ECEN720: High-Speed Links Circuits and Systems Spring 2025

Lecture 9: Noise Sources



Sam Palermo Analog & Mixed-Signal Center Texas A&M University

Announcements

- Lab Report 5 and Prelab 6 due Mar 25
- Stateye theory paper posted on website

Noise in High-Speed Link Systems



 Multiple noise sources can degrade link timing and amplitude margin

Noise Source Overview

- Common "noise" sources
 - Power supply noise
 - Receiver offset
 - Crosstalk
 - Inter-symbol interference
 - Random noise
- Power supply noise
 - Switching current through finite supply impedance causes supply voltage drops that vary with time and physical location
- Receiver offset
 - Caused by random device mismatches

- Crosstalk
 - One signal (aggressor) interfering with another signal (victim)
 - On-chip coupling (capacitive)
 - Off-chip coupling (t-line)
 - Near-end
 - Far-end
- Inter-symbol interference
 - Signal dispersion causes signal to interfere with itself
- Random noise
 - Thermal & shot noise
 - Clock jitter components

Bounded and Statistical Noise Sources

- Bounded or *deterministic* noise sources
 - Have theoretically predictable values with defined worst-case bounds
 - Allows for simple (but pessimistic) worst-case analysis
 - Examples
 - Crosstalk to small channel count
 - ISI
 - Receiver offset

- Statistical or *random* noise sources
 - Treat noise as a random process
 - Source may be psuedo-random
 - Often characterized w/ Gaussian stats
 - RMS value
 - Probability density function (PDF)
 - Examples
 - Thermal noise
 - Clock jitter components
 - Crosstalk to large channel count

 Understanding whether noise source is bounded or random is critical to accurate link performance estimation

Proportional and Independent Noise Sources

- Some noise is *proportional* to signal swing
 - Crosstalk
 - Simultaneous switching power supply noise
 - ISI
- Can't overpower this noise
 - Larger signal = more noise

- Some noise is *independent* to signal swing
 - RX offset
 - Non-IO power supply noise
- Can overpower this noise



Common Noise Sources

- Power supply noise
- Receiver offset
- Crosstalk
- Inter-symbol interference
- Random noise

Power Supply Noise



- Circuits draw current from the VDD supply nets and return current to the GND nets
- Supply networks have finite impedance
- Time-varying (switching) currents induce variations on the supply voltage
- Supply noise a circuit sees depends on its location in supply distribution network

Power Routing

Bad – Block B will experience excessive supply noise

-	Block A	Block B		
		and the second		
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Even Better – Block A & B will experience similar supply noise



Better – Block B will experience 1/2 supply noise, but at the cost of double the power routing through blocks

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- Section 2		
		[Hoages]

Best – Block A & B are more isolated



Supply Induced Delay Variation

- Supply noise can induce variations in circuit delay
 - Results in deterministic jitter on clocks & data signals



- CMOS delay is approximately directly proportional to VDD
 - More delay results in more deterministic jitter

Simultaneous Switching Noise

- Finite supply impedance causes significant
 Simultaneous Switching
 Output (SSO) noise
 (xtalk)
- SSO noise is proportional to number of outputs switching, n, and inversely proportional to signal transition time, t_r

$$V_N = L\frac{i}{t_r} = n\frac{LV_s}{Z_0 t_r}$$



Common Noise Sources

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Receiver Input Referred Offset



• The input referred offset is primarily a function of V_{th} mismatch and a weaker function of β (mobility) mismatch

$$\sigma_{V_t} = \frac{A_{V_t}}{\sqrt{WL}}, \quad \sigma_{\Delta\beta/\beta} = \frac{A_{\beta}}{\sqrt{WL}}$$

Receiver Input Referred Offset

$$\sigma_{V_t} = \frac{A_{V_t}}{\sqrt{WL}}, \quad \sigma_{\Delta\beta/\beta} = \frac{A_{\beta}}{\sqrt{WL}}$$

- To reduce input offset 2x, we need to increase area 4x
 - Not practical due to excessive area and power consumption
 - Offset correction necessary to efficiently achieve good sensitivity
- Ideally the offset "A" coefficients are given by the design kit and Monte Carlo is performed to extract offset sigma
- If not, here are some common values:
 - $A_{Vt} = 1mV\mu m \text{ per nm of } t_{ox}$
 - For our default 90nm technology, $t_{ox}{=}2.8nm \rightarrow A_{Vt} \sim \!\! 2.8mV \mu m$
 - A_{β} is generally near 2% μ m

Common Noise Sources

- Power supply noise
- Receiver offset
- Crosstalk
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- Random noise

