### Basics of Jitter in Wireline Communications

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### Outline

#### **Part One: Basics of Jitter**

- Motivation
- □ Jitter Definitions: What is Jitter?
- □ Characterizing and Classifying Jitter
- Example: Jitter in Ring Oscillator
- Summary of Part One

#### Part Two: Jitter in CDR

- □ Jitter in Clock and Data Recovery
- Effects of Jitter on Bang-Bang CDR Operation
- □ Jitter Monitoring and Jitter Mitigation
- □ Intentional Jitter: How Jitter can help
- □ Summary
- References

### Wireline Transceiver Building Blocks



- $\Box$  Transceiver = Transmitter (TX) + Receiver (RX)
- □ TX pre-equalizes and sends data timed with CK<sub>TX</sub>
- □ RX equalizes RX data, recovers CK<sub>REC</sub>, and detects data
- □ Goal: Minimize Bit Error Rate (BER), typically < 10<sup>-15</sup>

## Effects of Timing Uncertainty on BER



- □ No clock is perfect: they are either slow or fast
- Uncertainty as to when they are slow or fast
- VDD noise, channel, EQ, cross-talk contribute to this
- □ Timing uncertainty leads to errors in detected bits

# Data Eye (with and without Jitter)

#### Without Jitter

#### With Jitter





Data eye at decision point; almost closed w/ jitter
Unacceptable bit error rate (BER) with jitter

Three Questions:

- 1. Can we live with this timing uncertainty yet be precise?
- 2. How to monitor this and to reduce/mitigate it?
- 3. If jitter is enemy of BER, how to best defeat it?

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#### Motivation

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### Absolute Jitter



□ Timing deviation between a jittery CK and an idea CK

- □ A discrete-time random signal, defined as  $a_k := t_k kT$
- Never have an ideal clock; how is this useful?

### **Relative Jitter**



- □ Timing difference between two non-ideal clocks
- Another discrete-time random signal

$$\Box \quad \mathbf{r}_{k} := t_{k} (CK1) - t_{k} (CK2) = \mathbf{a}_{k} (CK1) - \mathbf{a}_{k} (CK2)$$

□ Where do we use this?

### Period Jitter



Also know as Cycle Jitter, defined as difference between edge-to-edge interval ("period") and the nominal period

$$\Box \quad \boldsymbol{p}_{k} := (t_{k+1} - t_{k}) - T = T_{k} - T = \boldsymbol{a}_{k+1} - \boldsymbol{a}_{k}$$

- Period jitter can be derived easily from absolute jitter
- □ Where do we use this?

### **N-Period** Jitter



- Also know as Accumulation Jitter, defined as an accumulation of period jitter over N consecutive intervals
- $\square \boldsymbol{p}_k(N) := (t_{k+N} t_k) NT = \boldsymbol{a}_{k+N} \boldsymbol{a}_k$
- □ Where do we use this?

### Data Jitter



- □ Jittery CK retimes random binary input data
- Due to random nature of data sequence (i.e. lack of transitions), jitter not fully observable at the output

### Data-Dependent Jitter



- Consider data at transmitter with no jitter
- Data is binary random sequence; random transition
- Channel has limited bandwidth; acts like RC
- □ A transition moves depending on preceding data
- □ This produces Data-Dependent Jitter (DDJ)
- □ Type of Deterministic Jitter (DJ) because it is predictable
- □ In contrast with Random Jitter (RJ) we discussed

### No Jitter versus Random Jitter (RJ)



### Bounded/Deterministic Jitter



- □ Sinusoidal jitter
- □ Histogram of sine
- Used to characterize links
- Inter-Symbol Interference (ISI) induced jitter
- Deterministic, bounded

## Duty-Cycle Distortion (DCD)



- □ Histogram over one UI
- UI: Unit Interval

DCD-Induced jitter
Histogram over 4 UIs

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### Characterizing Jitter

#### What we said so far:

- Jitter in all its forms (absolute, relative, period, N-period) is a discrete-time random signal
- Interestingly, all can be derived from absolute jitter
- Data jitter can be deterministic, data dependent
- □ How do we characterize a random signal?
- □ Statistics:
  - Histogram, Probability Density Function (PDF)
  - mean, rms, signal power
- □ Time Domain:
  - How the signal statistics changes with time
  - Autocorrelation function
- □ Frequency Domain:
  - Fourier of Autocorrelation function: Power Spectral Density (PSD)

### Jitter Histogram



Plots the number of hits for each jitter amplitude
Mean, rms, and peak-to-peak jitter can be calculated

### Jitter Probability Density Function



Normalize vertical axis of histogram to have unit area
Red area indicates probability of jitter in the interval

### Other Histogram Examples



### Jitter Histogram/PDF Enough?



- Histogram or PDF only shows:
  - Relative occurrence of a jitter amplitude (range)
  - But, not the time behavior of jitter
- □ Two waveforms above have same histogram (uniform)
- □ But, they have totally different time behavior
  - Black samples are correlated (predictable), red samples not
- Swapping samples in time does not affect the PDF!

