Basics of Jitter in Wireline Communications

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Outline

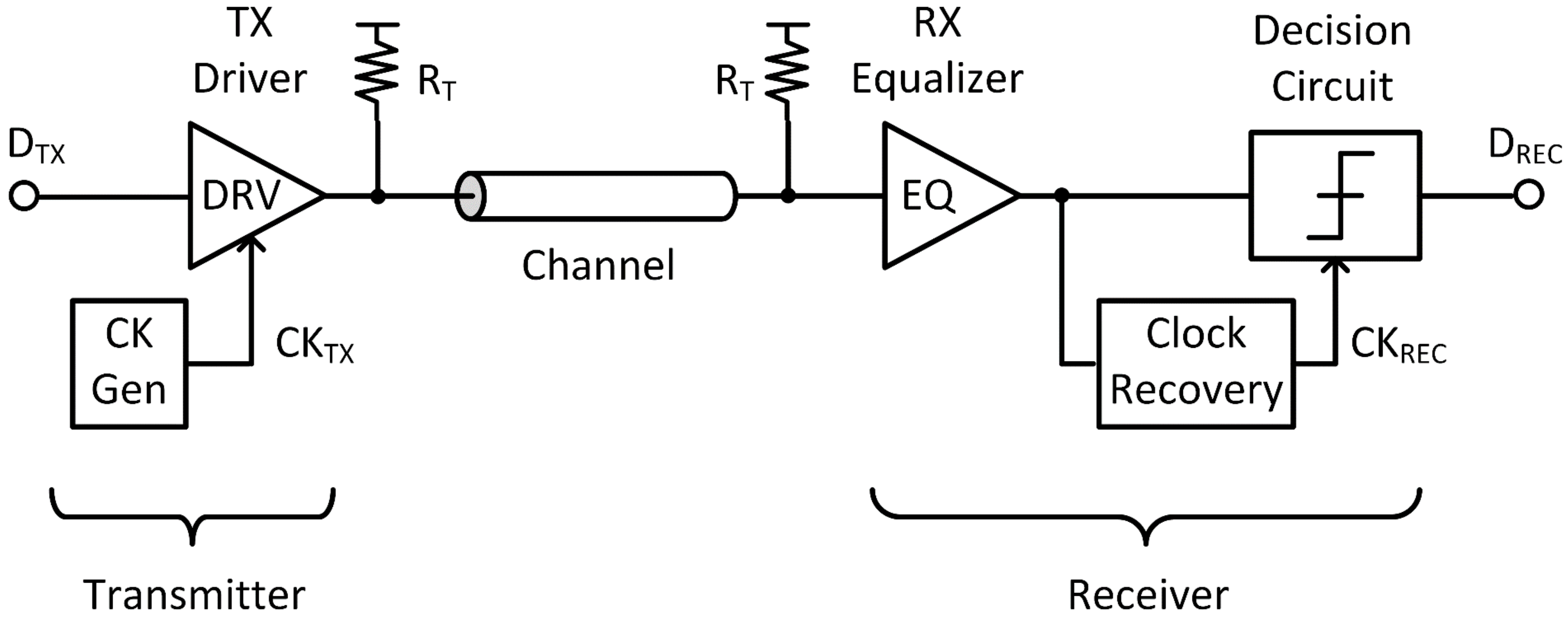
Part One: Basics of Jitter

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

Part Two: Jitter in CDR

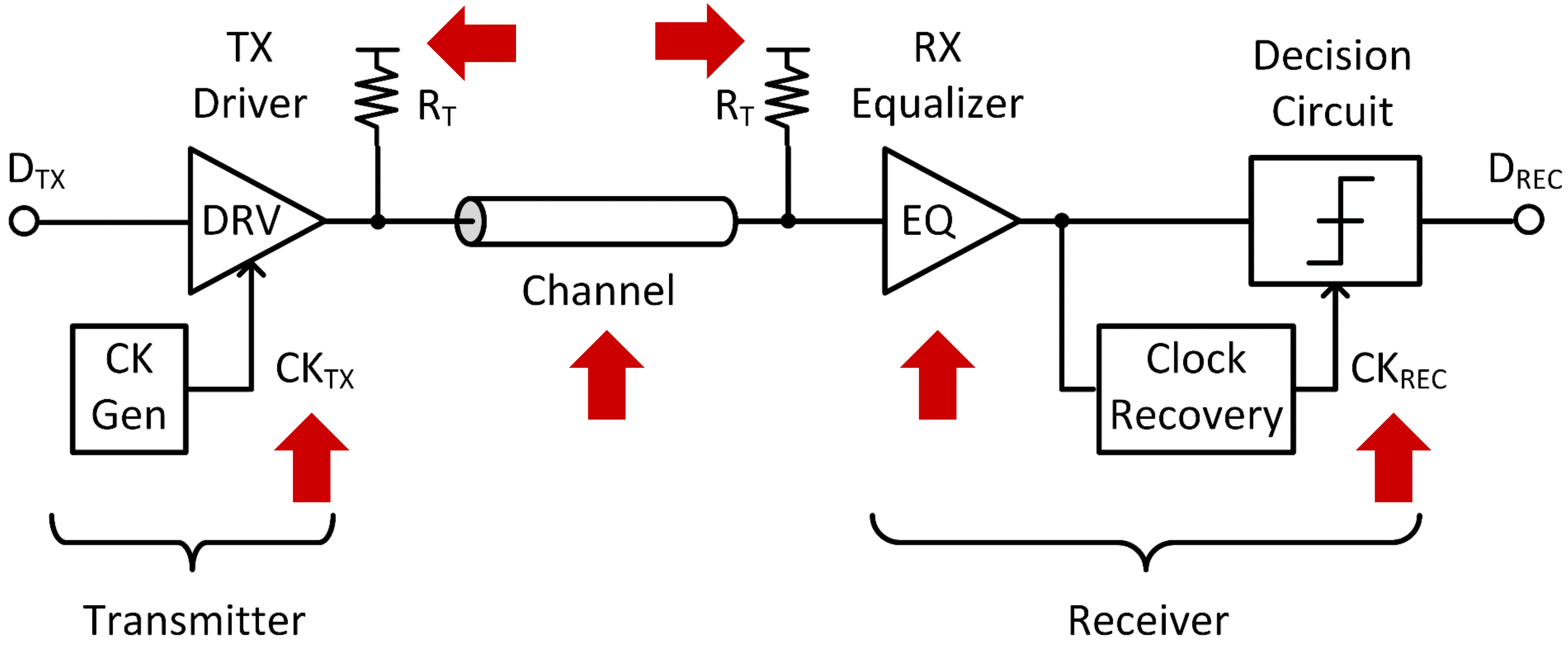
- ☐ Jitter in Clock and Data Recovery
- ☐ Effects of Jitter on Bang-Bang CDR Operation
- ☐ Jitter Monitoring and Jitter Mitigation
- ☐ Intentional Jitter: How Jitter can help
- ☐ Summary
- ☐ References

Wireline Transceiver Building Blocks



- Transceiver = Transmitter (TX) + Receiver (RX)
- TX pre-equalizes and sends data timed with CK_{TX}
- RX equalizes RX data, recovers CK_{REC}, and detects data
- Goal: Minimize Bit Error Rate (BER), typically $< 10^{-15}$

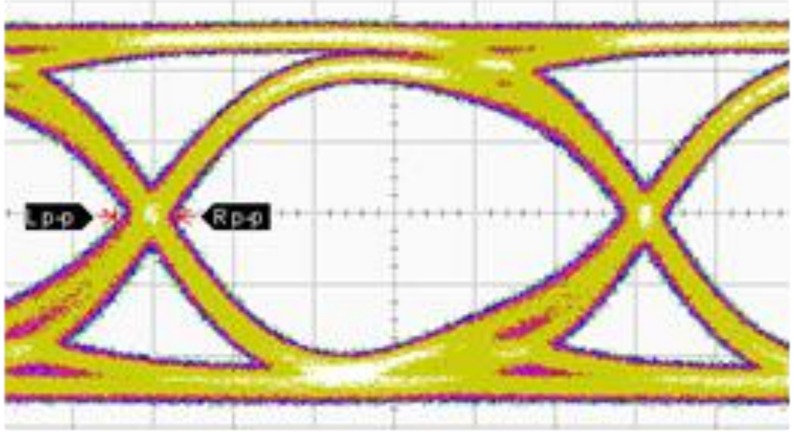
Effects of Timing Uncertainty on BER



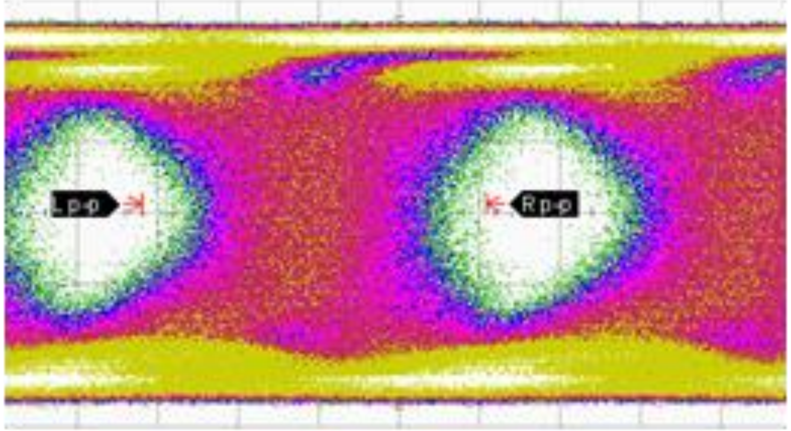
- ☐ No clock is perfect: they are either slow or fast
- ☐ Uncertainty as to when they are slow or fast
- ☐ VDD noise, channel, EQ, cross-talk contribute to this
- ☐ Timing uncertainty leads to errors in detected bits

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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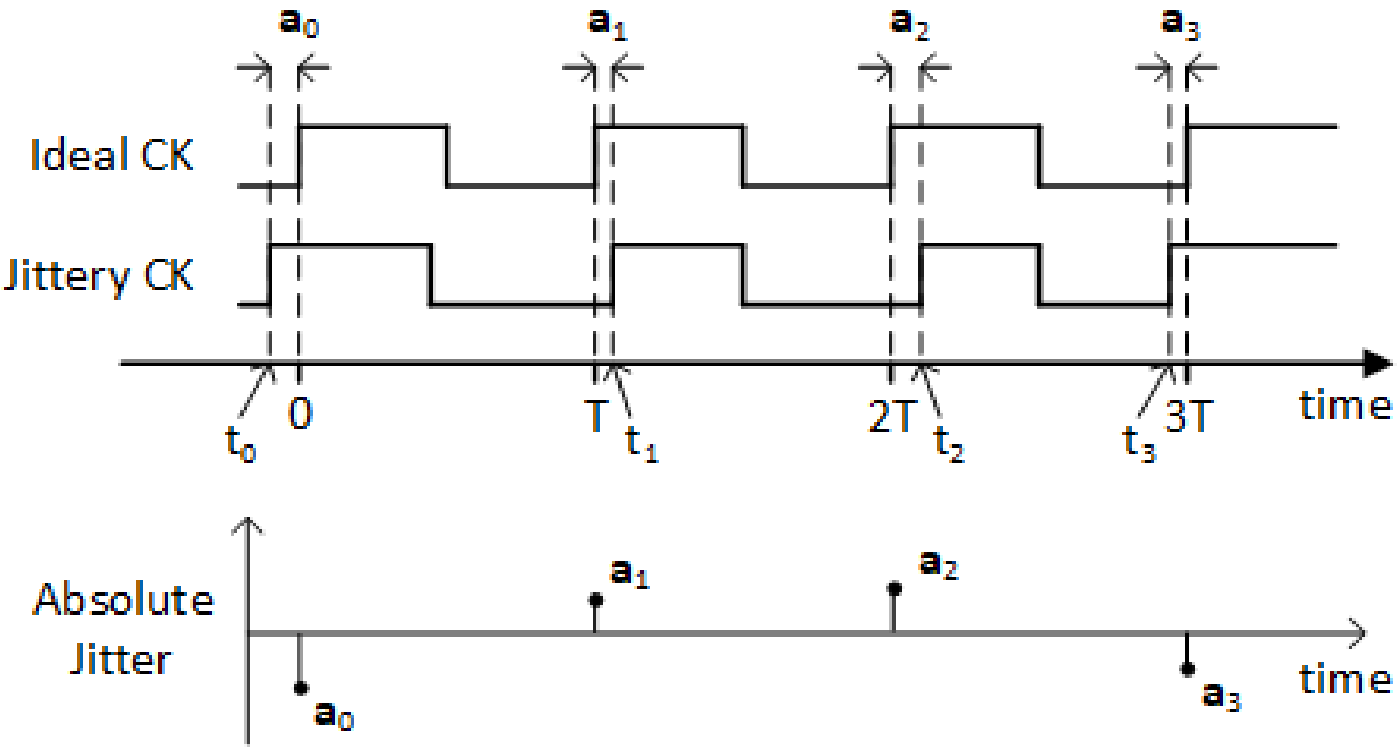
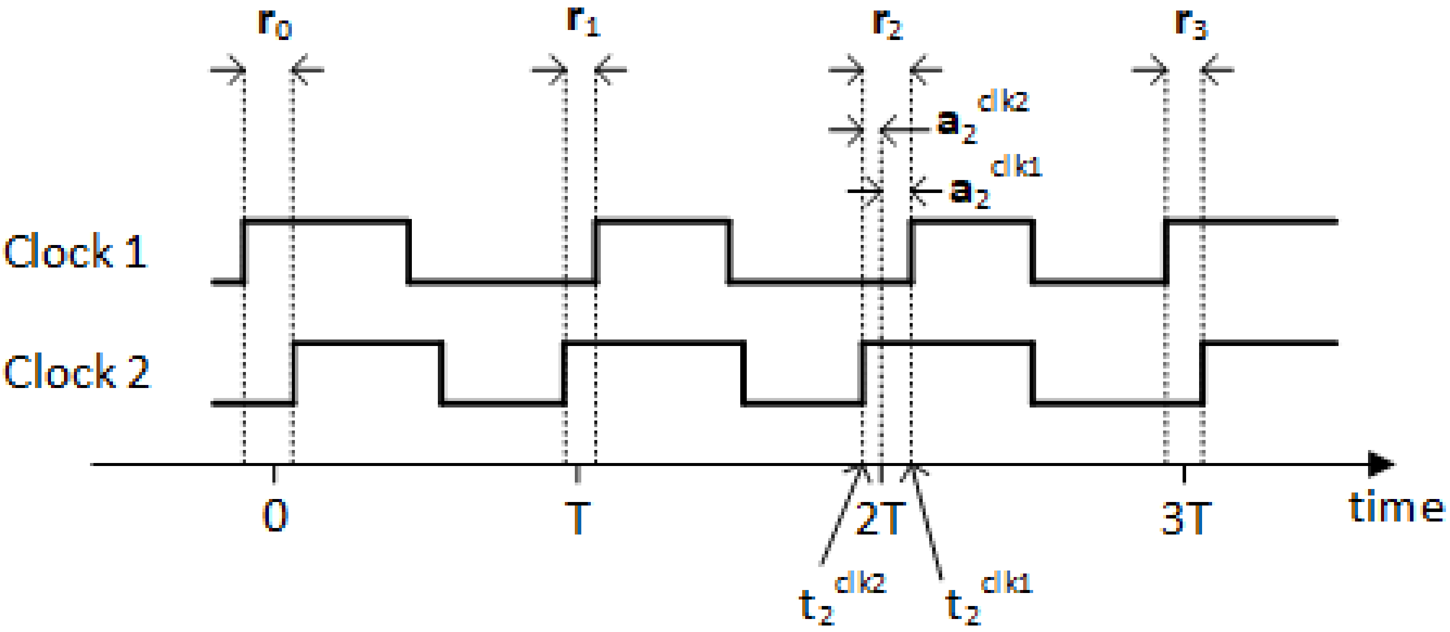
Absolute Jitter



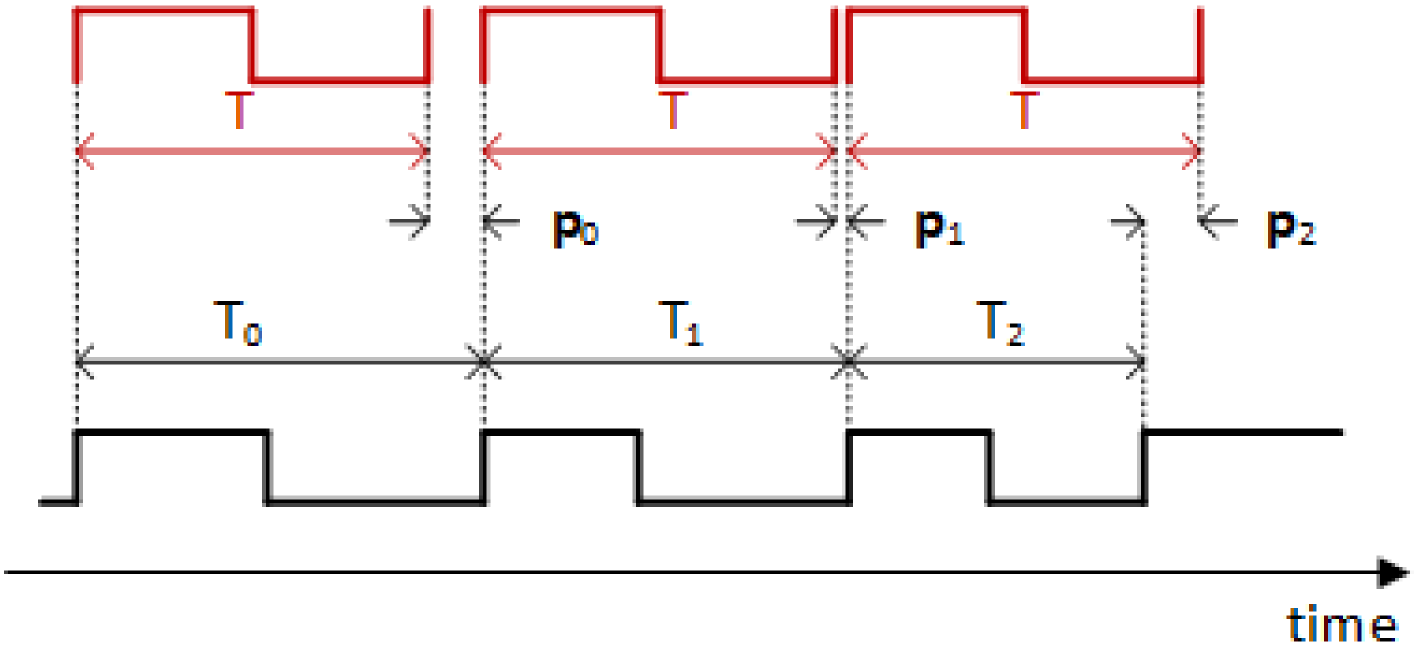
- Timing deviation between a jittery CK and an idea CK
- A discrete-time random signal, defined as $a_k := t_k - kT$
- Never have an ideal clock; how is this useful?