Crosstalk

- Crosstalk is noise induced by one signal (aggressor) that interferes with another signal (victim)
- Main crosstalk sources
 - Coupling between on-chip (capacitive) wires
 - Coupling between off-chip (t-line/channel) wires
 - Signal return coupling
- Crosstalk is a proportional noise source
 - Cannot be reduced by scaling signal levels
 - Addressed by using proper signal conventions, improving channel and supply network, and using good circuit design and layout techniques

Crosstalk to Capacitive Lines

- On-chip wires have significant capacitance to adjacent wires both on same metal layer and adjacent vertical layers
- Floating victim
 - Examples: Sample-nodes, domino logic
 - When aggressor switches
 - Signal gets coupled to victim via a capacitive voltage divider
 - Signal is not restored



Crosstalk to Driven Capacitive Lines

 Crosstalk to a driven line will decay away with a time-constant

 $\tau_{xc} = R_O (C_C + C_O)$

• Peak crosstalk is inversely proportional to aggressor transition times, t_r , and driver strength $(1/R_0) \Delta V_B(t)$



Ideal Unit Step :

$$\Delta V_B(t) = k_c \exp\left(-\frac{t}{\tau_{xc}}\right)$$

Step with Finite Rise Time, t_r :

$$) = \begin{cases} k_c \left(\frac{\tau_{xc}}{t_r}\right) \left[1 - \exp\left(-\frac{t}{\tau_{xc}}\right)\right] & \text{if } t < t_r \\ k_c \left(\frac{\tau_{xc}}{t_r}\right) \left[\exp\left(-\frac{t - t_r}{\tau_{xc}}\right) - \exp\left(-\frac{t}{\tau_{xc}}\right)\right] & \text{if } t \ge t_r \end{cases}$$

Capacitive Crosstalk Delay Impact

- Aggressor transitioning near victim transition can modulate the victim's effective load capacitance
- This modulates the victim signal's delay, resulting in deterministic jitter



Aggressor Static : $C_L = C_{gnd} + C_C$ Aggressor Switching Same Way : $C_L = C_{gnd}$ Aggressor Switching Opposite Way : $C_L = C_{gnd} + 2C_C$

Mitigating Capacitive (On-Chip) Crosstalk

- Adjacent vertical metal layers should be routed perpendicular (Manhattan routing)
- Limit maximum parallel routing distance
- Avoid floating signals and use keeper transistors with dynamic logic
- Maximize signal transition time
 - Trade-off with jitter sensitivity
- For differential signals, periodically "twist" routing to make cross-talk common-mode
- Separate sensitive signals
- Use shield wires
- Couple DC signals to appropriate supply

Transmission Line Crosstalk

• 2 coupled lines:



• Transient voltage signal on A is coupled to B capacitively

$$\frac{dV_B(x,t)}{dt} = k_{cx} \frac{dV_A(x,t)}{dt} \quad \text{where} \quad \left[k_{cx} = \frac{C_C}{C_S + C_C}\right]$$

 Capacitive coupling sends half the coupled energy in each direction with equal polarity

Transmission Line Crosstalk

• 2 coupled lines:



• Transient current signal on A is coupled to B through mutual inductance

$$\frac{\partial I_A(x,t)}{\partial t} = -\frac{\partial V_A(x,t)}{L\partial x}$$
$$\frac{dV_B(x,t)}{dx} = -M \frac{dI_A(x,t)}{dt} = \frac{M}{L} \left[\frac{dV_A(x,t)}{dx} \right] = k_{lx} \frac{dV_A(x,t)}{dx} \quad \text{where} \quad \left[k_{lx} = \frac{M}{L} \right]$$

 Inductive coupling sends half the coupled energy in each direction with a negative forward traveling wave and a positive reverse traveling wave

Near- and Far-End Crosstalk



Figure 4-22 Summary of propagation of forward- and backward-coupled noise: (a) initial wave launch; (b) halfway down the line; (c) one full trip down the line; (d) round trip.



- Near-end crosstalk (NEXT) is immediately observed starting at the aggressor transition time and continuing for a round-trip delay
- Due to the capacitive and inductive coupling terms having the same polarity, the NEXT signal will have the same polarity as the aggressor
- Far-end crosstalk (FEXT) propagates along the victim channel with the incident signal and is only observed once
- Due to the capacitive and inductive coupling terms having the opposite polarity, the FEXT signal can have either polarity, and in a homogeneous medium (stripline) cancel out

Near- and Far-End Crosstalk



Off-Chip Crosstalk

- Occurs mostly in package and boardto-board connectors
- FEXT is attenuated by channel response and has band-pass characteristic
- NEXT directly couples into victim and has high-pass characteristic