### Voltage Spectrum of Jittery Clock



- Clock is a periodic signal with period  $T_0 (=1/f_0)$
- $\Box$  Clock spectrum will contain harmonics at nf<sub>0</sub>
- □ In addition, jitter causes "skirts" around delta functions
- D Power level of skirt (relative to carrier power) is called phase noise; typically measured at an offset from  $f_0$
- □ Phase noise serves as a figure of merit for the oscillators

### Phase Noise



### **PSD** of Jitter



- □ Can prove PSD of jitter is equal to phase noise
- □ Note:  $\mathcal{L}(f)$  is one-sided whereas  $S_{\varphi}(f)$  is two-sided
- $\square S_{\varphi}(f) = \mathcal{L}(f)u(f) + \mathcal{L}(-f)u(-f)$

### From Phase Noise to Jitter rms



### Sum of two jitter: Convolve PDFs



### Combined Jitter in Eye Diagram





# Combined DCD & RJConvolution of two PDFs

# Combined jitter is sum of individual jitter signals Combined jitter PDF is convolution of individual PDFs

## **Classifying Jitter**



- Total Jitter is sum of DJ and RJ
- DJ includes:
  - Data-Dependent, Duty-Cycle-Distortion (DCD) Jitter
  - Sinusoidal, any other bounded periodic/non-periodic jitter
- □ RJ is unbounded and uncorrelated

### **Example Calculations**



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### Example: A Ring Oscillator



For any output, say v<sub>1</sub>, the period is 6t<sub>pd</sub>
But t<sub>pd</sub> is random variable (signal) changing with time

### Example: Delay of an Inverter



- $\Box$  I<sub>n1</sub>(t) and I<sub>n2</sub>(t) represent the thermal (and other) noise currents of M1 and M2, respectively
- □  $I_{n1}(t)$  and  $I_{n2}(t)$  will cause  $v_o$  to reach a threshold ( $V_{DD}/2$ ) faster or slower than nominal; causing delay of each stage to be a random variable

### Modeling Jitter in Ring Oscillator



- Let X<sub>i</sub>[n] represent the random excess delay introduced by inverter i in n-th cycle
- $\Box$  X<sub>i</sub>[n] is a random signal with expected value of zero
- $\Box$  What can we say about the jitter in the output y[n]?
- $\Box \quad y[n] = y[n-1] + X_1[n] + X_2[n] + X_3[n]$
- $\square$  Reasonable to assume X<sub>i</sub>[n] is stationary & uncorrelated
- □ Then, y[n] shows characteristics of a random walk

### Random Walk Process



- □ Start at 0 and toss a coin
  - If head, move one step forward, then repeat
  - If tail, move one step backward, then repeat
- □ Graph shows 10 difference trials (imagine for 10 people)
- □ The *expected* distance for all trials are zero
- But the variation around 0 grows over time

### Jitter Variance over Time



□ Jitter variance increases linearly with time

Jitter rms increases with root square of time

### Jitter Variance of a PLL



- Oscillator can be placed inside a PLL loop to compare its timing against a clean reference clock
- Jitter variance increase with time until one loop delay, at which point jitter variance no longer grows
# Summary of Part One

#### □ Jitter definitions:

- Absolute jitter: deviation from an ideal clock timing
- Relative jitter: timing difference between two real clocks
- Period jitter: deviation in period from average period
- □ Jitter histogram, PDF, PSD
  - Histogram/PDF provide statistics: mean, rms, peak-to-peak
  - PSD is based on jitter behavior over time (autocorrelation)
  - PSD provides information in frequency domain
- □ Jitter variance in a ring increases linearly with time
- □ A control loop (in a PLL) is used to limit jitter

# Part Two: Jitter in CDR

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#### □ Jitter in Clock and Data Recovery

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# Clock and Data Recovery Blocks