Relative Jitter



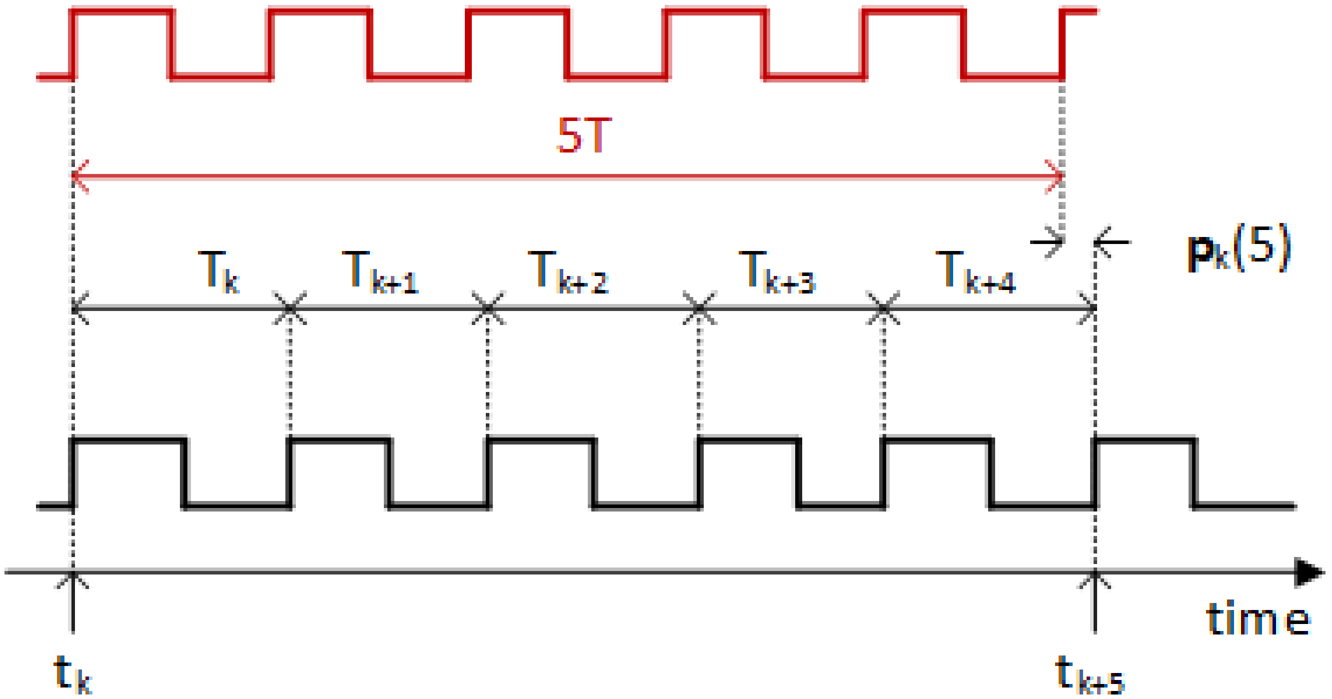
- Timing difference between two non-ideal clocks
- Another discrete-time random signal
- $\boldsymbol{r}_k := t_k(CK1) - t_k(CK2) = \boldsymbol{a}_\boldsymbol{k}(CK1) - \boldsymbol{a}_\boldsymbol{k}(CK2)$
- Where do we use this?

Period Jitter



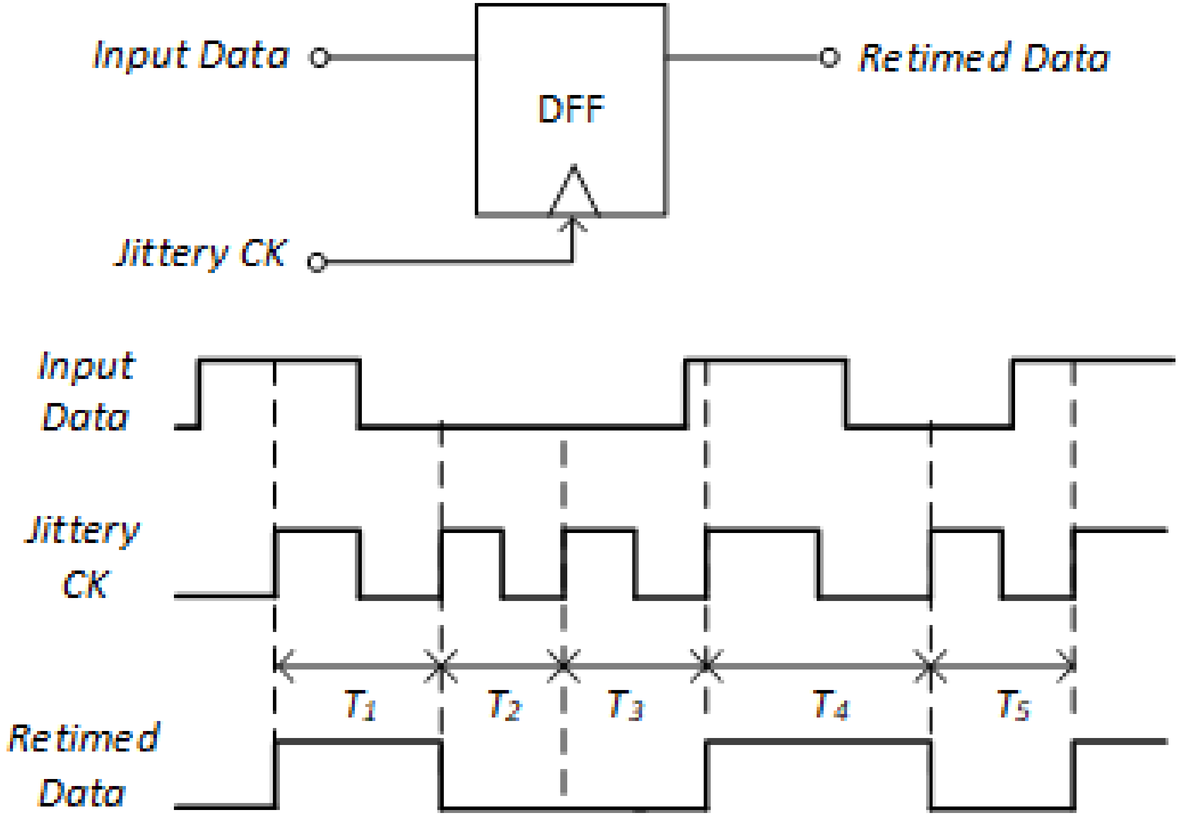
- ☐ Also know as Cycle Jitter, defined as difference between edge-to-edge interval ("period") and the nominal period
- ☐ $\mathbf{p}_k := (t_{k+1} - t_k) - T = T_k - T = \mathbf{a}_{k+1} - \mathbf{a}_k$
- ☐ Period jitter can be derived easily from absolute jitter
- ☐ Where do we use this?

N-Period Jitter



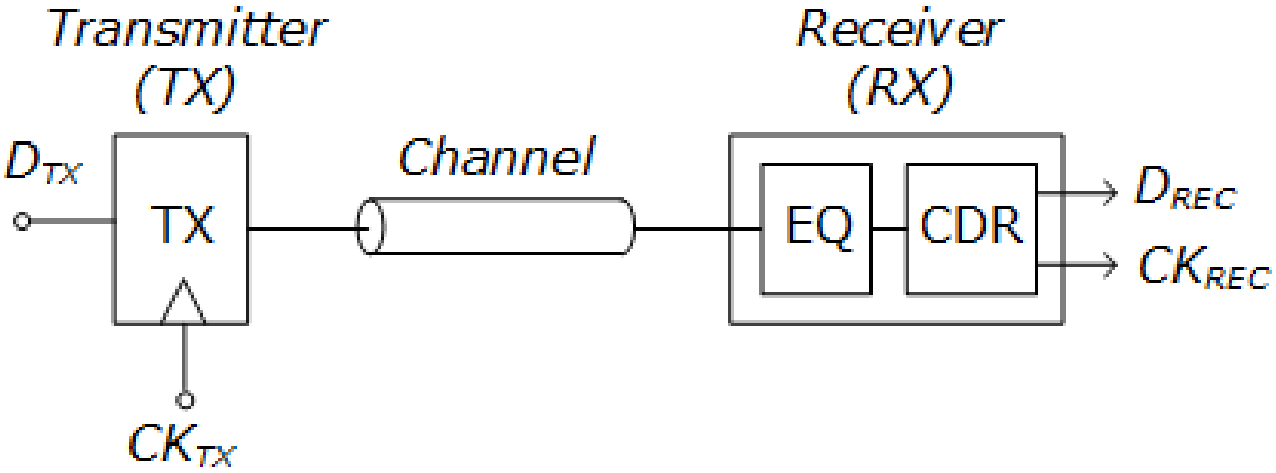
- ☐ Also know as Accumulation Jitter, defined as an accumulation of period jitter over N consecutive intervals
- ☐ $\boldsymbol{p}_k\,(N) := (t_{k+N} - t_k) - NT = \boldsymbol{a}_{k+N} - \boldsymbol{a}_k$
- ☐ Where do we use this?

Data Jitter



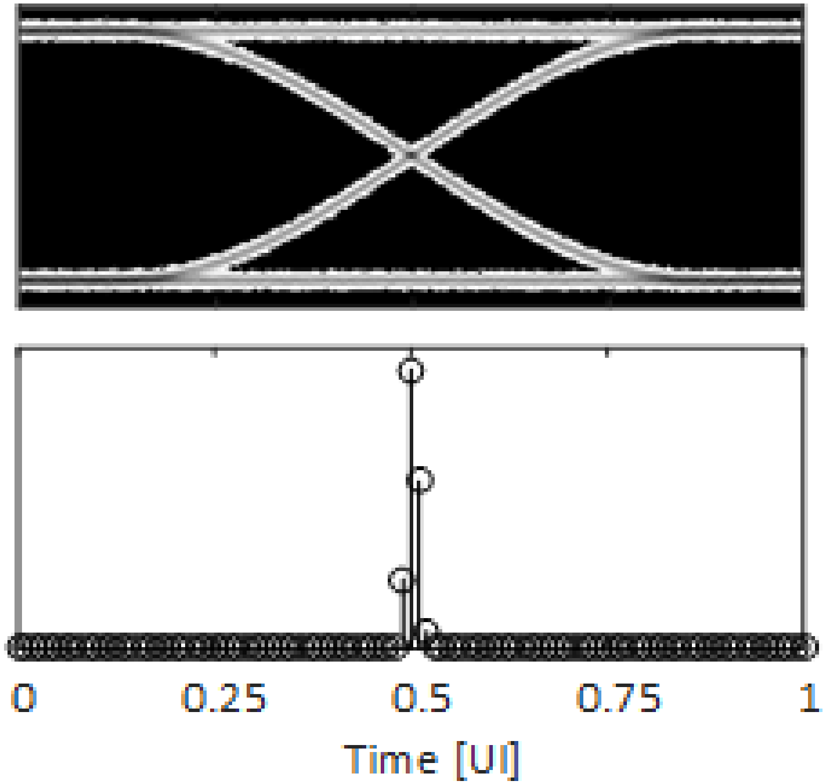
- ☐ Jittery CK retimes random binary input data
- ☐ Due to random nature of data sequence (i.e. lack of transitions), jitter not fully observable at the output

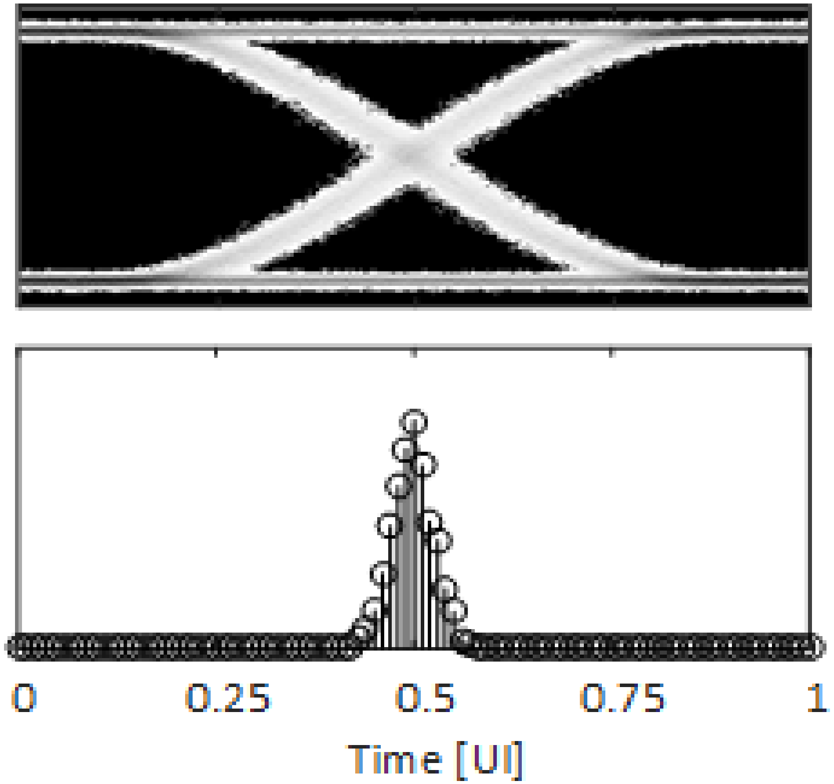
Data-Dependent Jitter



- ☐ 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)

