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

Elad Alon[1,2], Vladimir Stojanovic[1,2],
and Mark Horowitz[1]

[1] Stanford University
[2] Rambus Inc.

Motivation and Challenges

- Scaling leads to drastic reduction in required supply grid impedance.
  - Z α 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

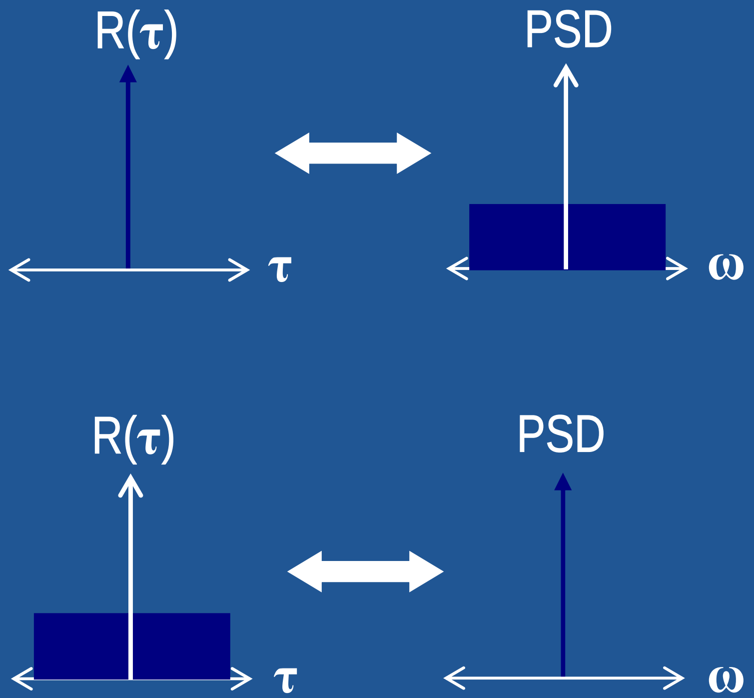
Random Supply Noise

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

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

Autocorrelation

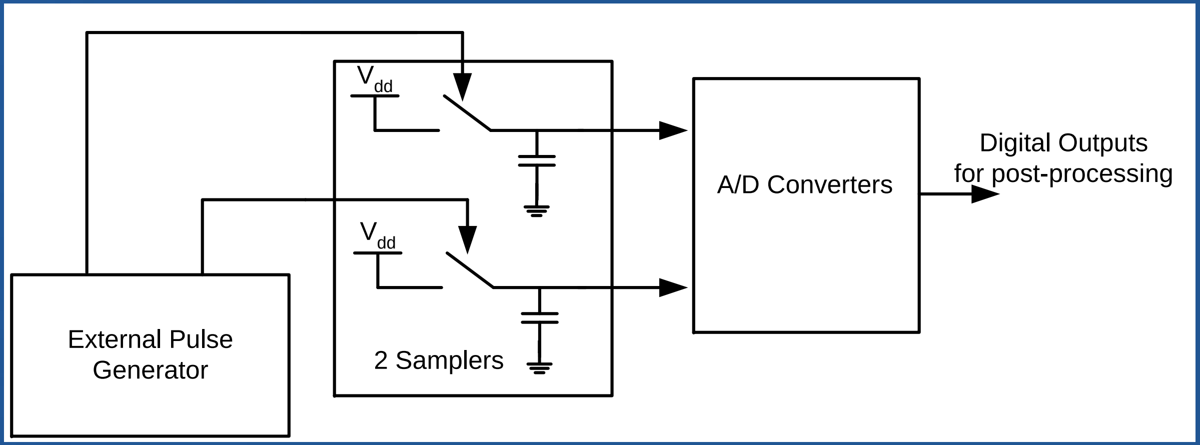
- Autocorrelation is a measure of how correlated the process is with itself at a different point in time.
    - Autocorrelation $R(\tau) = E[V(t-\tau/2)\cdot V(t+\tau/2)]$
    - For a zero mean process, $R(0) = \sigma^2$
- The power spectral density (PSD) of a process is the Fourier Transform of R.
    - High bandwidth – narrow R
    - Low bandwidth – wide R
- These definitions hold for stationary (time-invariant) processes.
    - Is supply noise really stationary?