Signal Return Crosstalk

- Shared return path with finite impedance
- Return currents induce crosstalk occurs among signals



Return Crosstalk Voltage:
$$V_{xr} = \Delta V \frac{Z_R}{Z_0} = k_{xr} \Delta V$$

Common Noise Sources

- Power supply noise
- Receiver offset
- Crosstalk
- Inter-symbol interference
- Random noise

Inter-Symbol Interference (ISI)



Peak Distortion Analysis Example



Worst-Case Eye vs Random Data Eye



Worst-Case Eye 100 Random Bits 1000 Random Bits 1e4 Random Bits

- Worst-case data pattern can occur at very low probability!
- Considering worst-case is too pessimistic

Constructing ISI Probability Density Function (PDF)



Convolving Individual ISI PDFs Together



Keep going until all individual PDFs convolved together

Complete ISI PDF



Cursor PDF – Data 1



- Data 1 PDF is centered about the cursor value and varies from a maximum positive value to the worst-case value predicted by PDA
 - This worst-case value occurs at a low probability!

Cursor Cumulative Distribution Function (CDF)

- For a given offset, what is the probability of a Data 1 error?
 - Data 1 error probability for a given offset is equal to the Data 1 CDF

$$BER(X) = \int_{-\infty}^{X} (PDF) dx$$



Combining Cursor CDFs



Bit-Error-Rate (BER) Distribution Eye

- Statistical BER analysis tools use this technique to account for ISI distribution and also other noise sources
 - Example from Stateye
 - Note: Different channel & data rate from previous slides



Common Noise Sources

- Power supply noise
- Receiver offset
- Crosstalk
- Inter-symbol interference
- Random noise

Random Noise

- Random noise is unbounded and modeled statistically
 - Example: Circuit thermal and shot noise
- Modeled as a continuous random variable described by
 - Probability density function (PDF)
 - Mean, μ
 - Standard deviation, σ

$$PDF = P_n(x), \ \mu_n = \int_{-\infty}^{\infty} x P_n(x) dx, \ \sigma_n^2 = \int_{-\infty}^{\infty} (x - \mu_n)^2 P_n(x) dx$$

Gaussian Distribution

- Gaussian distribution is normally assumed for random noise
 - Larger sigma value results in increased distribution spread



Signal with Added Gaussian Noise



 Finite probability of noise pushing signal past threshold to yield an error

Cumulative Distribution Function (CDF)

1

0.9

 The CDF tells what is the probability that the noise signal is less than or equal to a certain value



Standard Normal & Cumulative Distributions

Error and Complimentary Error Functions

- Error Function:
- Relationship between normal CDF (0,1) and Error Function:

$$Q_{\mu\sigma}(x) == \frac{1}{2} \operatorname{erfc}\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)$$

$$erf(x) = \frac{2}{\sqrt{\pi}} \int_{u=0}^{x} \exp(-u^2) du$$

$$\Phi(x) = \frac{1}{2} \left[1 + erf\left(\frac{x}{\sqrt{2}}\right) \right]$$

$$Q(x) = 1 - \Phi(x) = \frac{1}{2} \left[1 - erf\left(\frac{x}{\sqrt{2}}\right) \right]$$
$$= \frac{1}{2} erfc\left(\frac{x}{\sqrt{2}}\right)$$

Bit Error Rate (BER)

• Using erfc to predict BER:



• Need a symbol of about 7σ for BER=10⁻¹²

• Peak-to-peak value will be 2x this

Noise Source Classifications

- Determining whether noise source is
 - Proportional vs Independent
 - Bounded vs Statistical
- is important in noise budgeting

Proportional Independent

nded	Residual ISI	RX Offset	
	Residuarior	RX Sensitivity	
Bou	Crosstalk	Power Supply Noise	
Statistical	Large-Channel Crosstalk	Random Noise	

Noise Budget Example

- Peak TX differential swing of 400mV_{ppd} equalized down 10dB
 - $\pm 200 \text{mV} \rightarrow \pm 63 \text{mV}$

Parameter	K _n	RMS	Value (BER=10 ⁻¹²)	
Peak Differential Swing			0.4V	
RX Offset + Sensitivity			5mV	
Power Supply Noise			5mV	
Residual ISI	0.05		20mV	
Crosstalk	0.05		20mV	
Random Noise		1mV	14mV	
Attenuation	10dB = 0.684		0.274V	
Total Noise			0.338V	
Differential Eye Height Margin			62mV	



- Conservative analysis
 - Assumes all distributions combine at worst-case
- Better technique is to use statistical BER link simulators

Next Time

- Timing Noise
- BER Analysis Techniques