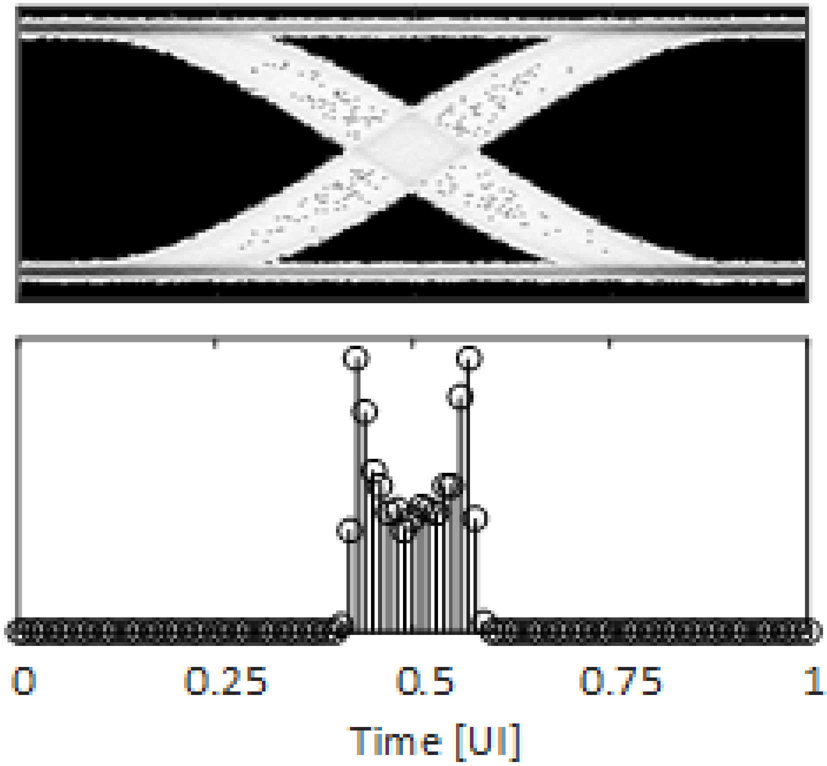




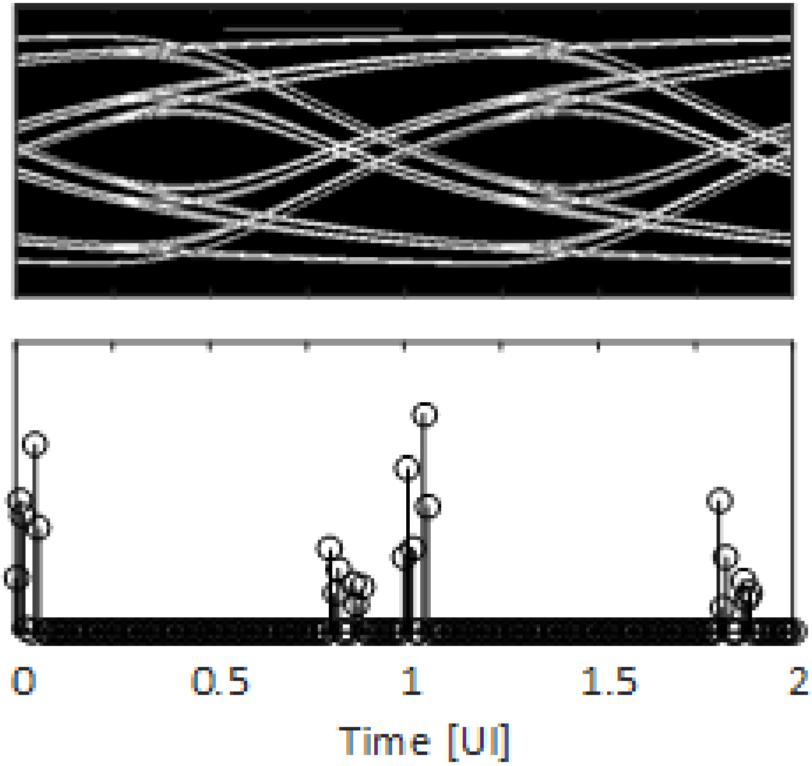
- One sharp transition
- Histogram like a delta

- Transitions distributed
- Gaussian Histogram
- Unbounded Jitter

Bounded/Deterministic Jitter

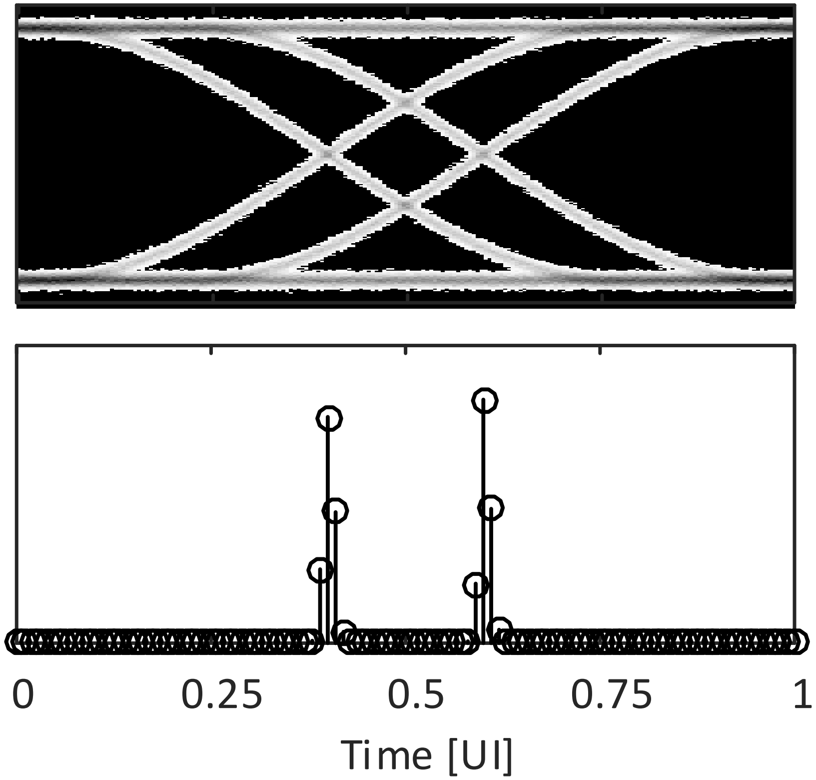


- Sinusoidal jitter
- Histogram of sine
- Used to characterize links

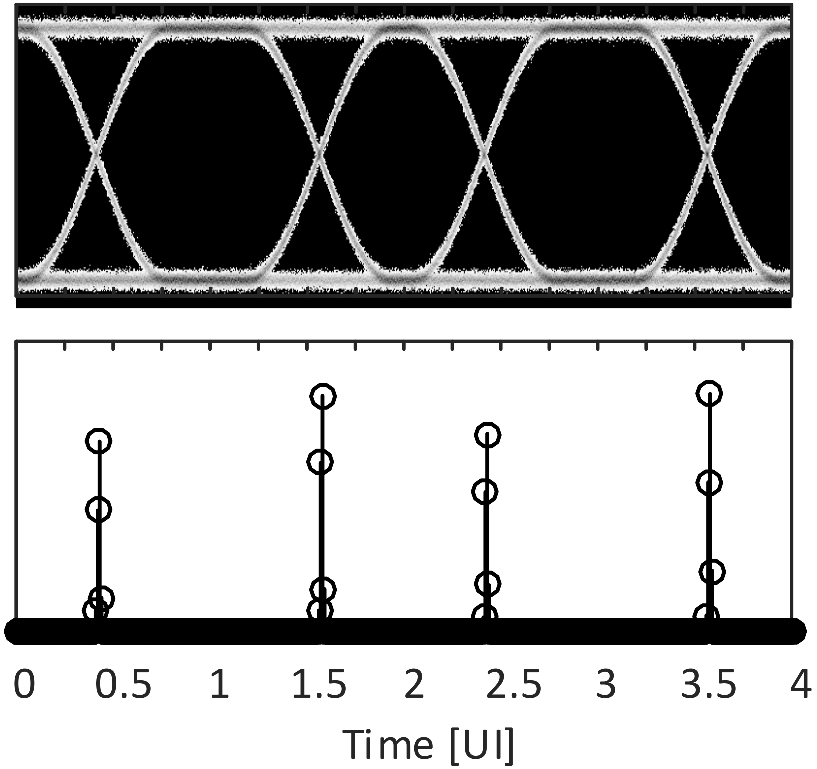


- Inter-Symbol Interference (ISI) induced jitter
- Deterministic, bounded

Duty-Cycle Distortion (DCD)



- DCD-Induced jitter
- Histogram over one UI
- UI: Unit Interval



- DCD-Induced jitter
- Histogram over 4 UIs

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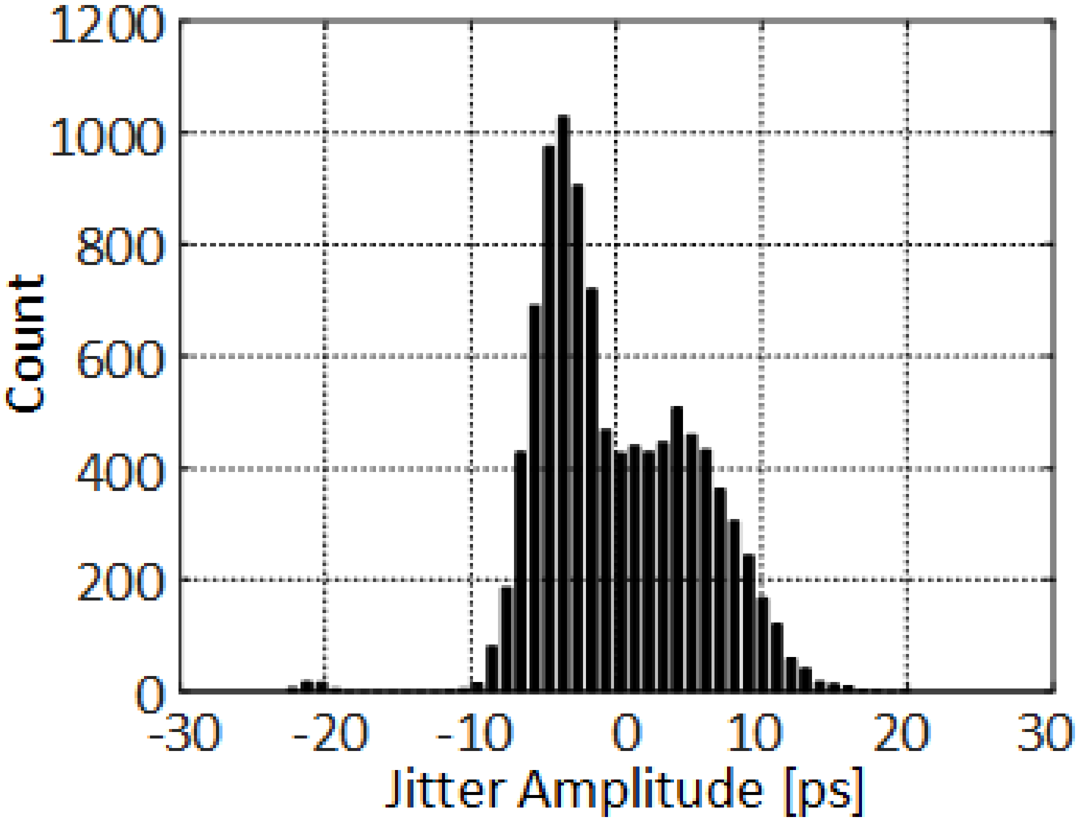
Characterizing Jitter

- 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

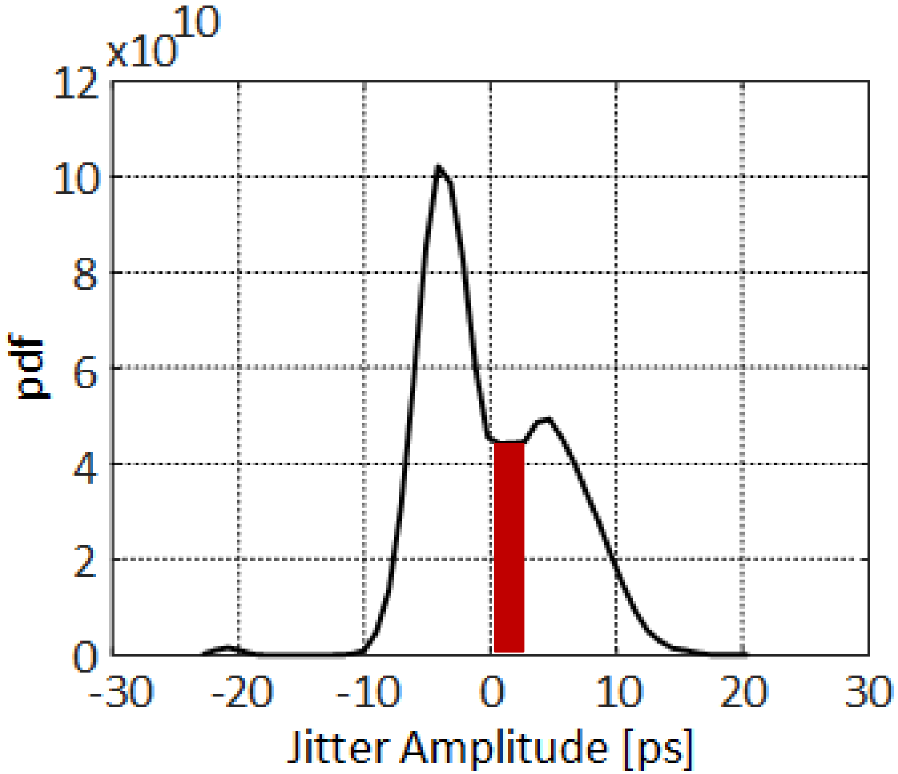
- How do we characterize a random signal?
- Statistics:
  - Histogram, Probability Density Function (PDF)
  - mean, rms, signal power
- Time Domain:
  - How the signal statistics changes with time
  - Autocorrelation function
- Frequency Domain:
  - Fourier of Autocorrelation function: Power Spectral Density (PSD)

Jitter Histogram



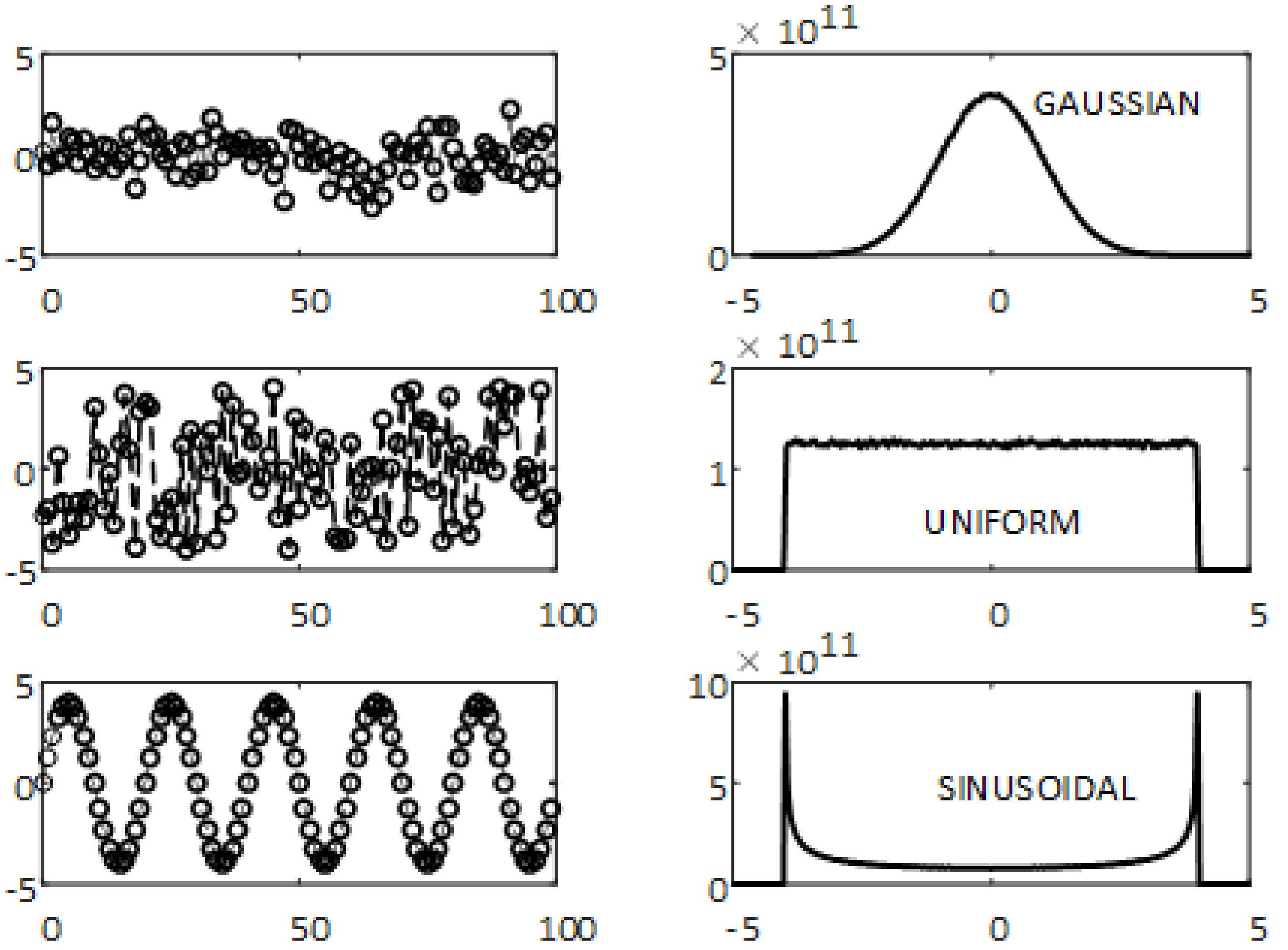
- ☐ Plots the number of hits for each jitter amplitude
- ☐ Mean, rms, and peak-to-peak jitter can be calculated