Autocorrelation (cont'd)

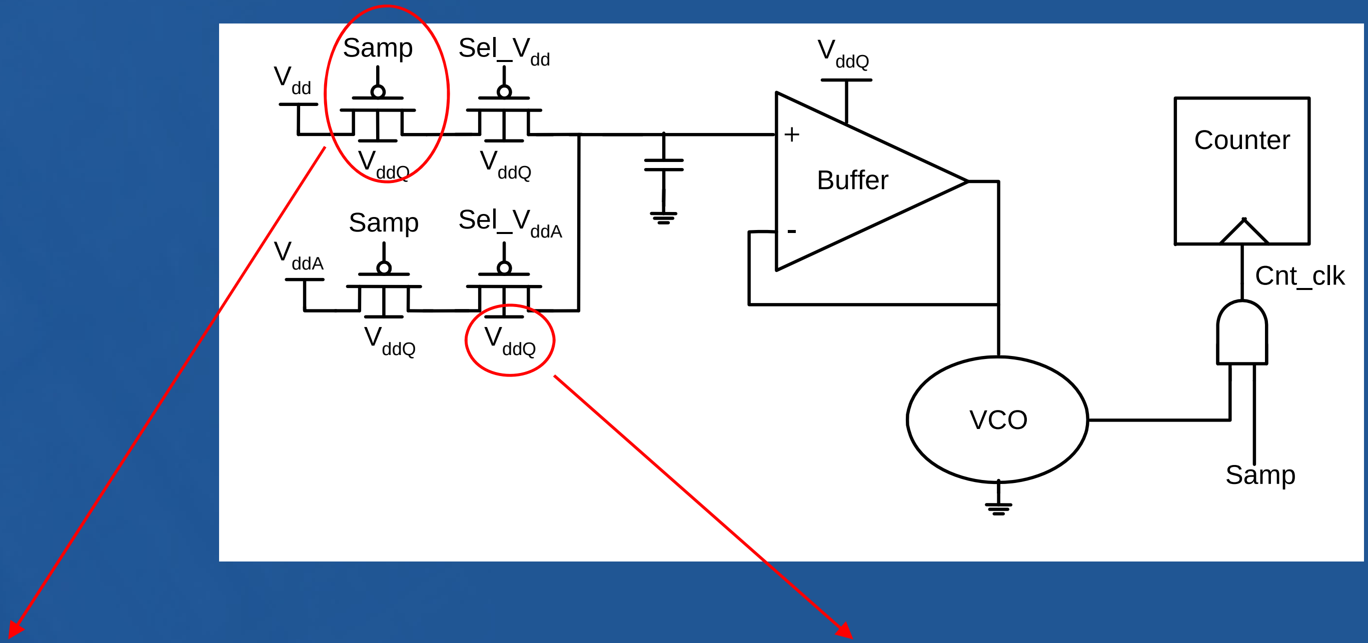
- Chip clocks modulate occurrence of noise events.
  - Modulation is repetitive – supply noise is cyclostationary
    - At same time point in each cycle, noise statistics are the same.
- Cyclostationary processes characterized by autocorrelation (PSD) at each point in time.
  - Stationary: $R(\tau)$
  - 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 τ** (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.

