Measurement and Regulation of On-Chip Supply Noise

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Scaling and Supply Impedance

- CMOS scaling led to lower supply voltages and constant (or increasing) power consumption
- This forces drastic drop in supply impedance
  - Even at constant power:
    - $V_{dd} \downarrow$, $I_{dd} \uparrow \rightarrow |Z_{required}| \downarrow \downarrow$
- Today’s chips:
  - $|Z_{required}| \approx 1 \text{ m}\Omega$
- Hard to achieve across broad frequency spectrum
  - Supply voltage will be noisy
Outline

• Motivation

• Supply Noise Measurement

• Regulation and Power Efficiency

• Conclusions
Review of Previous Approaches

- Sub-sampling to avoid high-speed interfaces or converters
  - Just like equivalent time oscilloscopes
- Very good at measuring repetitive (deterministic) waveforms
  - Can also collect statistical distribution of noise
- However, can’t measure “random” noise dynamics
Measured Supply Noise from 90nm Itanium Microprocessor

Measuring “Random” Supply Noise

• Supply noise is basically deterministic
  • But extremely complicated to calculate

• “Noise” is a label for a random process
  • Can be characterized by its frequency spectrum

• Measure **autocorrelation** to find spectrum of supply noise
  • Extension of sub-sampling technique
  • Only needs 2 low rate samplers
Autocorrelation Review

- Autocorrelation measures how correlated a process is with a delayed version of itself.

- For a stationary (time-invariant) process:
  - \( R(\tau) = E[V(t-\tau/2) \cdot V(t+\tau/2)] \)

- Power Spectral Density (PSD) is Fourier Transform of \( R(\tau) \):

  Band-limited Noise:

  \[ R(\tau) \quad \tau \]
  \[ \text{PSD} \quad \omega \]
Measuring Autocorrelation

- Autocorrelation is an average property
  - Don’t need V for all t – just need sample pairs

- Nyquist frequency set by minimum $\tau$
  - Not by sampling rate

- Can extend to cyclostationary noise too
  - Noise properties vary repetitively with time
Measurement System Block Diagram

Sampler Implementation

Sampling Switch

VSD

Vsd*

VCO-based ADC

Buffer

Vdd*

Vdd

Counter

Cnt_clk

VCO

Samp

Samp

VCO-based ADC
VCO-based ADC

- **Simple, cheap ADC**
  - Scan circuitry bigger than ADC

- **High Resolution**
  - $1 \text{ LSB} = \frac{1}{(T_{\text{win}}K_{\text{VCO}})}$
  - Can increase resolution with external averaging too
    - VCO random phase creates dither – whitens the quantization noise

- **Bad accuracy**
  - But don’t care since we’re calibrating
Measured Chips

- Measurement circuits included in several chips:
  - Rambus (0.13 µm, 90 nm SOI), Intel/HP (90 nm, 45 nm), AMD (65 nm SOI), TI (90 nm), NEC (90 nm)

- 1st chip: Rambus 0.13 µm serial transceiver
  - Could measure $V_{dd}$ (link digital supply) and $V_{ddA}$ (link analog supply)
Measured PSD

- Measured PSDs with system off (noise floor), then all 4 links running at 4 Gb/s
- Peaks mostly from repetitive waveform
  - 4 GHz on $V_{ddA}$: differential 2 GHz clock
- Random noise has some peaking on $V_{dd}$
  - Otherwise looks white
Averaging-Based Measurement

- Exploit VCO dither:
  - Averaging dithered low-resolution samples can reconstruct waveforms and autocorrelation
- Sampling switch was for long $T_{\text{win}}$ (to get resolution)
  - Low resolution $\rightarrow$ short $T_{\text{win}}$
  - No need for sampling switch

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Supply Noise and Digital Logic

- Since gate delay depends on $V_{dd}$:
  - To hit a desired frequency
  - Need to guarantee some minimum voltage

- Supply variations force higher nominal voltage
  - Looks like another source of power loss

- Can regulators be efficient enough to improve power by reducing noise?
  - Regulator power needs to be less than recovered power
Linear Regulators

**Series Regulator**

**Shunt (Parallel) Regulator**
Improved Efficiency with Series Regulator?

- Clearly won’t meet efficiency goal:
  - Regulator doesn’t really change noise on $V_{dd}$
  - So still need same margin
  - But added an extra $V_{drop}$ from variable resistor…
Improved Efficiency with Shunt Regulator?

- Regulator can only pull current out of supply
  - To counter noise in both directions, need to burn significant static current
  - Again, clearly inefficient

- Need to allow shunt to deliver energy to the load
  - Not just dissipate it
Push-Pull Shunt Regulator

- Use an additional, “shunt” supply to push current into $V_{reg}$
  - Regulator capable of countering large variations
  - But regulator loss set mostly by (significantly smaller) average variation

- Similar to Active Clamp* for board VRMs
  - Build on previous work to improve on-die impedance

Quiescent Output Current

- Went to push-pull to minimize regulator power overhead
- But many designs have significant $I_{\text{static}}$
- Similar issues in RF and audio power amplifiers
  - In all cases, need to efficiently deliver energy based on a (small) input signal
- Build on PA knowledge to achieve high efficiency:
  - Non-linearly switch the output power devices
Switched-Output Regulator: Comparator Feedback with Dead-Band

- Need to convert small signal on $V_{\text{reg}}$ into full-swing to drive switch
  - Use comparator in feedback path

- To avoid unnecessary limit cycle:
  - Offset thresholds to create dead-band
Noise Reduction and Power Efficiency

- Measured results from 65 nm SOI AMD test-chip:
  - Regulator reduces noise by ~30%
  - Reduces overall power dissipation by ~1%

- Transistors slower than expected
  - Expect to reach ~50% noise and ~4% power reduction
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- Voltage scaling made power supply noise a significant source of variability

- Noise measurements needed to validate CAD tools, tune design
  - Fortunately, can be done with relatively simple circuits

- Variations in supply hurt power efficiency
  - But can reduce both noise and power with carefully designed regulator