Jitter Probability Density Function

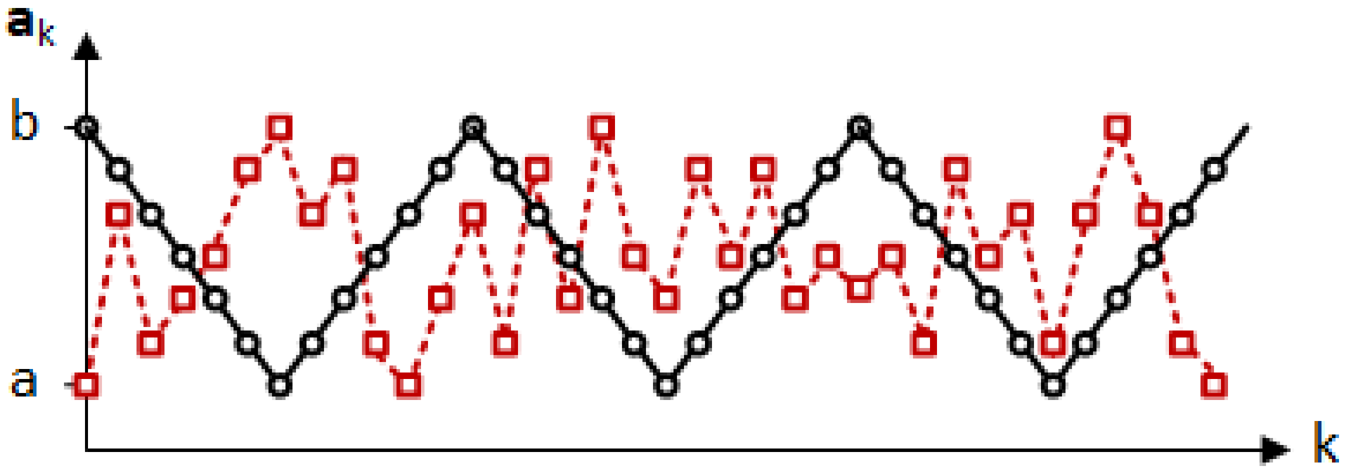


- Normalize vertical axis of histogram to have unit area
- Red area indicates probability of jitter in the interval

Other Histogram Examples

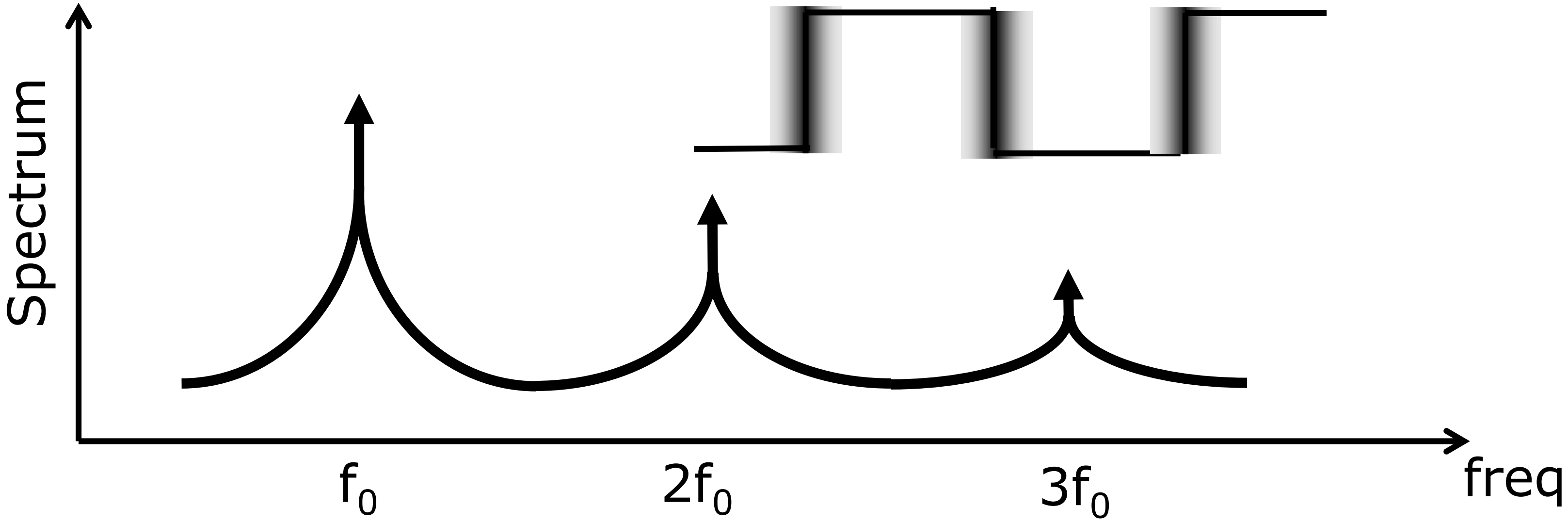


Jitter Histogram/PDF Enough?



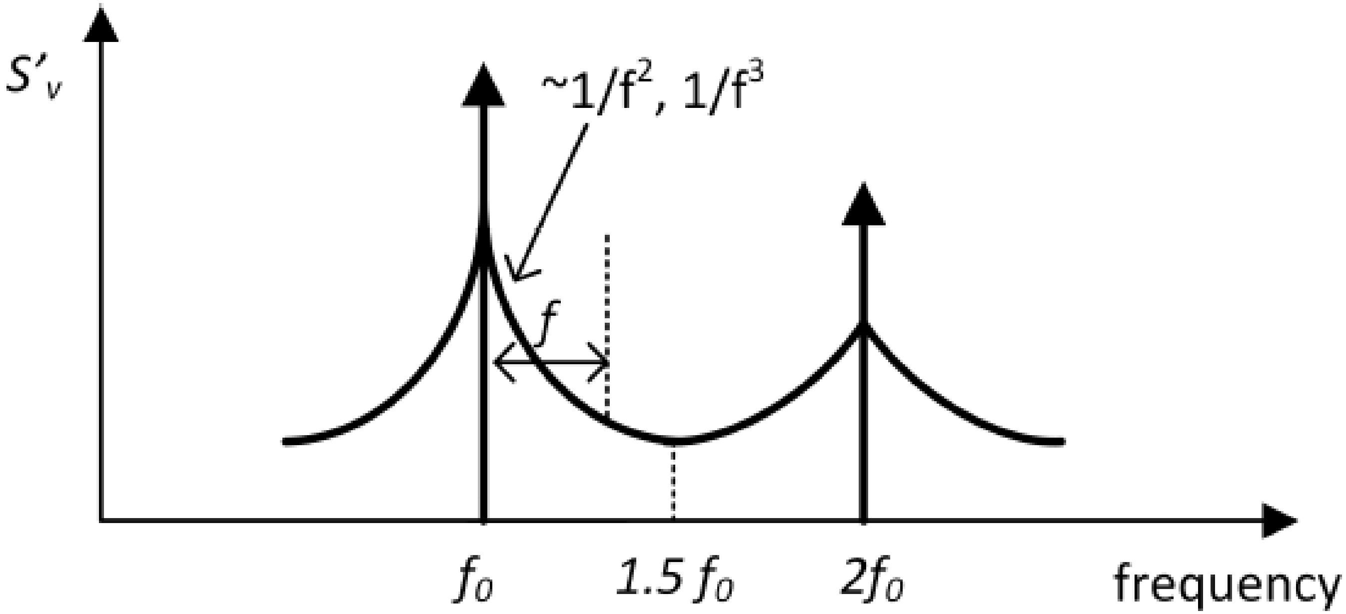
- Histogram or PDF only shows:
    - Relative occurrence of a jitter amplitude (range)
    - But, not the time behavior of jitter
- Two waveforms above have same histogram (uniform)
- But, they have totally different time behavior
    - Black samples are correlated (predictable), red samples not
- Swapping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

Voltage Spectrum of Jittery Clock



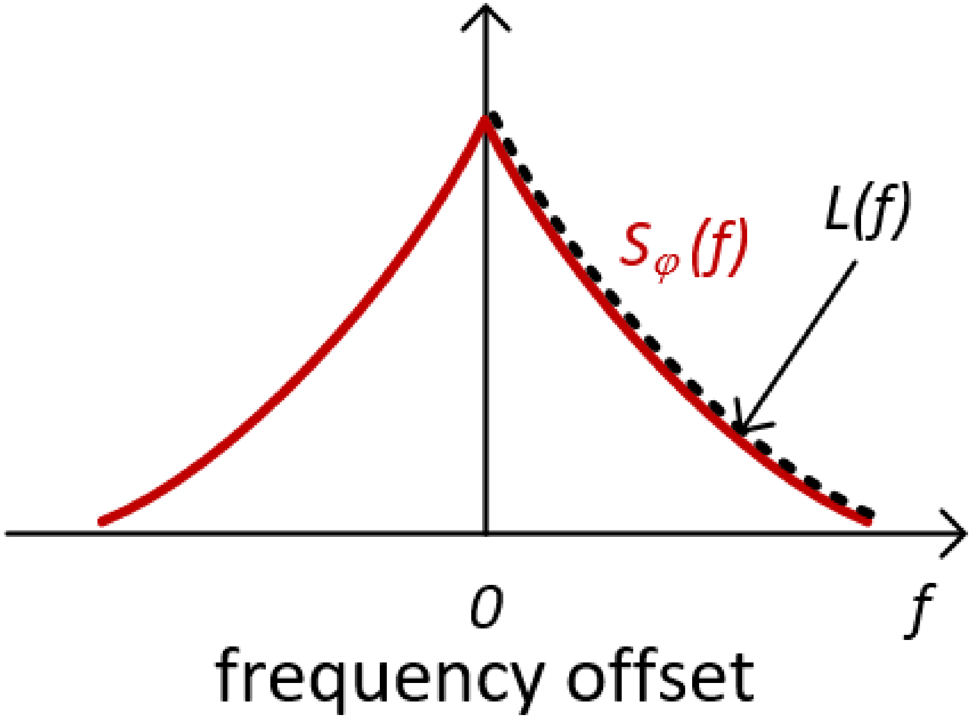
- Clock is a periodic signal with period T_0 ($=1/f_0$)
- Clock spectrum will contain harmonics at nf_0
- In addition, jitter causes “skirts” around delta functions
- Power level of skirt (relative to carrier power) is called phase noise; typically measured at an offset from f_0
- Phase noise serves as a figure of merit for the oscillators

Phase Noise



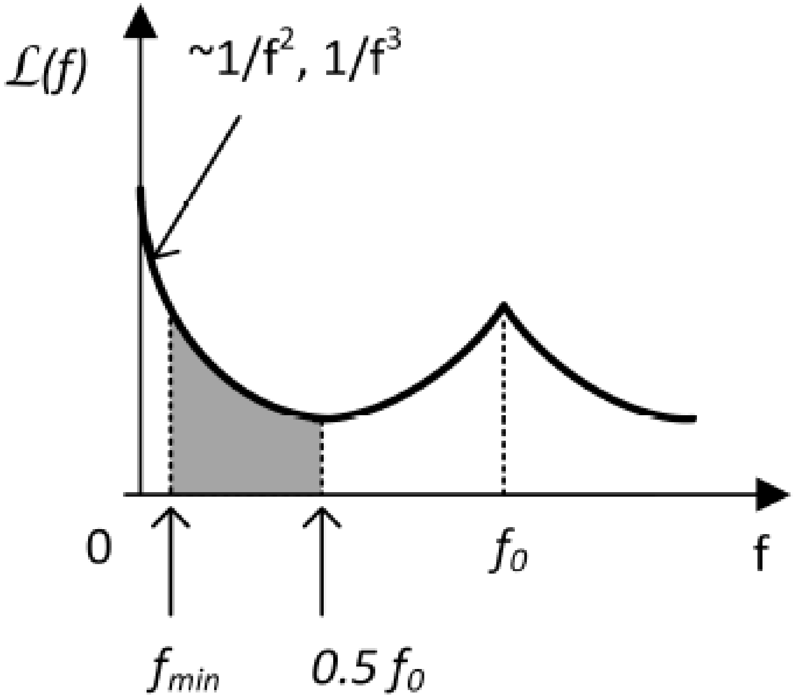
$$\mathcal{L}(f) := \frac{S'_v(f_0+f) \text{ in 1 Hz bandwidth}}{P}$$

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
- $S_\varphi(f) = \mathcal{L}(f)u(f) + \mathcal{L}(-f)u(-f)$

From Phase Noise to Jitter rms



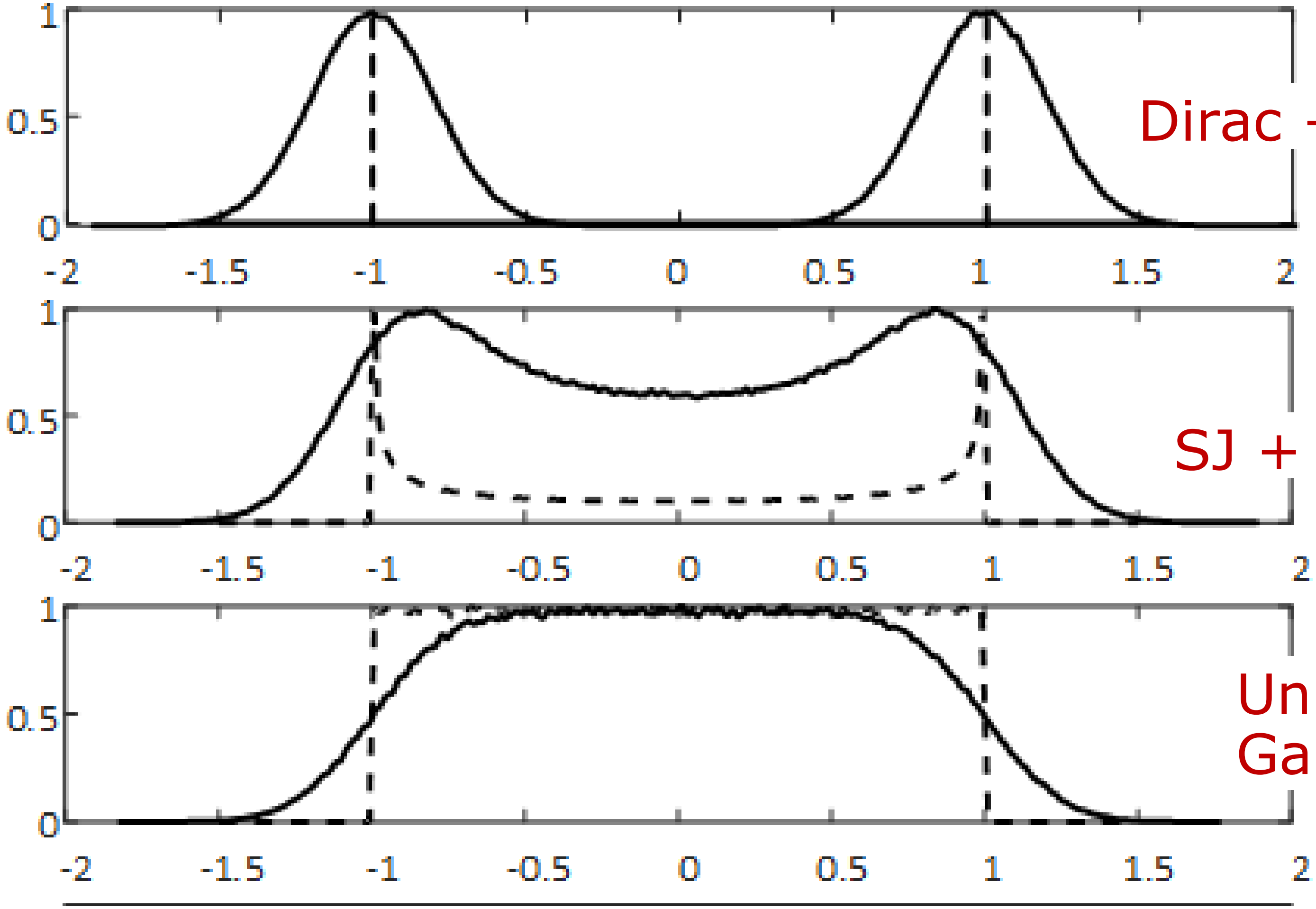
$$\boldsymbol{\varphi} = \omega_0 \, \boldsymbol{a} \qquad \sigma_\varphi = \omega_0 \sigma_a$$

$$\frac{\boldsymbol{a}}{T} = \frac{\boldsymbol{\varphi}}{2\pi} \qquad \frac{\sigma_a}{T} = \frac{\sigma_\varphi}{2\pi}$$

$$\sigma_{\mathrm{a}}^2 = \int_{-f_0/2}^{+f_0/2} S_{\mathrm{a}}(f)\, df$$

$$\sigma_{\mathrm{a}} = \sqrt{\frac{2}{\omega_0^2} \int_0^{+\infty} \mathcal{L}(f)\, df} \qquad \sigma_{\mathrm{a}} = \sqrt{\frac{2}{\omega_0^2} \int_{f_{min}}^{+f_0/2} \mathcal{L}(f)\, df}$$