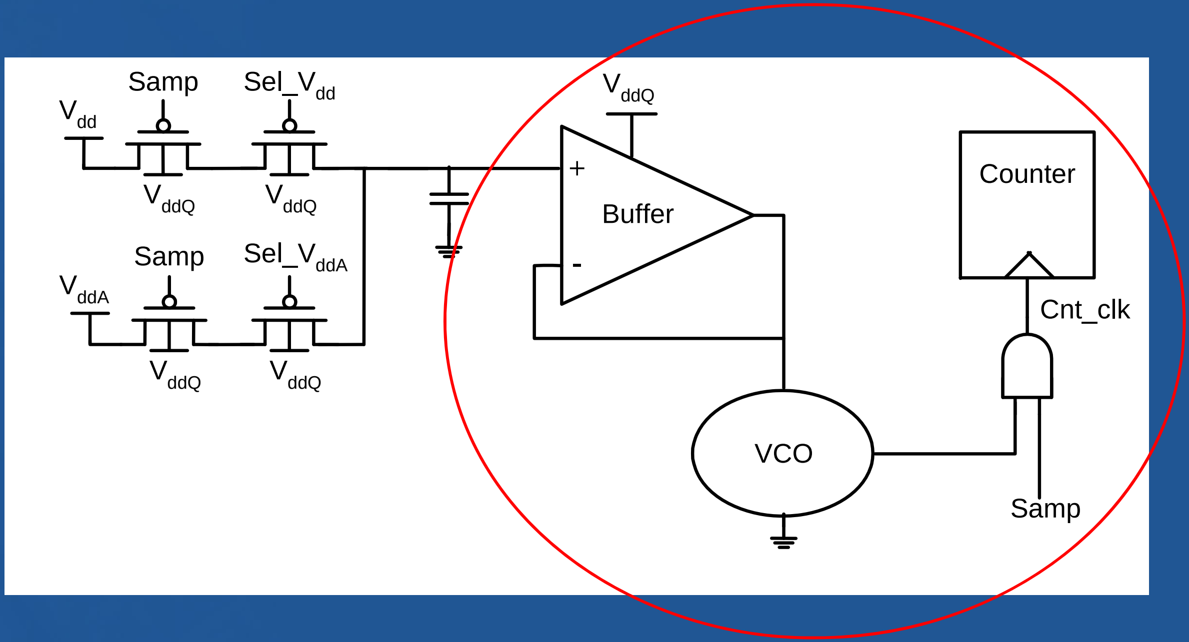
Sampling switches



- PMOS switches to achieve required bandwidth.

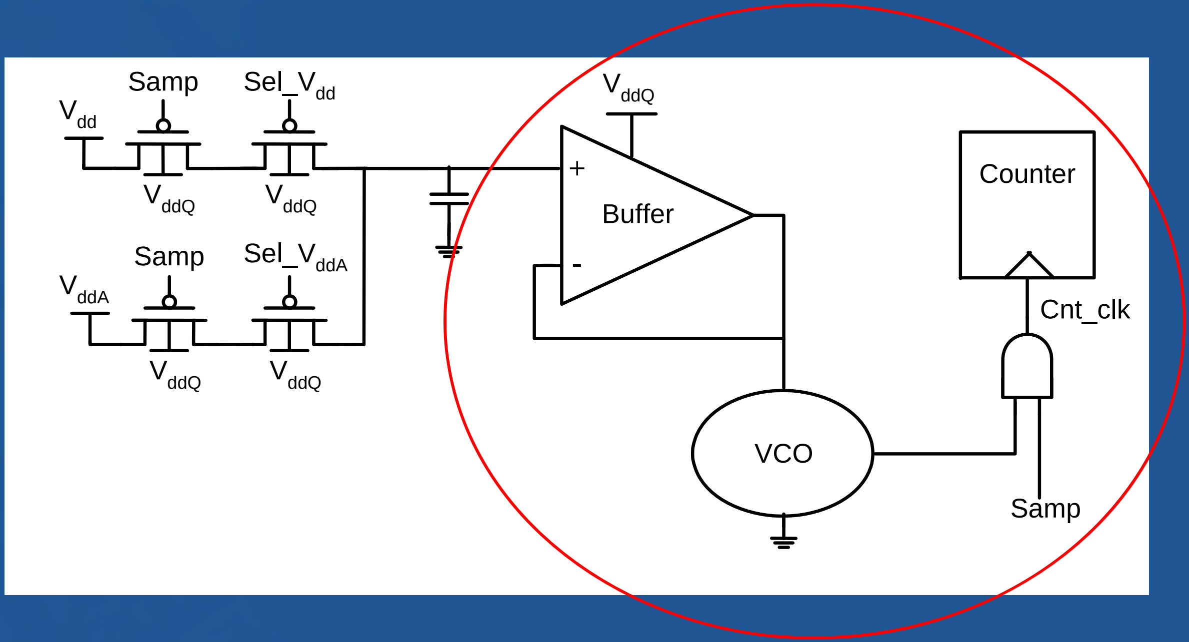
- Separate, higher than nominal supply
  - V_{ddQ} = 1.3 V
  - Minimizes coupling between V_{dd} and sample node during hold.
- Noise on V_{ddQ} capacitively couples to sample node through switch parasitics.
  - V_{ddQ} heavily decoupled to V_{ss}.