- □ A loop measures the phase difference between  $D_{IN}$ and  $CK_{REC}$  and controls the VCO frequency
- □ Loop dynamics shaped by PD, CP, LF, and VCO behavior
- $\Box$  CK<sub>REC</sub> is used to sample D<sub>IN</sub> and produce D<sub>REC</sub>

### Linear Model of CDR



$$S_{out}(f) = |H_T(f)|^2 S_{in}(f) + |H_G(f)|^2 S_{VCO}(f)$$

$$|H_T(f)|^2 = \left| \frac{K_{PD} K_{VCO} H_{LF}(f)}{j2\pi f + K_{PD} K_{VCO} H_{LF}(f)} \right|^2$$
$$|H_G(f)|^2 = \left| \frac{j2\pi f}{j2\pi f + K_{PD} K_{VCO} H_{LF}(f)} \right|^2$$

# Model of CDR with Charge Pump



### **Jitter Transfer Function**



### Zero/Pole Locations



# Jitter Peaking



Undesirable as it enhances jitter, esp. in repeaters
Standards requirement < 0.1dB</li>

### Jitter Generation Function



### Jitter Tolerance Concept



Maximum tolerable peak-to-peak jitter on CK edge
1UI<sub>pp</sub> for high jitter frequencies

### □ Higher than 1UI<sub>pp</sub> for lower jitter frequencies

### Jitter Tolerance Curve



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### Bang-Bang PD Operation (1 of 3)



# Bang-Bang PD Operation (2 of 3)



D <sub>n</sub>	В	D <sub>n+1</sub>	Early	Late	PDout
х	x	×	0	1	1
Х	Х	×	1	0	-1
Х	Х	Х	0	0	0



# Bang-Bang PD Operation (3 of 3)

[Lee JSSC 2004]



Jitter in Wireline Communications

### **BB-PD** Model with Jitter

#### [Liang JSSC 2015]



# Effects of Jitter on CDR Stability



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# Why Jitter Monitoring?

![](_page_54_Figure_1.jpeg)

- Simulated/measure jitter budget for a 25Gb/s optical link [Takemoto JSSC 2014]
- □ Jitter difficult to predict and mitigate at simulation time

# Ideal Sampling Position

![](_page_55_Figure_1.jpeg)

- □ Sample in the middle of horizontal eye opening
- □ Slice it with a level at the middle of vertical eye opening
- These are hard to predict at design time

# **Eye-Opening Monitor**

```
[Noguchi JSSC '08]
```

![](_page_56_Figure_2.jpeg)

- EOM samples data at a phase/voltage offset away from CDR sampling point
- Comparing the two samples creates an "eye map"

### Search for Ideal Sampling Position

[Noguchi JSSC '08]

![](_page_57_Figure_2.jpeg)

□ Comparing CDR and EOM data creates eye contours

Adaptive algorithms will position CDR sampling location

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# CDR with Eye-Opening Monitor

![](_page_58_Figure_1.jpeg)

# Moving to Ideal Position

[Noguchi JSSC '08]

![](_page_59_Figure_2.jpeg)

Initial sampling position of CDR is detected using EOM

Sampling position is moved to the center of the eye

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# Jitter Monitoring for Jitter Tolerance

![](_page_60_Figure_1.jpeg)

Adapt loop gain  $(K_G)$  to maximize JTOL in PI-based CDR

### Monitoring Jitter at BB-PD Output

![](_page_61_Figure_1.jpeg)

# PSD of Relative Jitter

![](_page_62_Figure_1.jpeg)

Power Spectral Density (PSD) versus loop gain (K)

- The total power is in units of (ps)<sup>2</sup>
- Desired K corresponds to no overshoot or undershoot
- Hard to measure

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### Measure Autocorrelation

![](_page_63_Figure_1.jpeg)

□ Use autocorrelation of PD output, R(n), instead

- Reveals similar behavior as PSD
- Adjust K to arrive at "critically damped" condition
- How? Start with max K, measure n<sub>peak</sub>
- Reduce K gradually to force R(n<sub>peak</sub>) to zero.