Sum of two jitter: Convolve PDFs

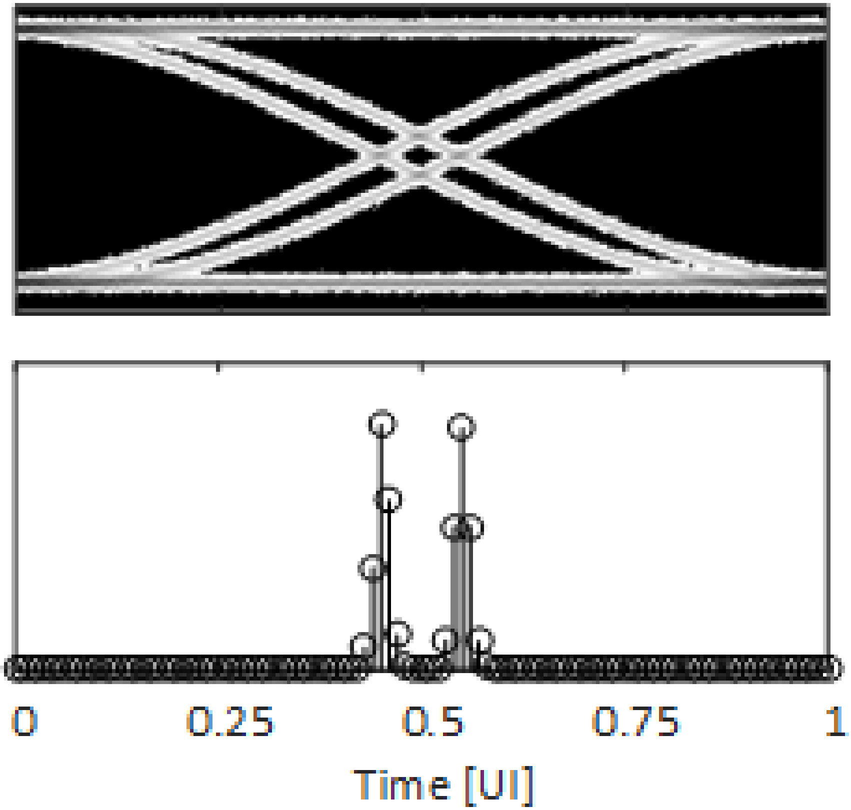


Dirac + Gaussian

SJ + Gaussian

Uniform +
Gaussian

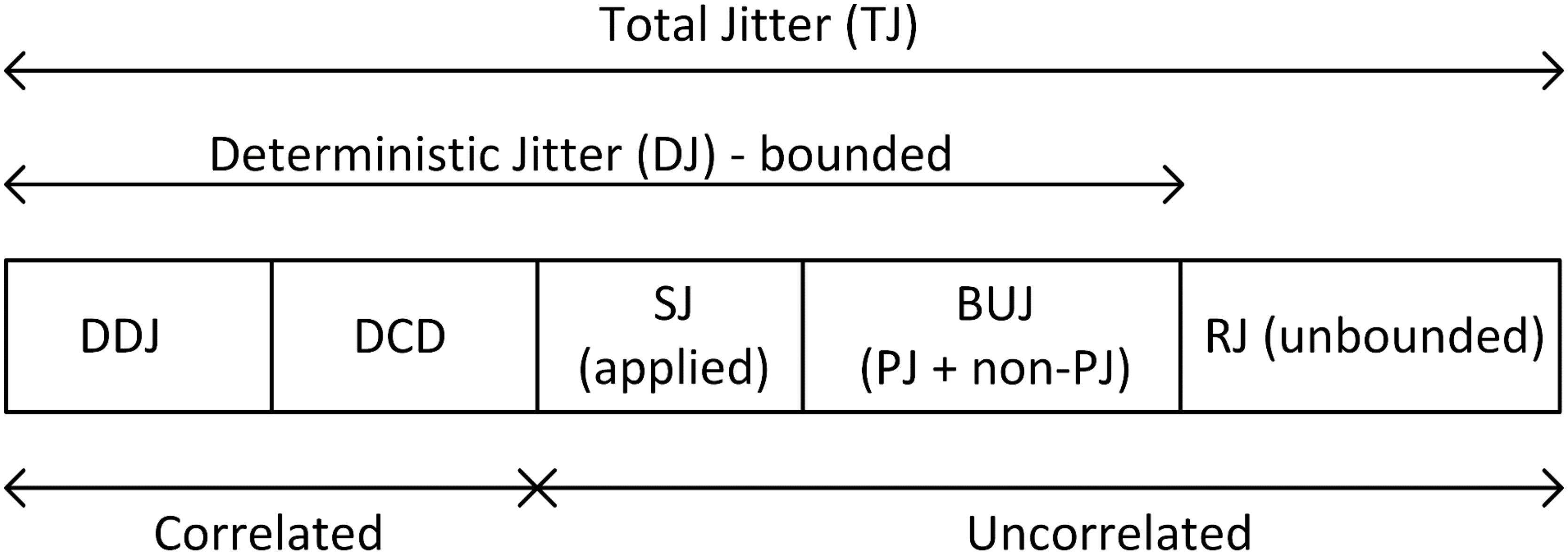
Combined Jitter in Eye Diagram



- Combined DCD & RJ
- Convolution of two PDFs

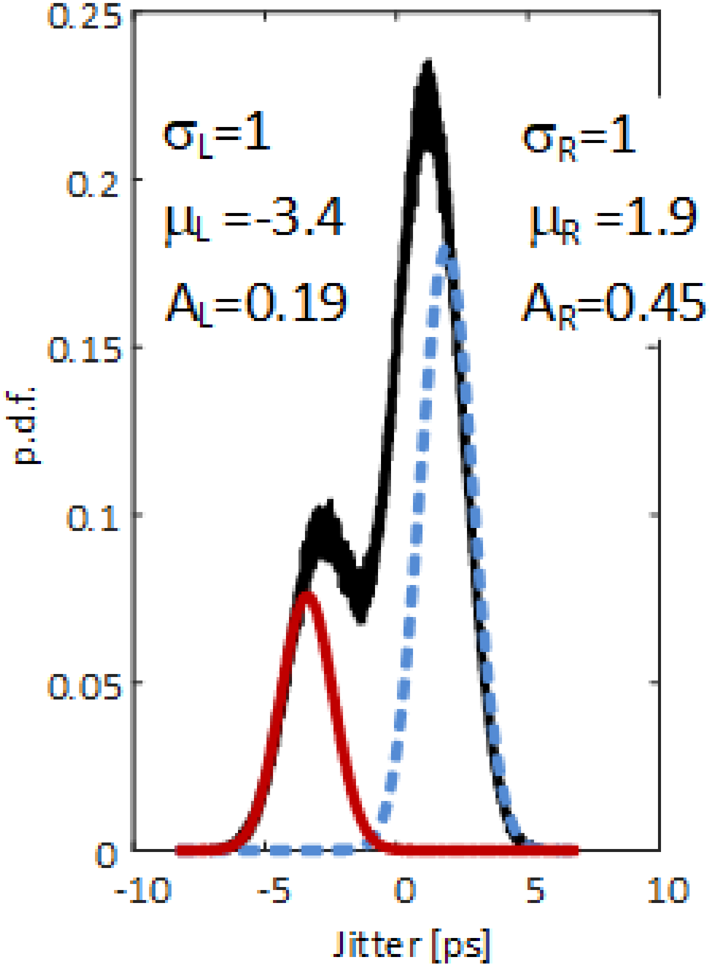
- Combined jitter is sum of individual jitter signals
- Combined jitter PDF is convolution of individual PDFs

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



- Tails at two ends
- Fit two tails to two Gaussian

- Calculate Total Jitter (TJ)
- TJ_{pp} for $BER=10^{-12}$

$TJ_{pp} = DJ_{pp} + RJ_{pp}$

$DJ_{pp} = \mu_R - \mu_L = 5.3ps$

$RJ_{pp} = RJ_p(L) + RJ_p(R)$

$RJ_{pp} = Q\sigma_L + Q\sigma_R = 14ps$

(assuming Q=7)

$TJ_{pp} = 19.3ps$

P(jitter outside TJ_{pp}) =0.82e-12

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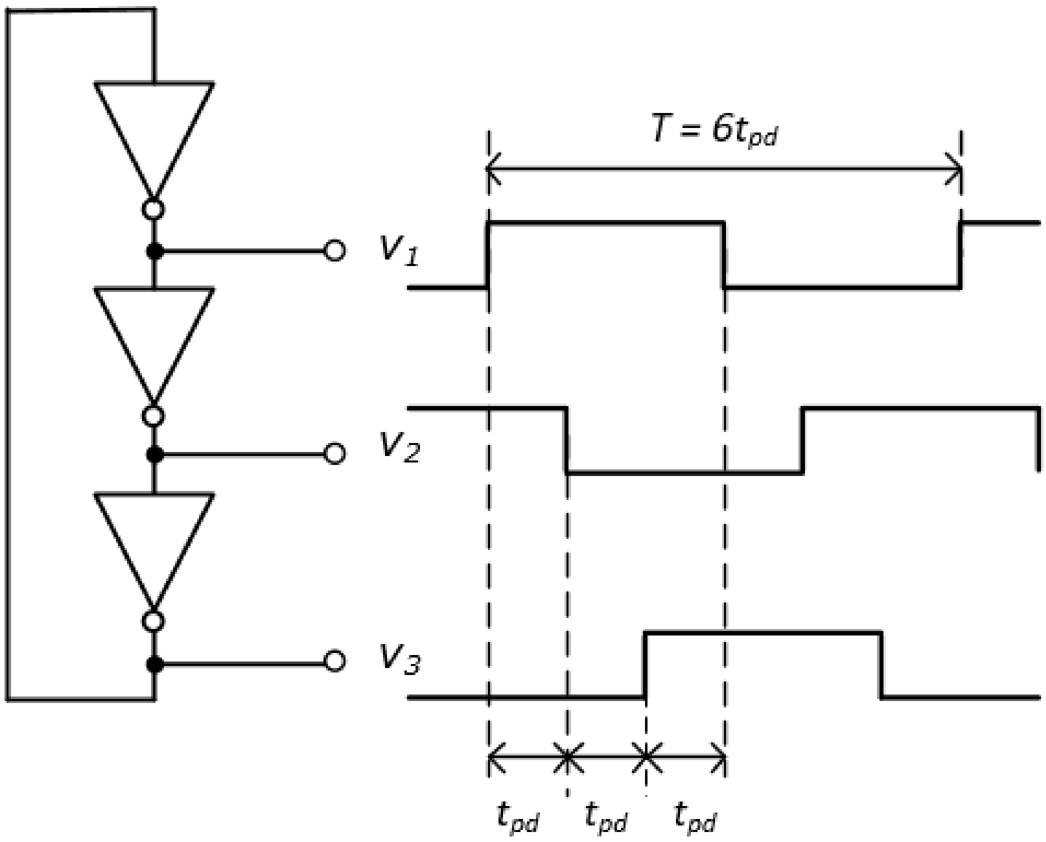
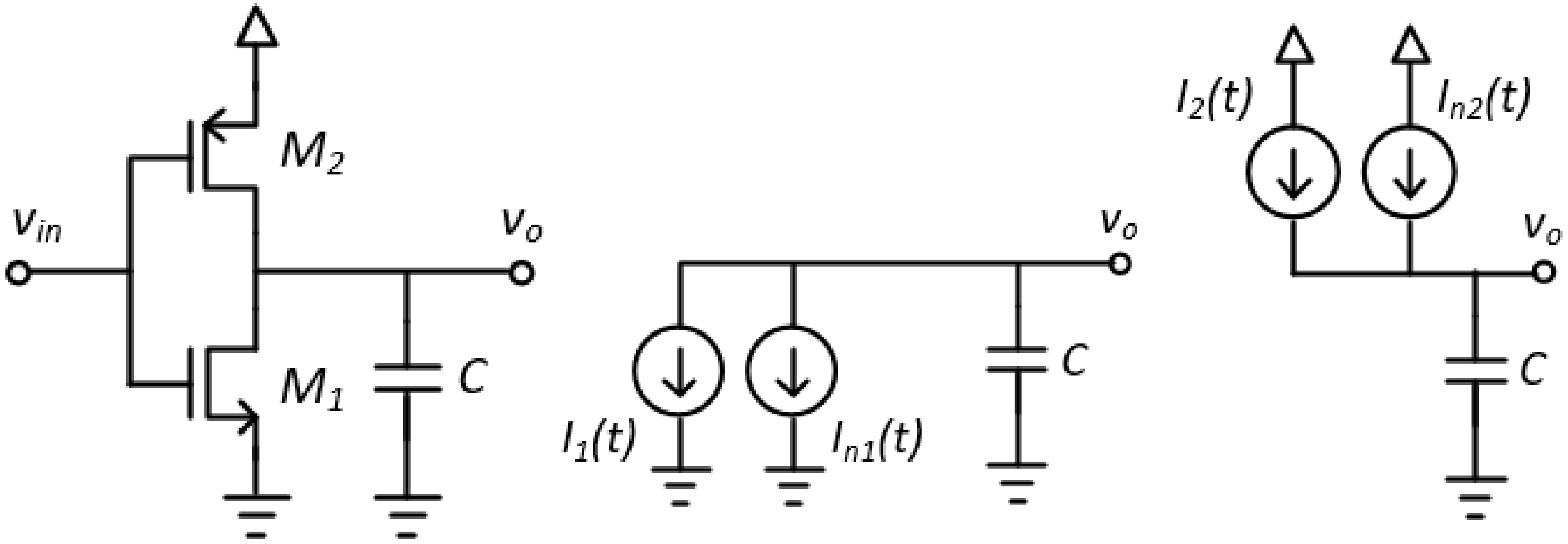
Example: A Ring Oscillator



- For any output, say v_1, the period is $6t_{pd}$
- But t_{pd} is random variable (signal) changing with time

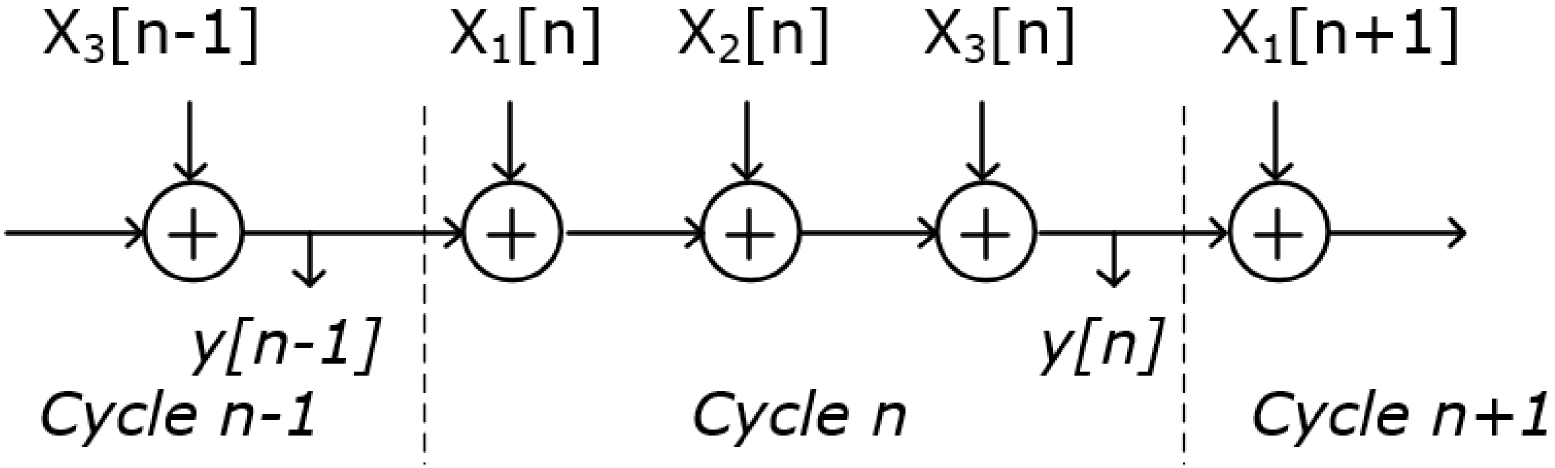
Example: Delay of an Inverter



- $I_{n1}(t)$ and $I_{n2}(t)$ represent the thermal (and other) noise currents of M1 and M2, respectively

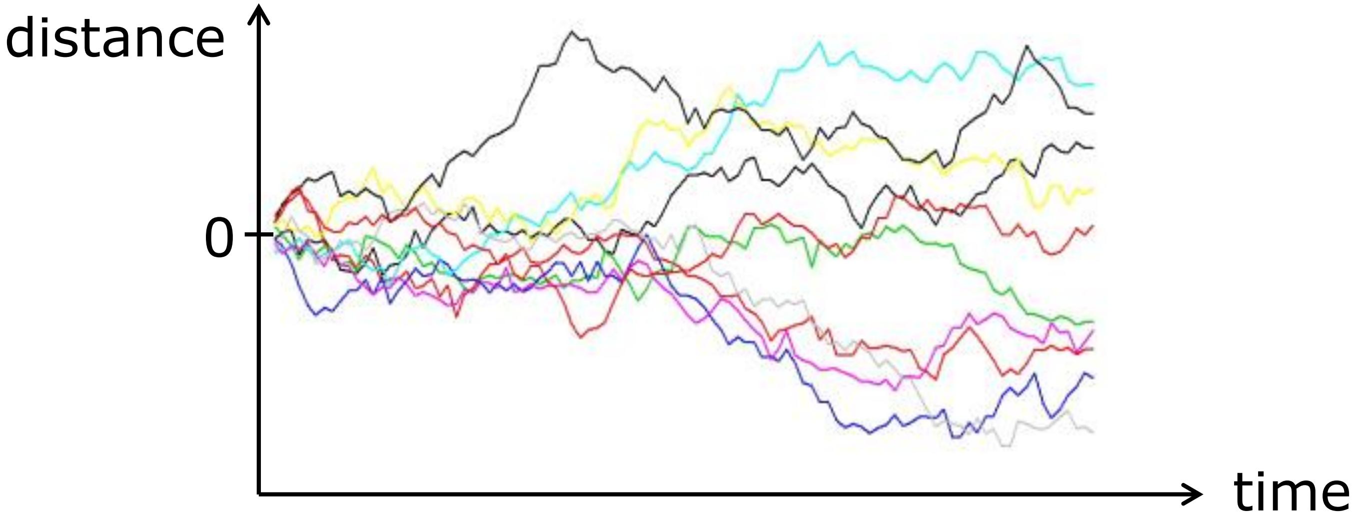
- $I_{n1}(t)$ and $I_{n2}(t)$ will cause v_o to reach a threshold ($V_{DD}/2$) faster or slower than nominal; causing delay of each stage to be a random variable

