Circuits and Techniques for High-Resolution Measurement of On-Chip Power Supply Noise

Elad Alon¹,², Vladimir Stojanovic¹,², and Mark Horowitz¹

¹ Stanford University
² Rambus Inc.
Motivation and Challenges

• Scaling leads to drastic reduction in required supply grid impedance.
  • $Z \alpha$ scaling factor$^2$
  • Achieving this low impedance (across all frequencies) is hard.
    • Supply noise becoming a concern even for standard digital circuits.

• Measuring supply noise for general chip operation is very challenging.
  • 20 GS/s, 8-bit ADC’s aren’t cheap.
Traditional Measurement Approaches

• Previous works rely on sub-sampling oscilloscope (or similar) approaches.
  • Accurately measure repetitive waveforms.
  • Collect information about distribution of supply noise.
• Limitation: dynamics of supply noise during normal operation can’t be measured.
  • Need to know distribution & spectrum of noise to characterize effects on analog or mixed signal circuits.

• This work: Treat supply noise as a random process, and find its spectrum by measuring autocorrelation.
  • Autocorrelation can be measured with only 2 samplers (without high sampling rate).
Outline

- Random Supply Noise and Autocorrelation
- Measurement circuits
- Measurement results
- Conclusions
Random Supply Noise

- Supply noise is basically deterministic.
  - But extremely complicated to calculate.

- Model supply noise as a random process.
  - Characterized by its spectrum or autocorrelation.
Autocorrelation

- Autocorrelation is a measure of how correlated the process is with itself at a different point in time.
  - Autocorrelation $R(\tau) = \mathbb{E}[V(t-\tau/2) \cdot V(t+\tau/2)]$
  - For a zero mean process, $R(0) = \sigma^2$

- The power spectral density (PSD) of a process is the Fourier Transform of $R$.
  - High bandwidth – narrow $R$
  - Low bandwidth – wide $R$

- These definitions hold for stationary (time-invariant) processes.
  - Is supply noise really stationary?
Autocorrelation (cont’d)

• Chip clocks modulate occurrence of noise events.
  • Modulation is repetitive – supply noise is cyclostationary
    • At same time point in each cycle, noise statistics are the same.

• Cyclostationary processes characterized by autocorrelation (PSD) at each point in time.
  • Stationary: $R(\tau)$
  • Cyclostationary: $R(t, \tau)$

• Autocorrelation is an average statistical property.
  • Don’t need to know signal at every point in time – just need pairs of signal values.
  • Nyquist frequency set by minimum $\tau$ (not by sampling rate).
    • Greatly reduces throughput requirements of sampling circuits.
  • For cyclostationary measurement, just need to be able to lock sampling instant to a time point in the cycle.
**Measurement Circuits**

- External pulse generator controls sampler timing.
- Supply noise on the chip is by definition variation of on-chip $V_{dd}$ relative to on-chip $V_{ss}$.
  - Samplers must be on-chip to avoid reference issues.
- Sampling switches are the only components in the system that are required to have high bandwidth.
- Calibration relaxes linearity and offset requirements of A/D converters.
  - Allows compact and simple on-chip implementation.
Sampling switches

- PMOS switches to achieve required bandwidth.
- Separate, higher than nominal supply
  - $V_{ddQ} = 1.3\, V$
  - Minimizes coupling between $V_{dd}$ and sample node during hold.
- Noise on $V_{ddQ}$ capacitively couples to sample node through switch parasitics.
- $V_{ddQ}$ heavily decoupled to $V_{ss}$. 
VCO Converter

- VCO acts as V-to-f, clock edge count gives digital estimate of $f$.
- $1\ \text{LSB} = 1/(T_{\text{win}}K_{vco})$
- Measuring **average** VCO frequency – insensitive to high frequency noise.
- Noise on same time scale as counting window unfiltered however.
  - Measurements show that decap + regulator keep VddQ well-coupled to on-chip Vss at these low frequencies.
VCO Converter (cont’d)