VCO Converter



- VCO acts as V-to-*f*, clock edge count gives digital estimate of *f.*
- 1 LSB = $1/(T_{win}K_{vco})$
- 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.

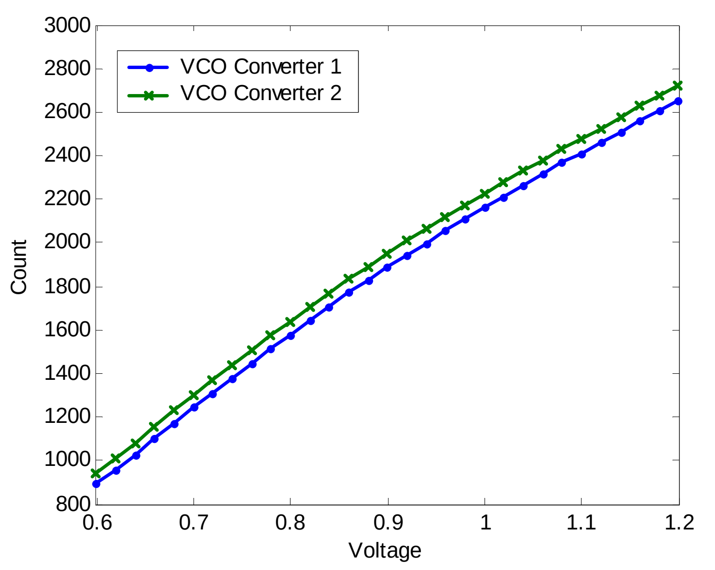
VCO Converter (cont'd)



- 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

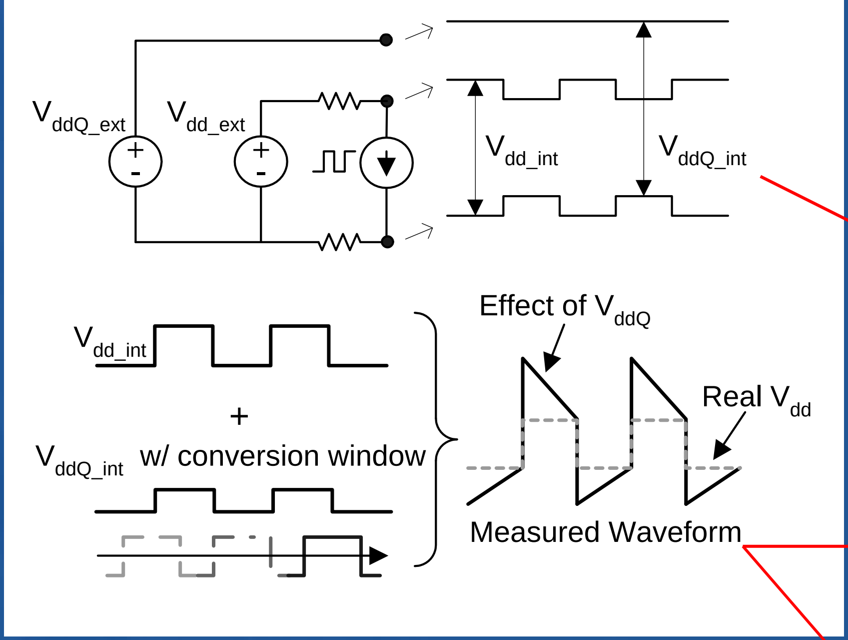
- Measurement circuits implemented in 0.13 μm process with 4 1-10 Gb/s serial links.
  - Can measure digital (V_{dd}) and analog (V_{ddA}) supplies.
  - Noise generators to validate measurement system.