Modeling Jitter in Ring Oscillator



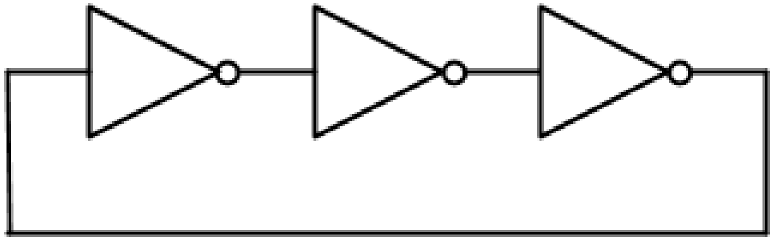
- Let $X_i[n]$ represent the random *excess delay* introduced by inverter i in n-th cycle
- $X_i[n]$ is a random signal with expected value of zero
- What can we say about the jitter in the output y[n]?
- $y[n] = y[n-1] + X_1[n] + X_2[n] + X_3[n]$
- Reasonable to assume $X_i[n]$ is stationary & uncorrelated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

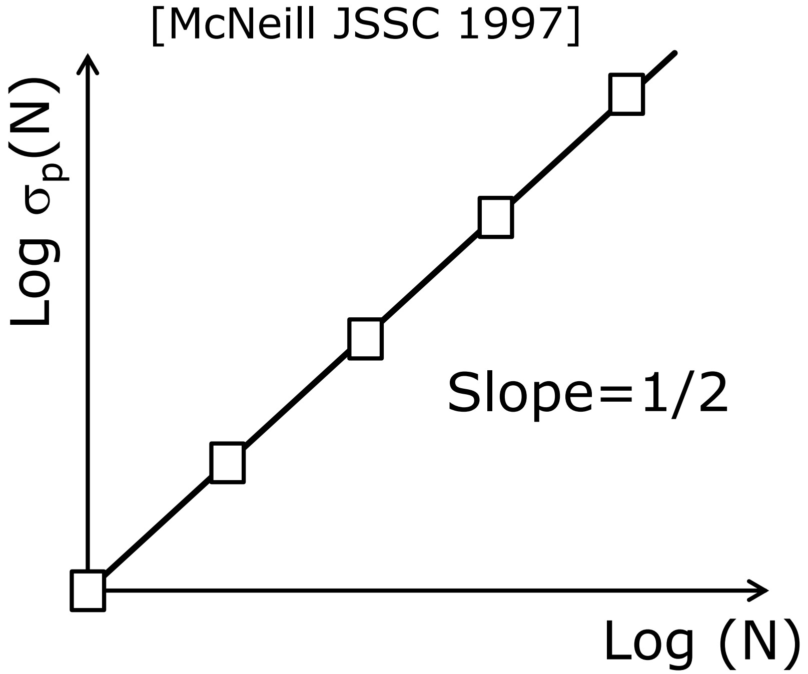
Random Walk Process



- 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



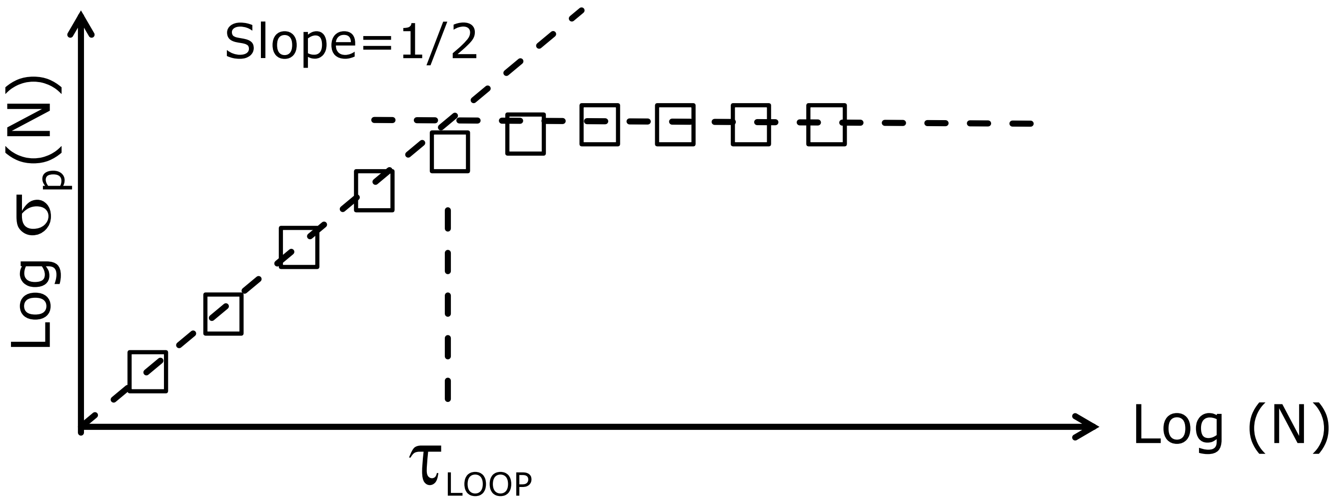


$$\sigma_p(N) = \sqrt{N}\,\sigma_p(1)$$

$$Log\left(\sigma_p(N)\right) = Log\left(\sigma_p(1)\right) + \frac{1}{2} Log(N)$$

- 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

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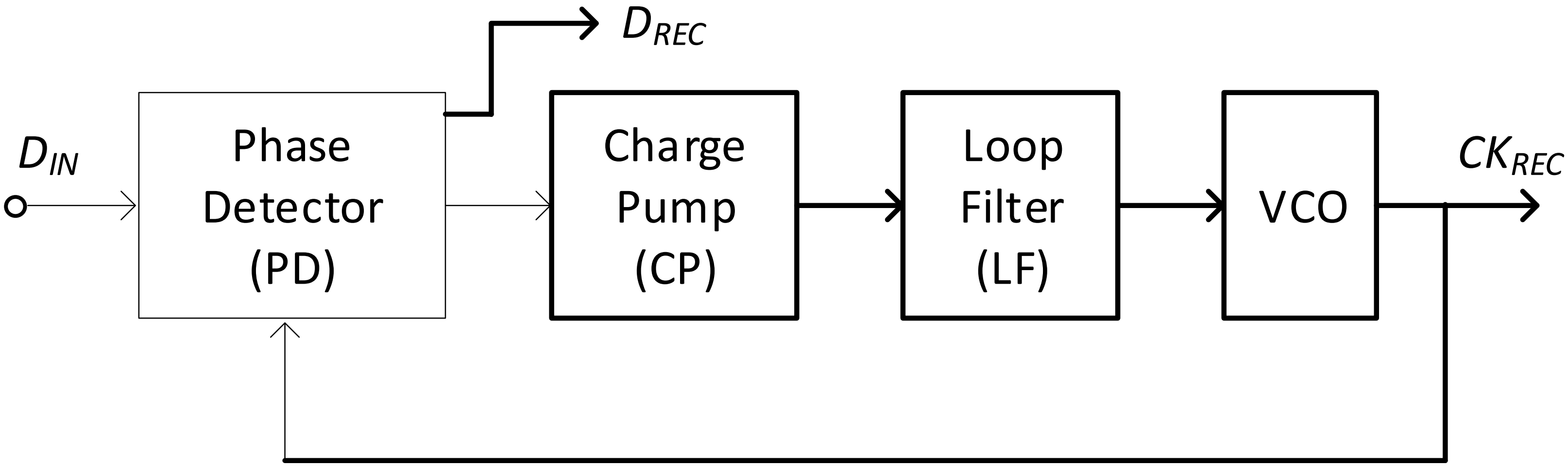
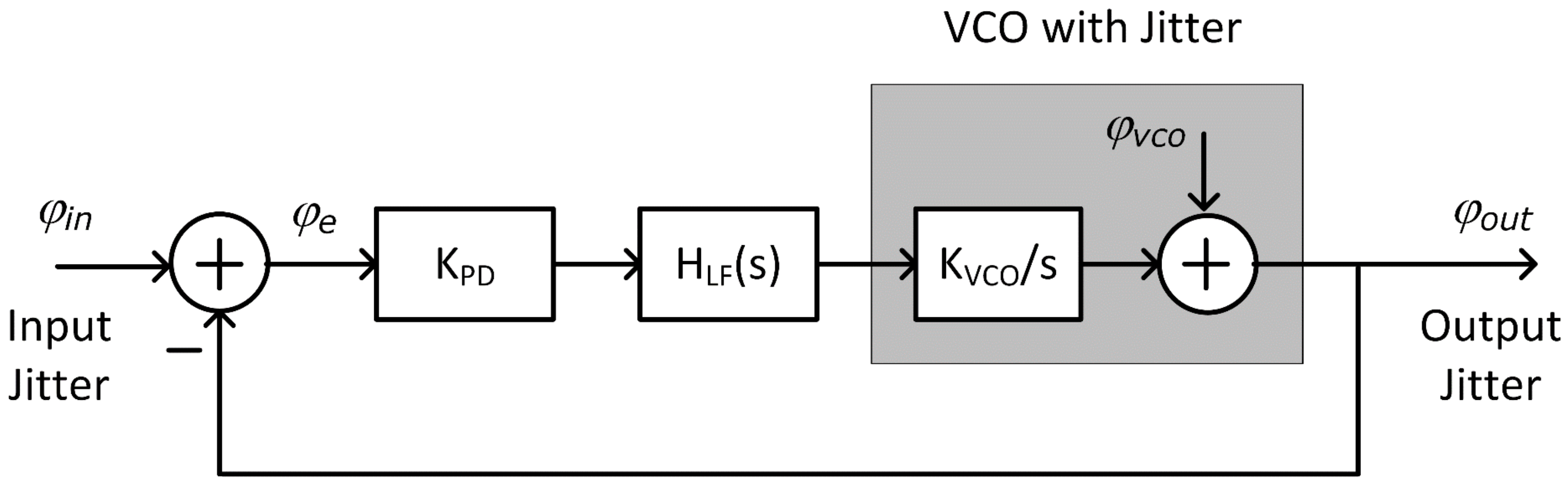
Clock and Data Recovery Blocks



- ☐ 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
- ☐ CK_{REC} is used to sample D_{IN} and produce D_{REC}

Linear Model of CDR

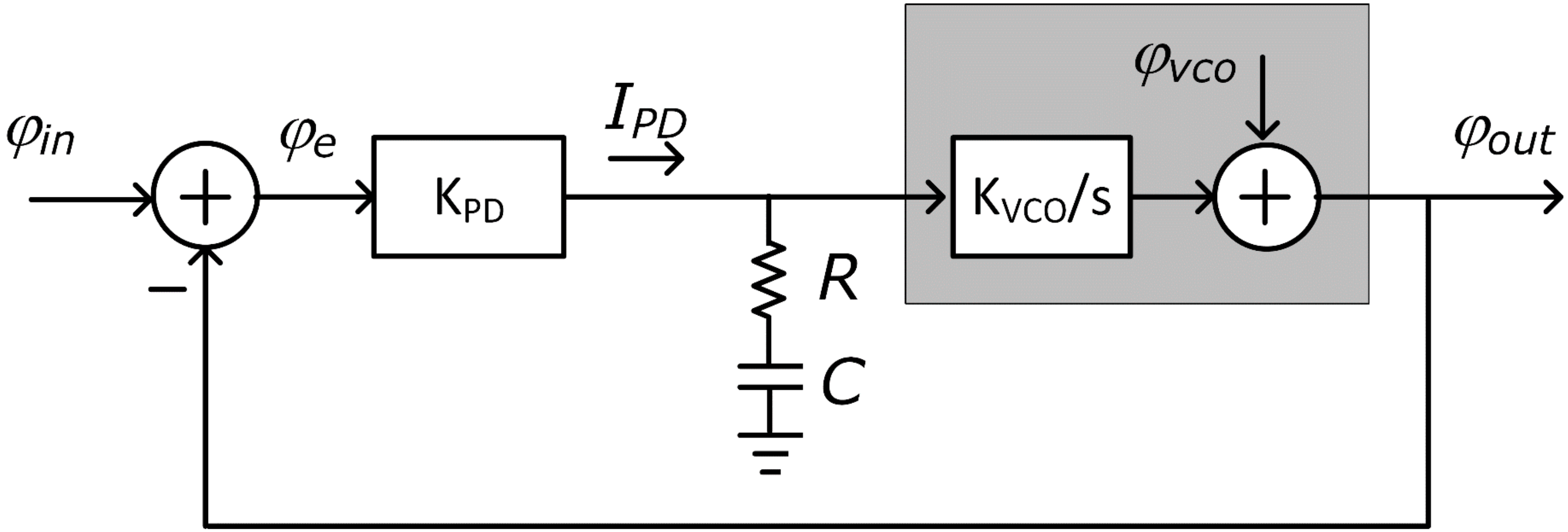


$$S_{out}(f) = |H_T(f)|^2 S_{in}(f) + |H_G(f)|^2 S_{VCO}(f)$$

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

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

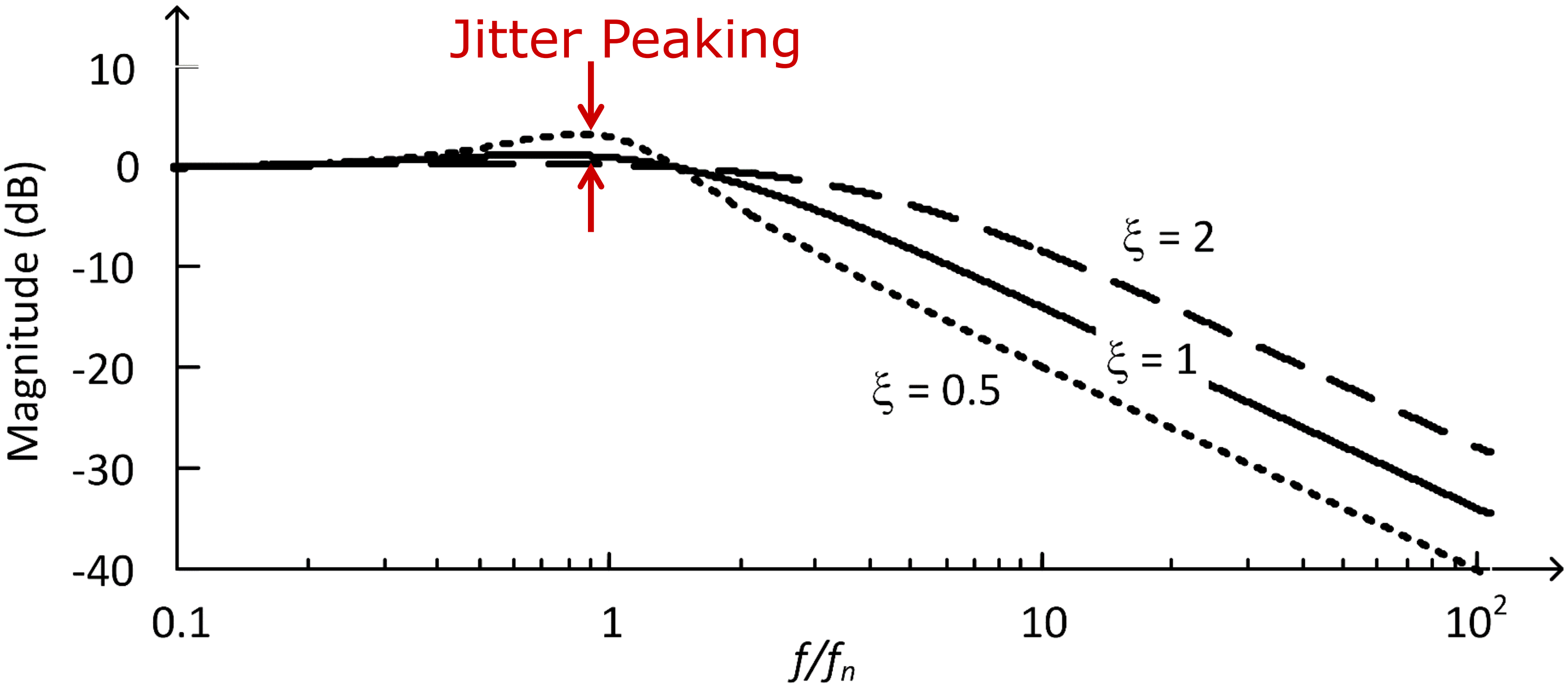
Model of CDR with Charge Pump



$$H_T(s) = \frac{2\xi\omega_n s + \omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \qquad \omega_n^2 := \frac{K_{PD}K_{VCO}}{C}$$