### Measured Jitter Tolerance

![](_page_64_Figure_1.jpeg)

### Measuring Absolute Jitter

[Liang JSSC `15]

![](_page_65_Figure_2.jpeg)

 $K_{P} \cdot \Phi_{ER} = K_{P} \cdot (\Phi_{DATA} - \Phi_{CK})$ 

- Interested in distinguishing between jitter in the incoming data and the recovered clock
- Only the relative jitter between the two is observable
- □ Without ideal clock, how to measure absolute jitter

### Use Two Phase Detectors

![](_page_66_Figure_1.jpeg)

- □ Assumes  $\Phi_{CK1}$  and  $\Phi_{CK1}$  are uncorrelated
- □ Insert adjustable delay on one side
- **Combine the two for autocorrelation function**  $R_{DATA}(k)$
- □ If jitter is stationary

$$E[\Phi_{DATA}(n) \cdot \Phi_{DATA}(n-k)] = R_{DATA}(k)$$

- □ LPF approximates the Expected Value
- **D** Fourier Transform of  $R_{DATA}(k)$  gives the PSD of  $\Phi_{DATA}$

# Implementation in Multi-Lane CDR

![](_page_67_Figure_1.jpeg)

### Measured Results [Liang JSSC'15]

![](_page_68_Figure_1.jpeg)

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### Intentional Jitter to Improve Linearity

[Takauchi JSSC '03]

![](_page_70_Figure_2.jpeg)

4-Phase 2.5GHz Edge Clock

### Jitter Injection for Measurement

![](_page_71_Figure_1.jpeg)

- □ Intentional jitter toggles LSB for PI of Edge CK
  - Helps calibrate BB-PD effective gain measurement
  - Improves accuracy of relative jitter measurement
# Injected Jitter Provides Observability



[Liang CICC'17]

\*Outstanding Student Paper Award from CICC2017!

# **Other Relevant Topics**

- Effect of Jitter on Data Converters
  - Both DAC and ADC
  - Time-Interleaved ADC's
- **Effects of Jitter on**  $\Delta\Sigma$  **ADC's** 
  - Jitter noise is shaped by the NTF
- □ Effects of Jitter on Wireless Systems/Circuits
- □ Jitter Amplifications by Passive Channel

# Summary

### □ Jitter definitions:

- Absolute jitter: deviation from an ideal clock timing
- Relative jitter: timing difference between two real clocks
- Period jitter: deviation in period from average period
- □ Jitter histogram, PDF, PSD
  - Histogram/PDF provide statistics: mean, rms, peak-to-peak
  - PSD is based on jitter behavior over time (autocorrelation)
  - PSD provides information in frequency domain
- □ Jitter monitoring unavoidable as we move to higher rate
  - Monitoring is the first step towards jitter mitigation
- □ Jitter is injected intentionally to improve observability

# References (1 of 2)

#### **Basics of Jitter**

- □ N. Da Dalt, ISSCC 2012 Tutorial, available online www.sscs.org
- N. Da Dalt and A. Sheikholeslami, "Understanding Jitter and Phase Noise A Circuits and Systems Perspective" by Cambridge University Press, 2018

#### Jitter in Ring Oscillators and CDR

- □ T. H. Lee et al., "A 155-MHz Clock Recover- and Phase-Locked Loop," JSSC,, pp. 1736-1746, Dec. 1992
- J. McNeill, "Jitter in Ring Oscillators," JSSC, pp. 870-879, June 1997
- □ J. Lee et al., "Analysis and Modeling of Bang-Bang Clock and Data Recovery Circuits," JSSC, pp. 1571-2004, Sep. 2004

#### **Jitter Monitoring and Mitigation**

- T. Takemoto, et al., "A 25-Gb/s 2.2-W 65-nm CMOS Optical Transceiver Using a Power-Supply-Variation-Tolerant Analog Front End and Data-Format Conversion," JSSC, vol. 49, no. 2, pp. 471–485, Feb 2014
- H. Noguchi, et al., "A 40-Gb/s CDR Circuit with Adaptive Decision-Point Control Based on Eye-Opening Monitor Feedback," JSSC, vol. 43, no. 12, pp. 2929-2938, Dec 2008

# References (2 of 2)

- □ J. Liang, et al., "A 28Gb/s Digital CDR with Adaptive Loop Gain for Optimum Jitter Tolerance," ISSCC, pp. 122-123, Feb 2017
- □ J. Liang, et al., "On-Chip Measurement of Clock and Data Jitter With Sub-Picosecond Accuracy for 10 Gb/s Multilane CDRs," JSSC, vol. 50, no. 4, pp. 845-855, Apr. 2015

#### **Intentional Jitter**

- H. Takauchi et al., "A CMOS Multichannel 10-Gb/s Transceiver," ISSCC 2003, paper 4.2. Expanded version in JSSC, pp. 2094-2100, Dec. 2003
- □ J. Liang, et al., "Jitter Injection for On-Chip Jitter Measurement in PI-Based CDRs," CICC, pp. 1–4, Apr. 2017

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