- Oscillator phase random w.r.t. counting window
  - Adds uniformly distributed noise with magnitude of 1 LSB.
  - Increases effective resolution with external averaging.
- Multi-phase information from VCO can increase resolution.
  - May be desirable in leaky processes.
- V-to-f curve can vary with temp.
  - Causes gain and/or offset errors
  - Local thermometer (e.g. VCO driven by a relatively constant voltage) can compensate for errors.
Measurement Results

- Measurement circuits implemented in 0.13 μm process with 4 1-10 Gb/s serial links.
  - Can measure digital (V_{dd}) and analog (V_{ddA}) supplies.
  - Noise generators to validate measurement system.

![Graph showing VCO Converter 1 and VCO Converter 2]

- \( K_{vco} \approx 2.6 \text{ GHz/V} \)
- With 1 μs conversion window:
  - 1 LSB = 385 μV
Measurement System Validation

- Key accuracy concern:
  - Is $V_{ddQ}$ really quiet at low frequencies?

- Use noise generators to inject square-wave currents onto grid (chip inactive).
  - If $V_{ddQ}$ not coupled to $V_{ss}$, $V_{ddQ}$ moves in same direction as $V_{dd}$.

- Converter integrates signal
  - If $T_{win} = \text{noise pulse-width}$, measured waveform (using oscilloscope technique) will have triangular characteristics
  - Height of triangle indicative of $V_{ddQ}$ noise level.
• Inject noise onto $V_{ddA}$ at 1 MHz and at 4 MHz
• Twin = 500 ns
• Height of “triangle” for 1 MHz noise is negligible.
  • $V_{ddQ}$ noise is minimal.
Autocorrelation Measurement Validation

- Inject 32 MHz square noise onto $V_{dd}$.

- PSD scaled by Nyquist frequency to calculate power.
  - Unit: dBV (instead of dB $V^2$/Hz)
  - In dBV, average level roughly corresponds to noise $\sigma$.

- Odd harmonics from square waveform
Measured Supply Noise: Deterministic Noise

- All 4 links running at 4 Gb/s, $2^{31}$ PRBS data.
  - Check for deterministic waveform with single sampler.

- 3 major noise frequencies:
  - 200 MHz (ASIC core)
    - Core shares $V_{ss}$ with links; noise due to ground bounce.
  - 400 MHz (ref clock & some link logic)
  - 4 GHz (data and edge clocks at 2 GHz)
- Engage second sampler and measure stationary (or average) PSD.
  - Deterministic noise dominant.
  - Random noise appears to be white in nature.
- This is the noise that non-periodic circuits will see.
  - Noise appears white b/c it has been time-averaged.
Cyclostationary Noise

- Cyclostationary noise distribution and PSD are different at each point in time.
  - Measuring PSD at all time points takes extremely large number of samples.

- Measure PSD of random noise at two different times to observe example behavior.
  - Reduce link data-rate to 2 Gb/s to make cyclostationarity more apparent.
    - Majority of logic should complete before the end of the cycle, causing period of relative calm on the power supply.
Measured Supply Noise: Cyclostationary PSDs

- Measurement verifies cyclostationary behavior.
  - 1 GHz noise at $t_2$, but not at $t_1$.
- Link clock is 1 GHz for this data-rate
  - Link relatively quiet at $t_1$, active at $t_2$. 
Conclusions

- 2 low-rate samplers can successfully measure entire frequency spectrum of supply noise.
  - Low-rate and calibration allow use of simple VCO ADC’s for high-resolution measurements.

- Measured both deterministic and random components of supply noise.
  - ~20 mV peak-to-peak deterministic noise on both digital and analog supplies.

- Verified cyclostationarity of random supply noise.
  - Need to extend modeling techniques for synchronous circuits (e.g. PLLs) to handle cyclostationary noise.

- Integrated supply noise measurement circuits allow designers to characterize effects of noise on their circuits using real, measured noise spectrums.