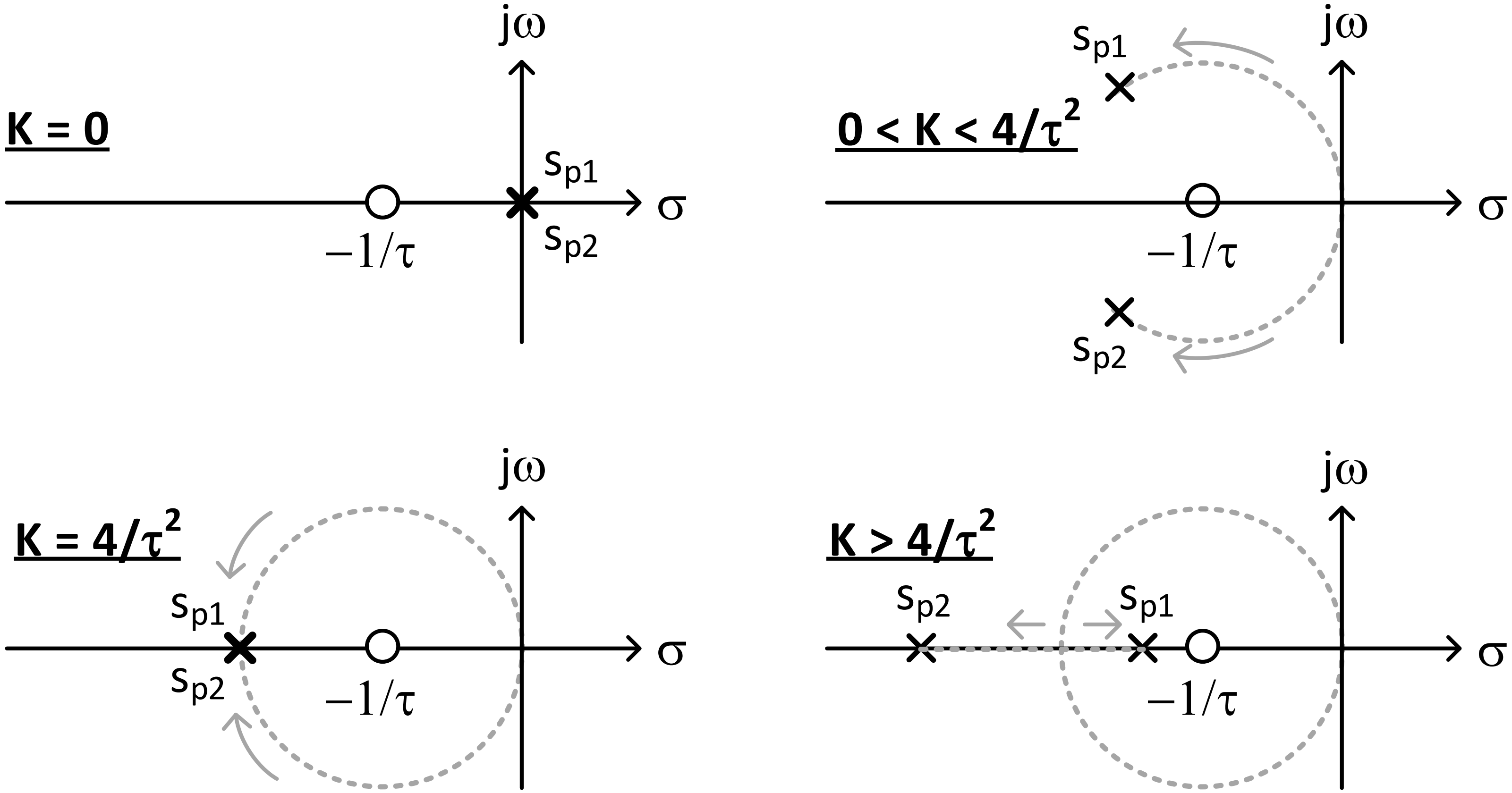
$$|H_T(f)|^2 = \frac{4\xi^2\omega_n^2\omega^2 + \omega_n^4}{(\omega_n^2 - \omega^2)^2 + 4\xi^2\omega_n^2\omega^2} \qquad \xi := \frac{K_{PD}K_{VCO}R}{2\omega_n}$$

Jitter Transfer Function

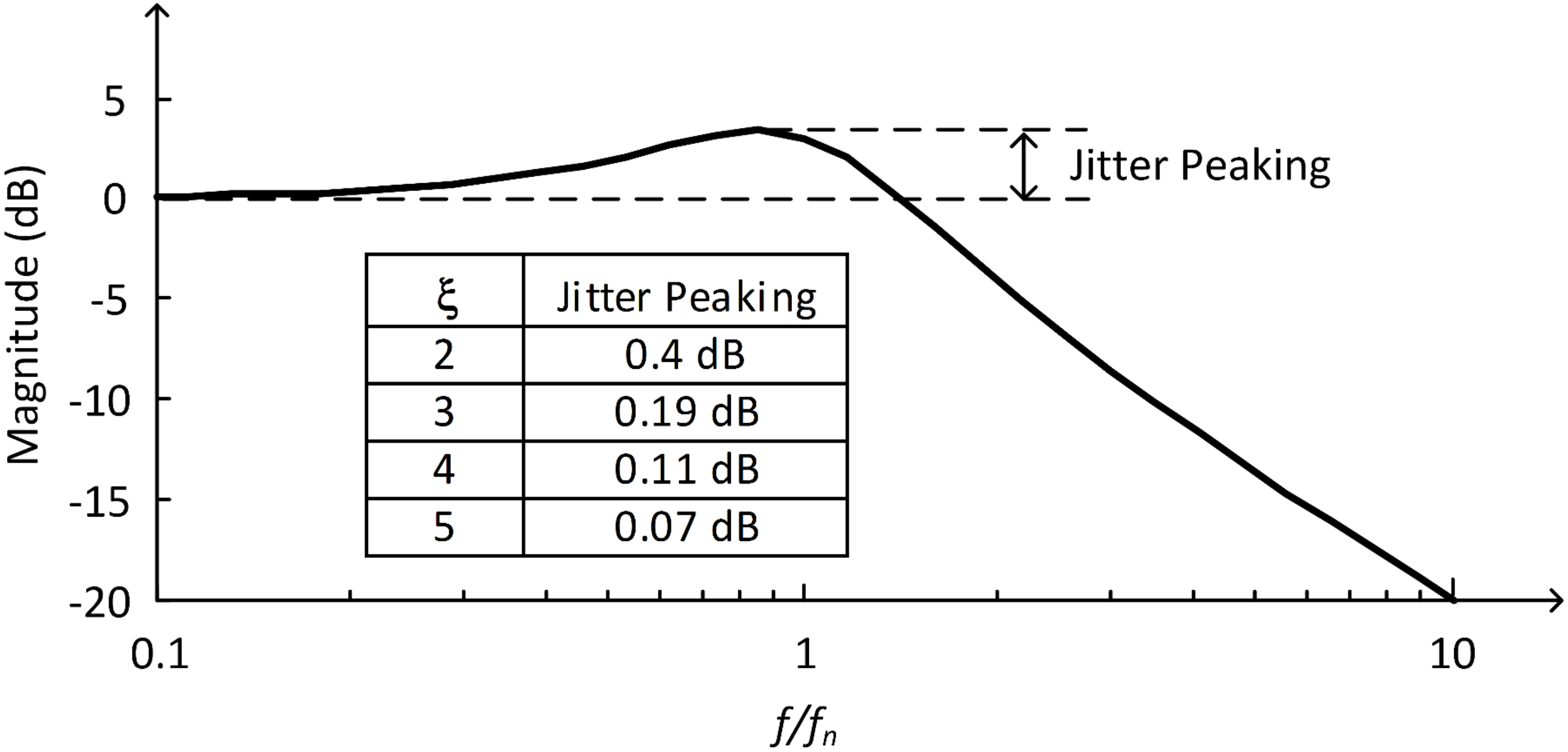


$$|H_T(f)|^2 = \begin{cases} 1 & \text{if } f << f_n \\ 4\xi^2(\frac{f_n}{f})^2 & \text{if } f >> f_n \end{cases}$$

Zero/Pole Locations



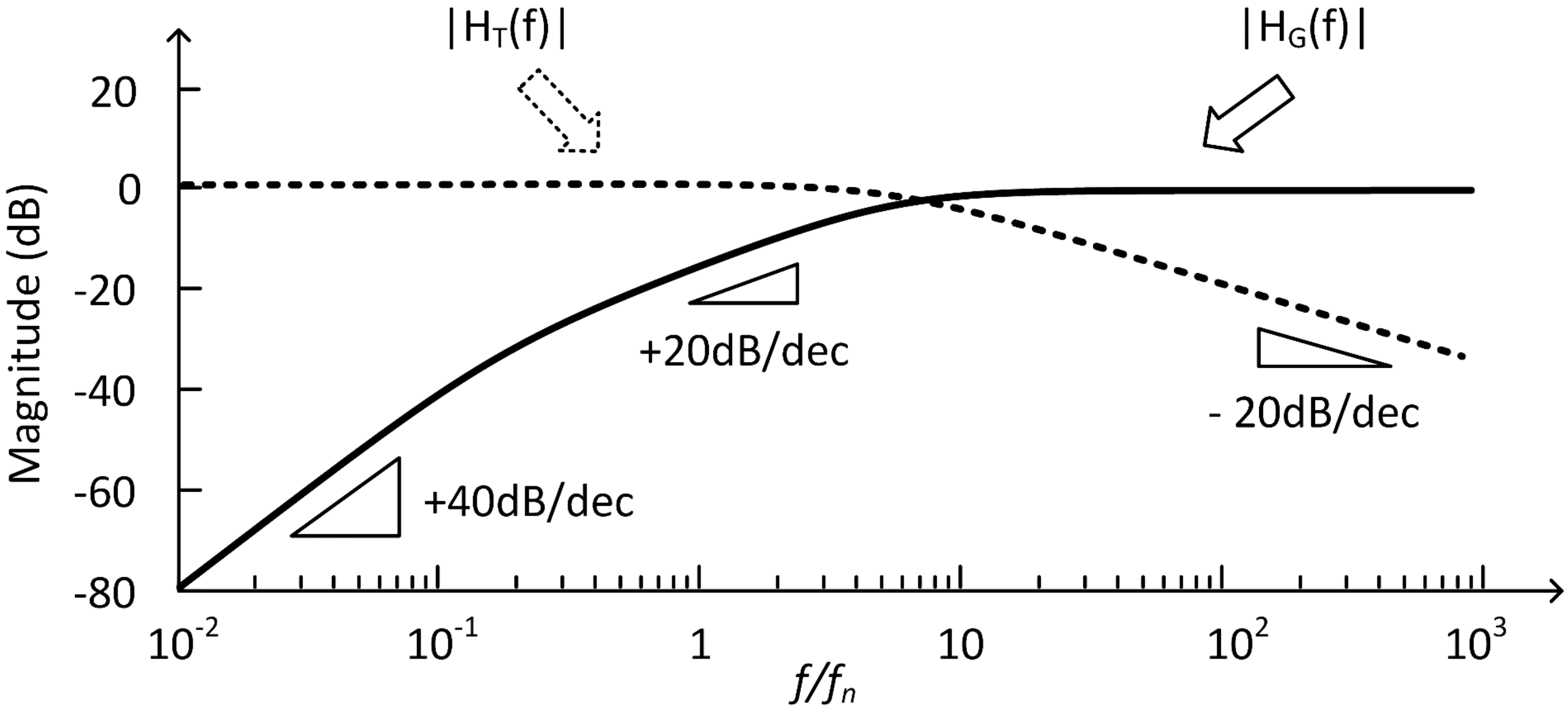
Jitter Peaking



ξ	Jitter Peaking
2	0.4 dB
3	0.19 dB
4	0.11 dB
5	0.07 dB

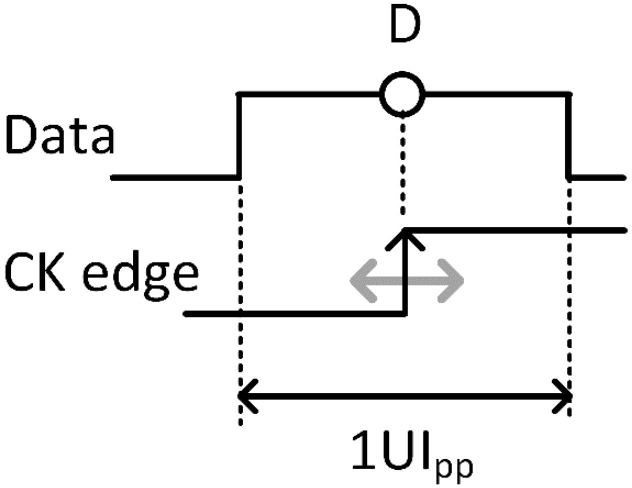
- Undesirable as it enhances jitter, esp. in repeaters
- Standards requirement < 0.1dB

Jitter Generation Function



$$|H_G(f)|^2 = \frac{\omega^4}{(\omega_n^2 - \omega^2)^2 + 4\xi^2\omega_n^2\omega^2}$$

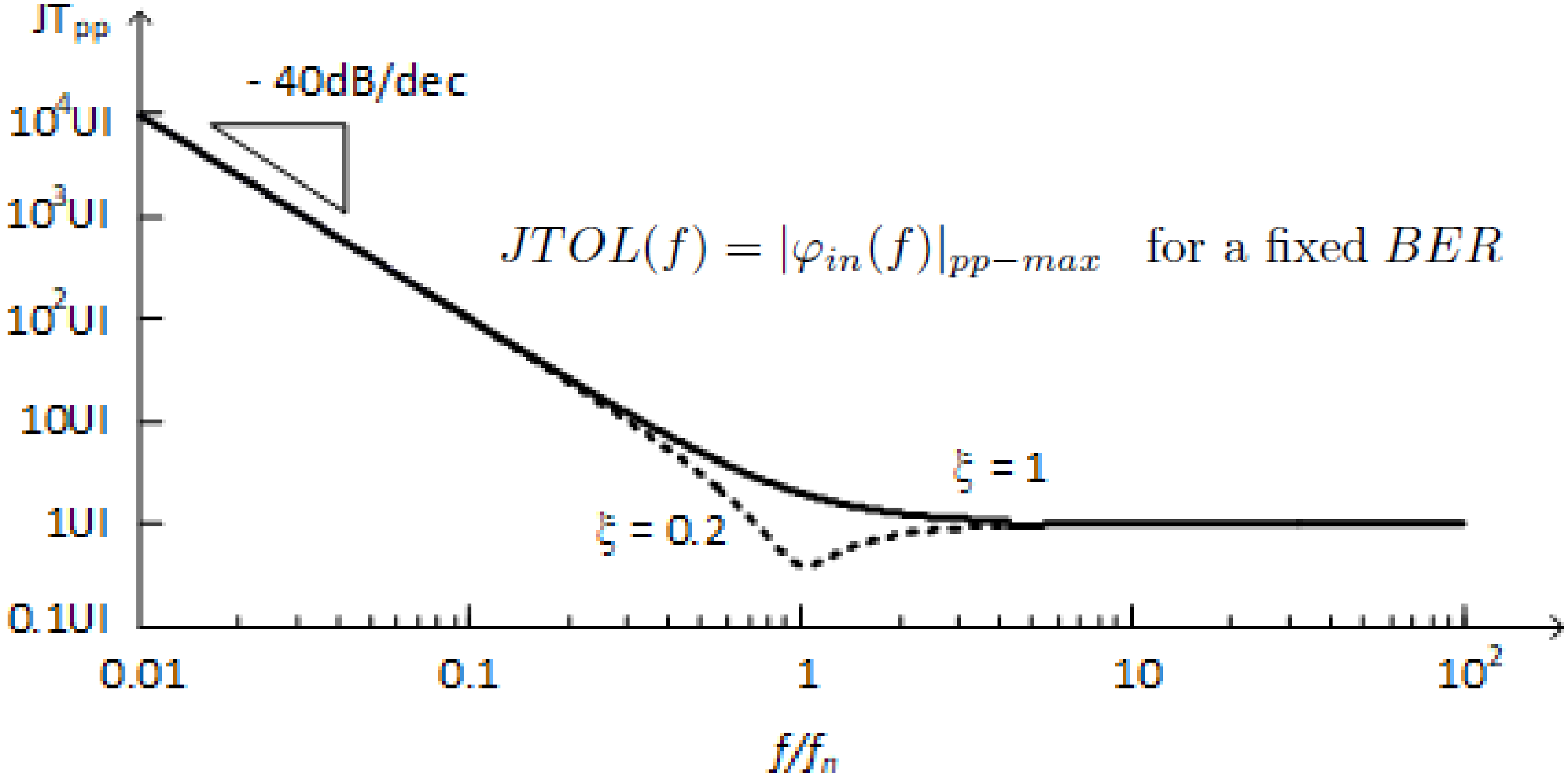
Jitter Tolerance Concept



- ☐ Maximum tolerable peak-to-peak jitter on CK edge
- ☐ $1UI_{pp}$ for high jitter frequencies