- $K_{vco} \approx 2.6$ GHz/V
- With 1 μs conversion window:
  - 1 LSB = 385 μV

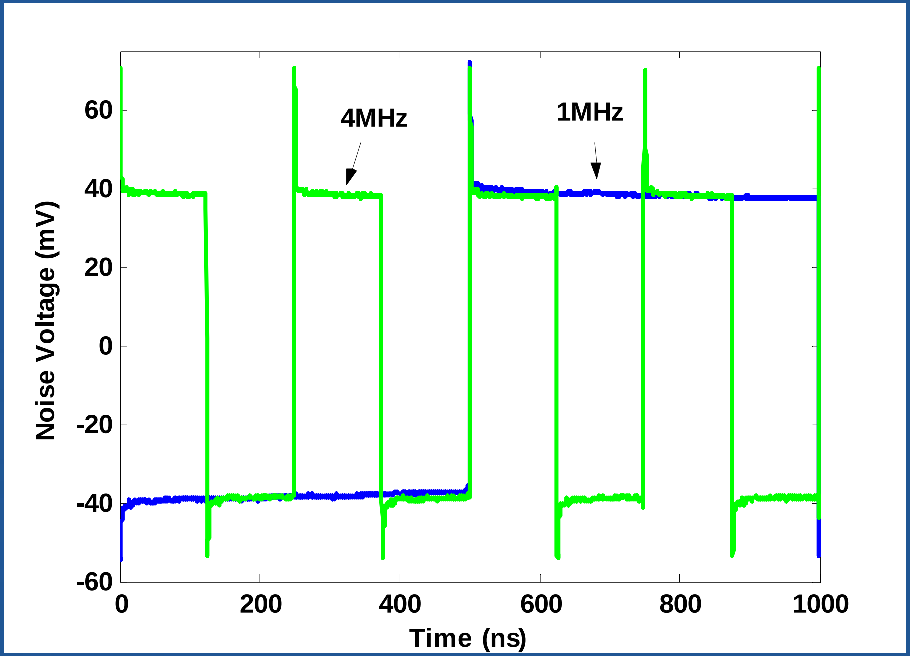
Measurement System Validation

- 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} = noise pulse-width, measured waveform (using oscilloscope technique) will have triangular characteristics
  - Height of triangle indicative of V_{ddQ} noise level.

