)
Noise (sp)
Linear 2-Port Noise
Noise Circles
Types of noise analysis in Spectre platform

• Noise analyses used for linear time invariant (LTI) circuits:
  – Sp noise analysis (sp) – Linear 2 port noise analysis. Done after S-parameter analysis.
  – Noise analysis (noise) – An ac noise analysis

• Small-signal noise analyses for (non) linear periodic time varying circuits:
  Pnoise/HBnoise analysis
  – Time averaged noise
    – USB, LSB, AM, PM
    – Use for mostly sinusoidal signals
  – Sampled noise
    – Time domain
    – Jitter
    – Use for pulsed or square-wave signals

• Noise analysis for non-periodic circuits: Transient noise
  – Usually used when noise, pnoise, or hbnoise cannot be used
  – Long runtimes
  – Works for any type of circuit except oscillators
Linear time invariant noise: Noise and sp analyses

Circuit is first linearized about the DC operating point

- **noise**: Computes the total-noise spectral density at the output. NF and F can also be computed.

- **sp**: Computes S-parameters of the circuit taken as an N-port. When noise selected, computes:
  - Noise correlation matrix
  - Linear two-port noise parameters (F, Fmin, NF, NFmin, Gopt, Bopt, and Rn)
  - Noise circles plotted on Smith Chart
Periodic Time-Varying circuits: pnoise/hbnoise simulation principles

Periodic steady state operating point calculated using pss/hb analysis prior to pnoise/hbnoise.

Three basic steps:

1. Identify an output node and frequency range (sideband) for the circuit

2. Calculate the PXF (Periodic XF) gains from the harmonic sidebands of each noise source to the output sideband

3. Multiply the sideband noise by the calculated gain and add them across each sideband and source to calculate the output noise

All noise types (timeaveraged, jitter, timedomain) perform the same basic operations
Flavors of pnoise/hbnoise: Timeaverage

Timeaverage is single-sided spectrum and harmonic referred (modulated) noise analysis

USB: equivalent to what is usually measured by a spectrum analyzer (with sufficiently low resolution bandwidth).

AM, PM: Computes the AM and/or PM components of output noise

ALL (AM/PM, USB, LSB): Computes the output noise spectral density in the upper sideband, the lower sideband, in addition to their correlation. The correlation term is used to compute the AM and PM components of output noise.

Oscillator FM jitter:

Full-spectrum pnoise: Recommended for the Shooting engine.

Note:
- Driven circuits: Noise is averaged over one period of the LO or clock cycle
- Oscillators: Used to measure the single sideband (SSB) total (AM+PM) noise that is averaged over the entire cycle of the oscillator waveform.

AM/PM: assumes output (1st harmonic) modeled as

\[ v(t) = A(1 + \frac{a(t)}{A})\cos(\omega_c t + \phi(t)) \]
Of special mention

- **Full-spectrum pnoise**
  - Useful for circuits like switched-capacitor filters or sampling circuits where aliasing occurs through very high harmonics of the clock
  - The runtime advantages are large with no loss in accuracy of the result
  - Available using the Shooting pss engine with Spectre® APS, all noise types
  - Does not require setting sidebands in most cases (if PSSfund<100K, then set maxsidebands=(1/f noise corner freq)/PSSfund

- **FM Jitter**
  - Subset of timeaverage noise under PM noise
  - Post processing option of PM pnoise for oscillators

- **Shooting pnoise**
  - Recent close-in phase noise accuracy improvements
Flavors of pnoise/hbnoise: Timedomain

- Noisetype=timedomain is a strobed noise analysis.
- Usually applied to driven digital dividers or oscillators that drive digital dividers where the average noise over the entire waveform is not appropriate.
- Noise matters only at the exact time where the trigger event is generated.
- User supplies list of times from the time-domain waveform. Noise analysis is performed at those instants in time, and the noise voltage is calculated at each timepoint.
- Once the noise voltage is known, the timing uncertainty can be determined by integrating the noise power, converting back to a voltage, and dividing by the slew rate at that instant.
- Sampling operation assumed to be ideal, performed mathematically.

tdnoise assumes output noise is sampled by an ideal periodic sampler.
Flavors of pnoise/hbnoise: PM jitter

Noisetype=jitter is derived from “timedomain” noise.

- Define jitter as the PSD (power spectral density) of the sequence of random timing delays between the ideal and the noisy waveform.

- Timing jitter is induced by voltage noise at the crossings, and related to the slope of the large-signal crossings at a user-defined threshold.

- Noisetype=jitter performs “timedomain” noise analysis at the large-signal crossing, and converts sampled noise to jitter.

Both noisetype=timedomain and noisetype=jitter are not only useful for digital dividers, but for all level-sensitive (“digital”) circuits. It is also useful for sampled circuits such as switched-capacitor filters.

\[ J(f) = \frac{S_n(f)}{\text{Slope}^2} \]

\( J(f) \) in above equation is in \( \text{s}^2 / \text{Hz} \).

To get actual jitter, you need to integrate \( J(f) \) and take the square root.
Transient noise simulation

• Performs like a regular transient analysis, with all noise sources in the circuit injecting random noise signals into the simulation at each time step

• Thermal, shot, and flicker noise from device models. Frequency dependent noise file supported

• The key technology that enables time-domain noise analysis is the ability to properly inject random device noise at each time step

• Parameters control things like bandwidth of random noise sources, lowest interested frequency of noise PSD, etc.