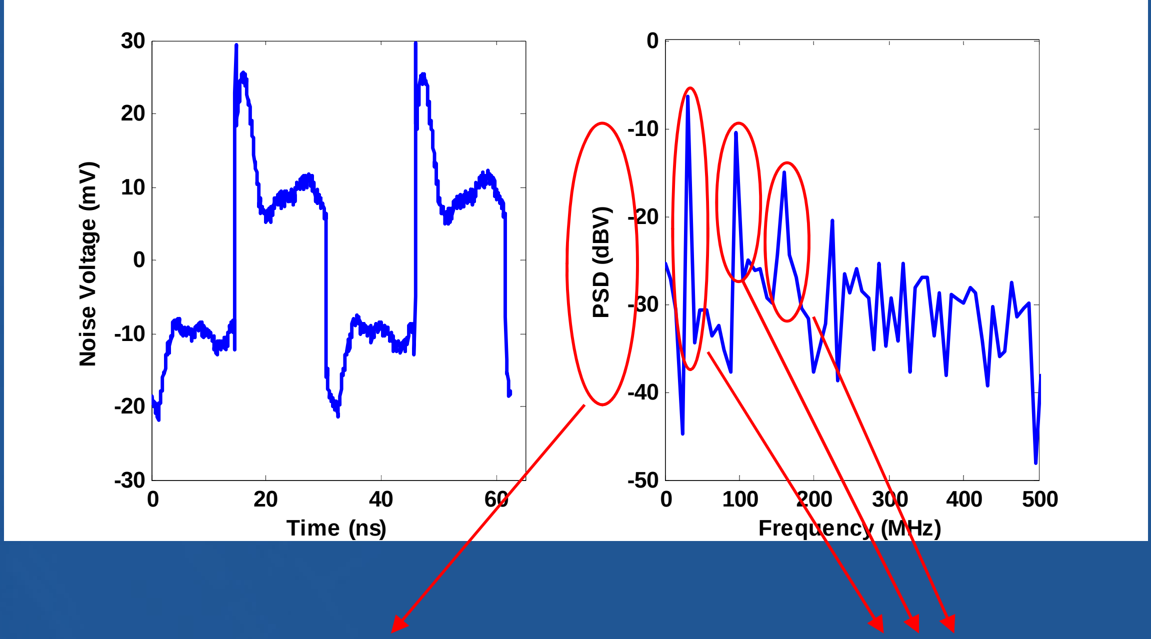
Measurement System Validation (cont'd)



- 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

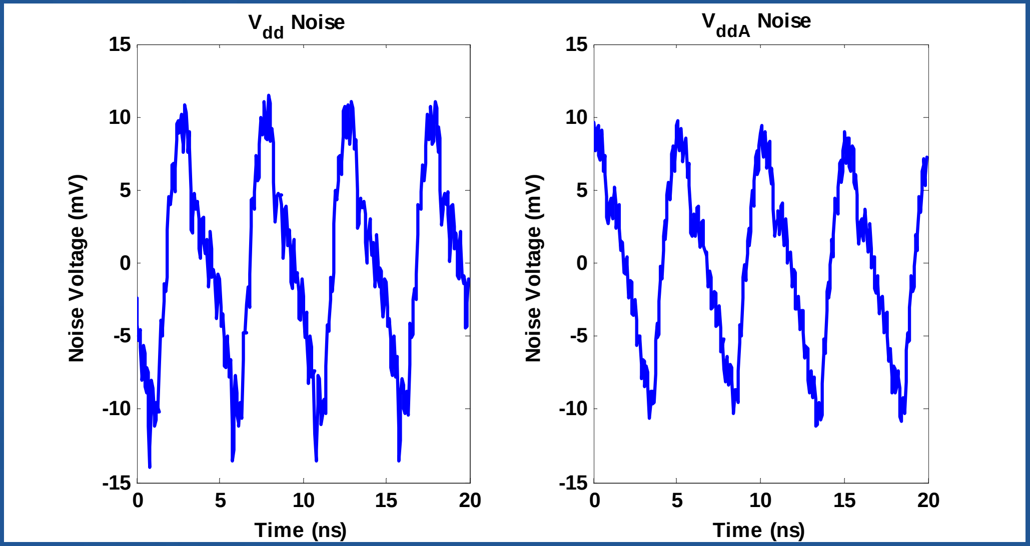
- Inject 32 MHz square noise onto V_{dd}.



- PSD scaled by Nyquist frequency to calculate power.
  - Unit: dBV (instead of dB V^2/Hz)
  - In dBV, average level roughly corresponds to noise σ.
- Odd harmonics from square waveform