• Post processing of transient noise done using waveform calculator: DFT, PSD, spectrum, eye diagram, jitter
## General noise analysis recommendations for various circuits

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<td><strong>Linear/weakly non-linear circuits</strong></td>
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| OPAMPS Filters                    | DC                       | noise or sp noise | ▪ Noise summary is provided.  
▪ Sp noise results can be plotted on Smith or rectangular Chart. (e.g. noise circles) |
| LNAs by themselves               |                          |                |                                                                                  |
| Chopper Stabilized Amplifier     | DC or Shooting PSS       | noise or pnoise |                                                                                  |
| **Nonlinear, non-periodic circuits** |                          |                |                                                                                  |
| Sigma-Delta ADCs Fract-N and Int-N PLLs SerDes and PHYs | Tran | Transient noise | ▪ Large signal noise analysis.  
▪ No noise summary is provided.  
▪ Must use noiseon/noiseoff feature |
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<td>LNA with mixers or mixers</td>
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<td>HBnoise is preferred.</td>
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<td><strong>Oscillators</strong></td>
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<td>LC oscillator</td>
<td>PSS/HB</td>
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<td>HBnoise is preferred.</td>
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<tr>
<td>Crystal oscillator</td>
<td>HB</td>
<td>HBnoise</td>
<td>If Shooting must be used, the method option must be set to traponly</td>
</tr>
<tr>
<td>Ring oscillator</td>
<td>PSS Shooting</td>
<td>Pnoise</td>
<td>Pnoise is preferred.</td>
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<td>PSS Shooting</td>
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<td>Switched capacitor S&amp;H</td>
<td>PSS Shooting</td>
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Individual noise contributions – Small signal noise analysis vs. transient noise

• Small-signal noise analysis
  – Allows computing individual contributions of every noise source in the circuit to the output noise spectral density
  – Composite noise spectral density is calculated afterwards as mean-square sum.
  – Ac noise, sp noise, pnoise, hbnoise

• Large signal noise analysis
  – Used when large signal steady state response is unavailable (no dc, hb, pss)
  – Equations are non-linear and individual noise contributions cannot be easily separated
  – noiseon and noiseoff feature used to calculate noise contribution from a device or circuit block, perform transient noise simulation repetitively with noise contribution from certain devices or blocks turned on or off
  – Transient noise
Demo and Related Content

• Demystifying Noise Simulation in RF Circuits: Spectre APS and RF Option (Video)

This video is a demo that complements the IMS microApp paper (with same title) presented at the IEEE International Microwave Symposium in May 2016. The video shows the new HBnoise GUI in IC6.1.7 Virtuoso with MMSIM15.1. The new HB/HBnoise Choosing Analyses forms are described and simulation of a simple oscillator performed. Next, the updated Direct Plot form is used to plot oscillator phase noise and hbnoise separation by sideband number. The video ends with a demonstration of printing Noise Summary results from various noise contributions (AM, PM, USB, etc.).

• Improvements to Pnoise / HBnoise Analysis in MMSIM15.1 and IC6.1.7 (Article)
Additional Notes for Advanced Users
High Q LC oscillator circuit is followed by a hard switching buffer

- If the output of the buffer is applied to a mixer where the entire waveform contributes noise to the system, then pnoise/hbnoise timeaverage should be used.
- If the output of the buffer drives a circuit which has a threshold e.g. a divider, then hbnoise pm jitter should be used.
- Many harmonics will be required in hb. This will slow hbnoise.

- When HB is used:
  - Set the number of harmonics to the period divided by the fastest rise/fall time in the circuit.
  - Set oversample to 2.
  - The risetime here is calculated by taking the highest slew rate in the transition, and calculating the 0 to 100% risetime based on that maximum slew rate.
Additional Notes:
When to Use Transient Noise

Use Transient Noise for circuits input and output are periodic, but circuit does not have a periodic or quasi-periodic steady state:

• ADC (typically has a number of threshold detectors)
  When analog input of threshold detector is close to the threshold voltage, a small variation of the input, due to the thermal noise can cause a state transition at the output - a large voltage change.

• Fractional-N PLL circuit
  Random dithering in the divider ratio is used to maintain non-integer ratio between output clock and reference clock frequencies, to avoid spurs in the output spectral density. While both the input and output of the circuit are periodic, the circuit does not have periodic or quasi-periodic steady state, due to the random dithering of the divider ratio
Additional Notes for Advanced Users
Guidelines for using Transient Noise analysis on a PLL circuit

Oscillator in the PLL generates most noise in the PLL circuit

- Sinusoidal oscillator:
  Setting noisefmax larger than the 3rd harmonic frequency is sufficient because the oscillator doesn’t produce much power in the higher harmonics to mix down with.

- Ring oscillator (or “square-ish” waveforms):
  Because there is power at the higher harmonics to mix with, must go higher in frequency with noisefmax. As a guideline for setting noisefmax, look at the spectrum and determine the harmonic that is about 20dB smaller than the fundamental.
Reference

• Testcase database, Scripts and references can be found at ‘Attachments’ and ‘Related Solutions’ sections below the PDF.

• This pdf can be searched with the document ‘Title’ on https://support.cadence.com