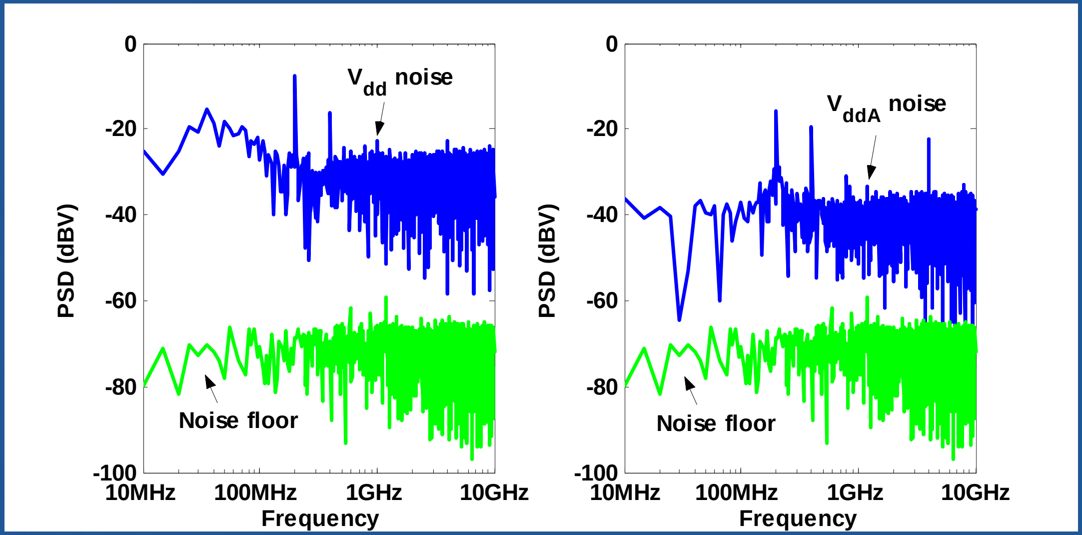
Measured Supply Noise: Deterministic Noise

- 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)

Measured Supply Noise: Stationary PSD



Noise floor measured w/chip disabled.

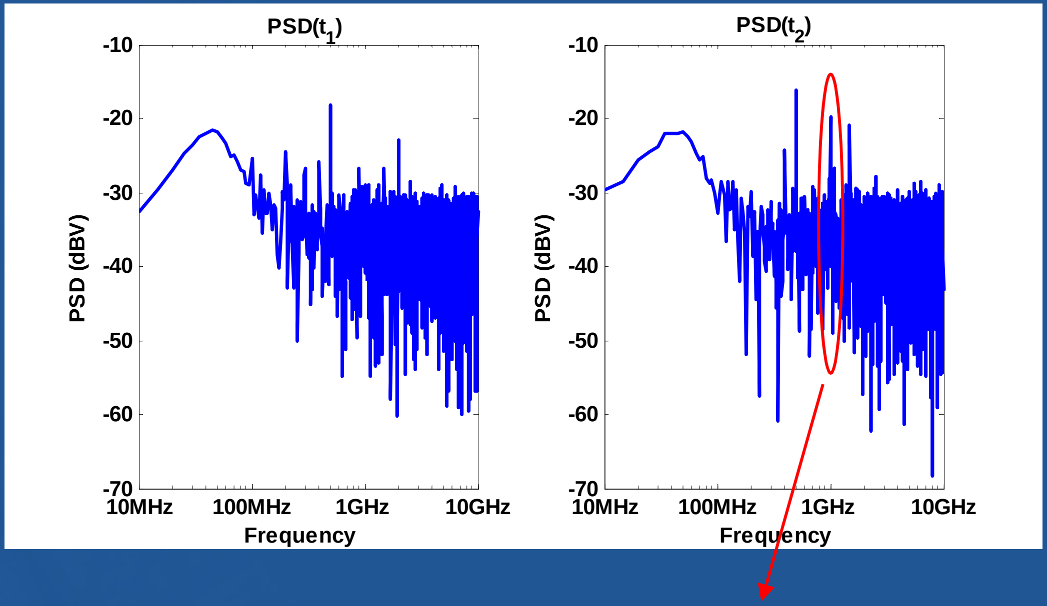
- Engage second sampler and measure stationary (or average) PSD.
  - Deterministic noise dominant.
  - Random noise appears to be white in nature.
- This is the noise that non-periodic circuits will see.
  - Noise appears white b/c it has been time-averaged.

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.