- ☐ Higher than $1UI_{pp}$ for lower jitter frequencies

Jitter Tolerance Curve

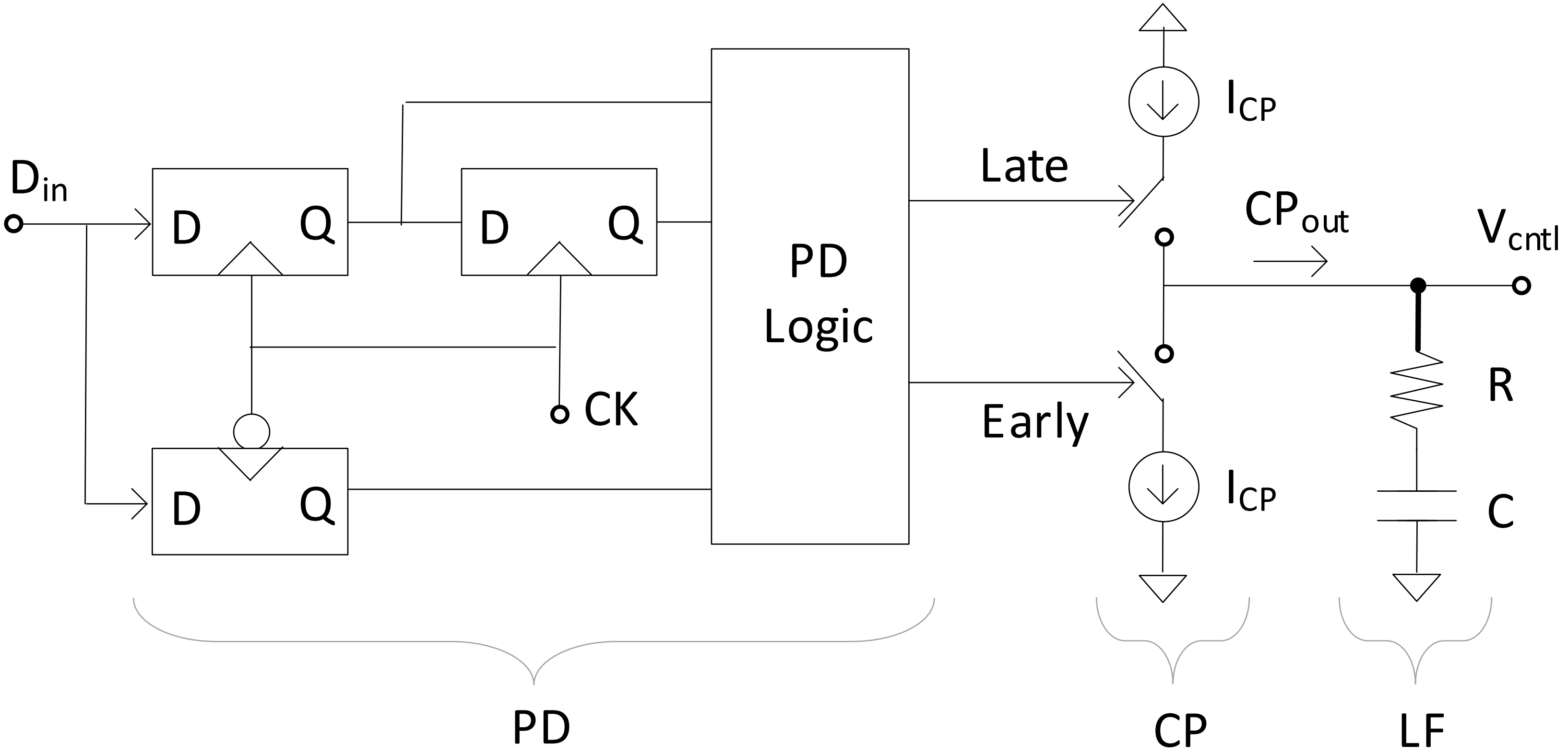


$$JTOL(f) = |\varphi_{in}(f)|_{pp-max} \quad \text{for a fixed } BER$$

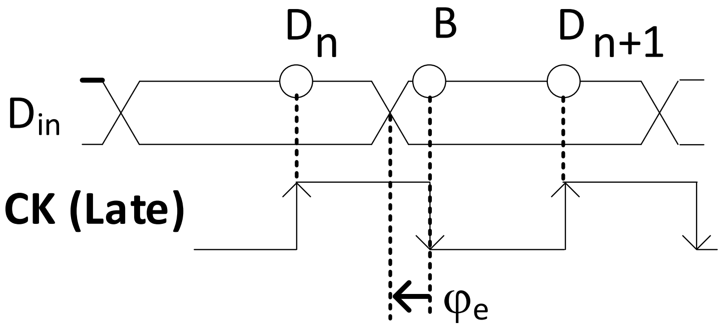
$$JTOL(f) = \left|\frac{\varphi_{in}(f)}{\varphi_e(f)}\right| \quad [\mathrm{UI}] \qquad JTOL(f) = \begin{cases} \left(\frac{f_n}{f}\right)^2 & \text{if } f << f_n \\ 1 & \text{if } f >> f_n \end{cases}$$

Outline

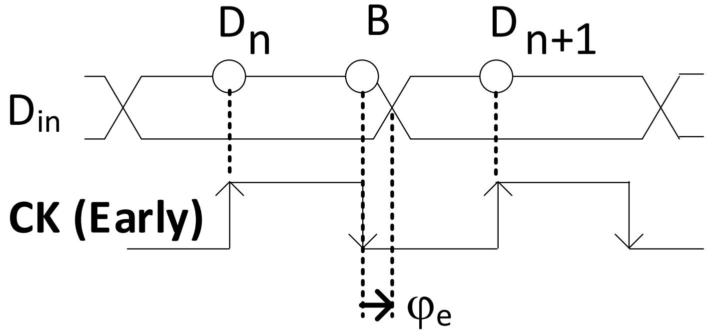
Bang-Bang PD Operation (1 of 3)

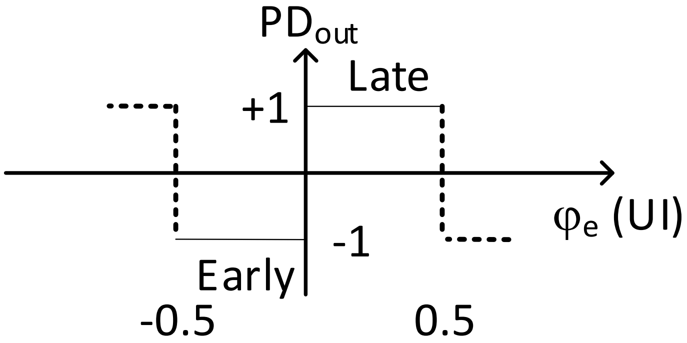


Bang-Bang PD Operation (2 of 3)



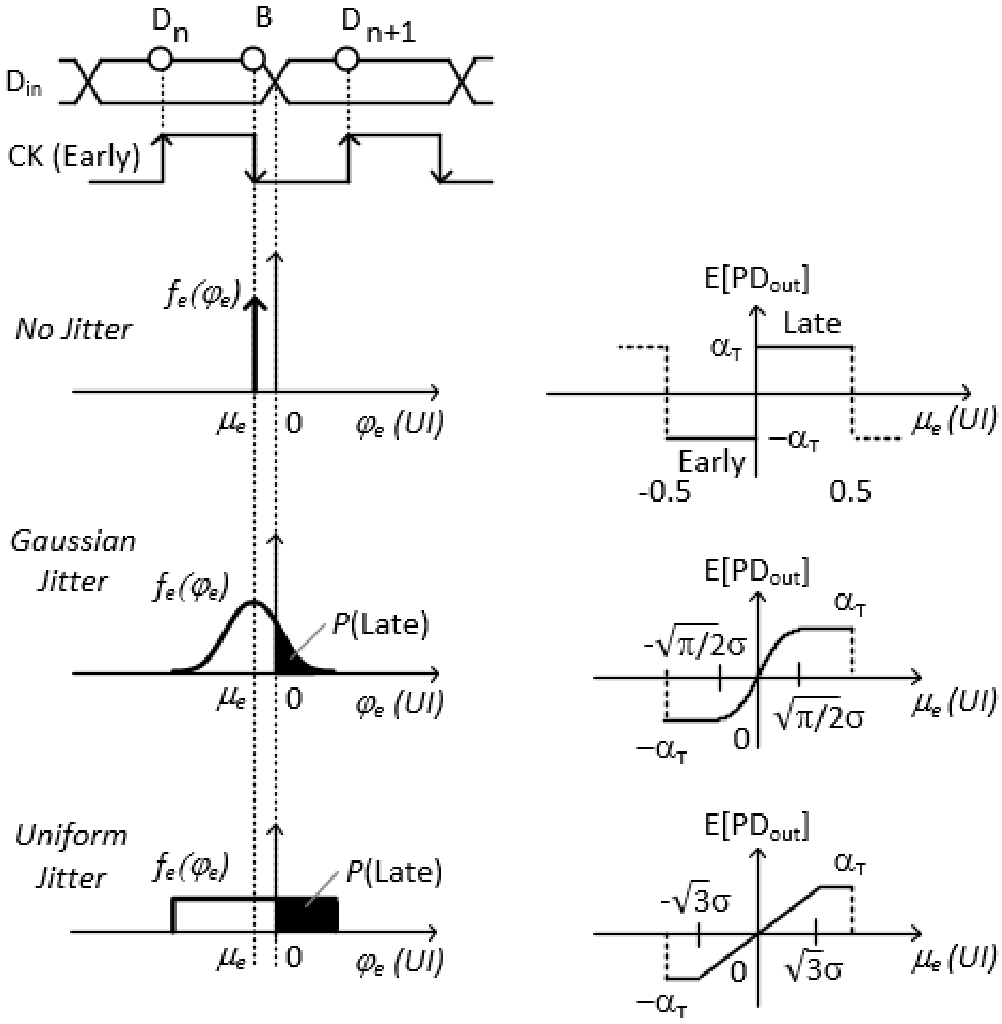
D_n	B	D_{n+1}	Early	Late	PDout
X	$\overline{X}$	$\overline{X}$	0	1	1
X	X	$\overline{X}$	1	0	-1
X	X	X	0	0	0





Bang-Bang PD Operation (3 of 3)

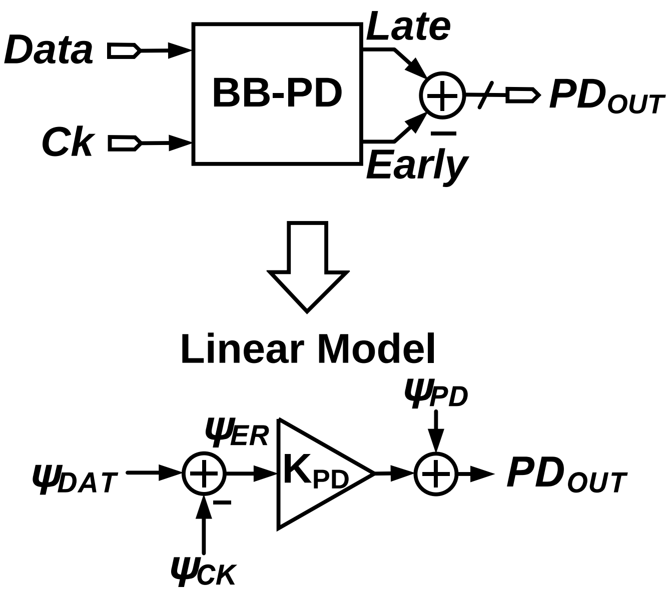
[Lee JSSC 2004]



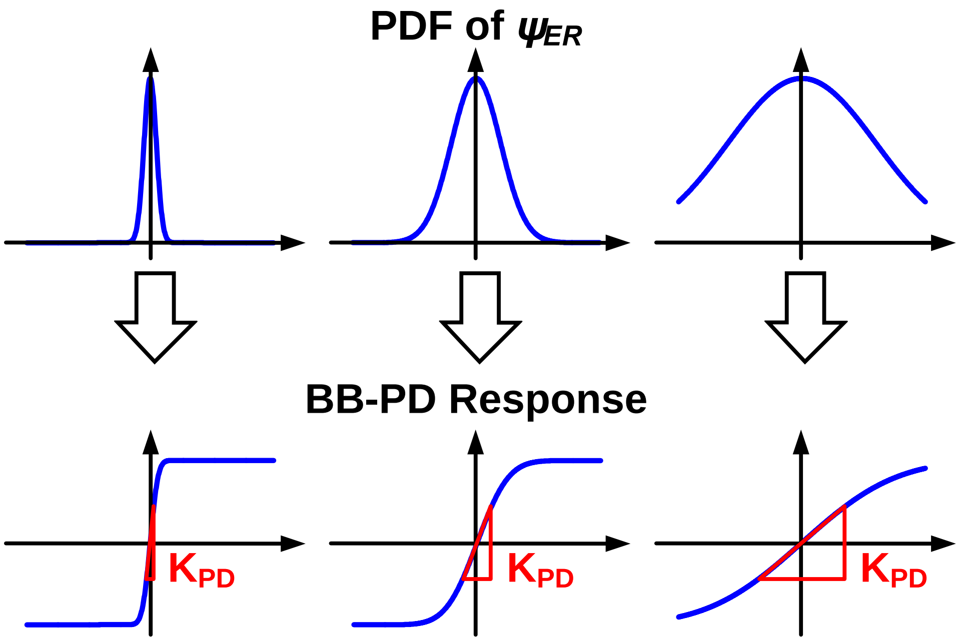
BB-PD Model with Jitter

[Liang JSSC 2015]

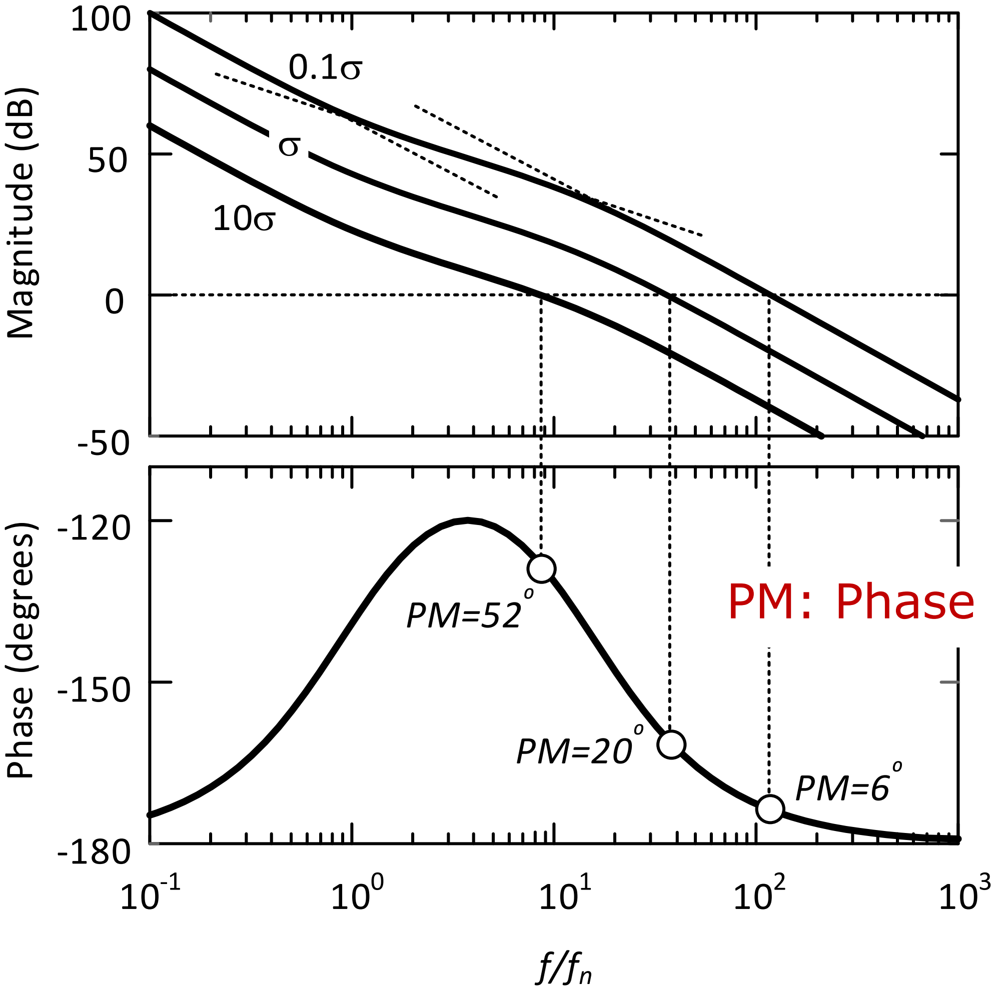
Linear Model of BB-PD



Effect of ψ_{ER} on PD Gain



Effects of Jitter on CDR Stability



PM: Phase Margin

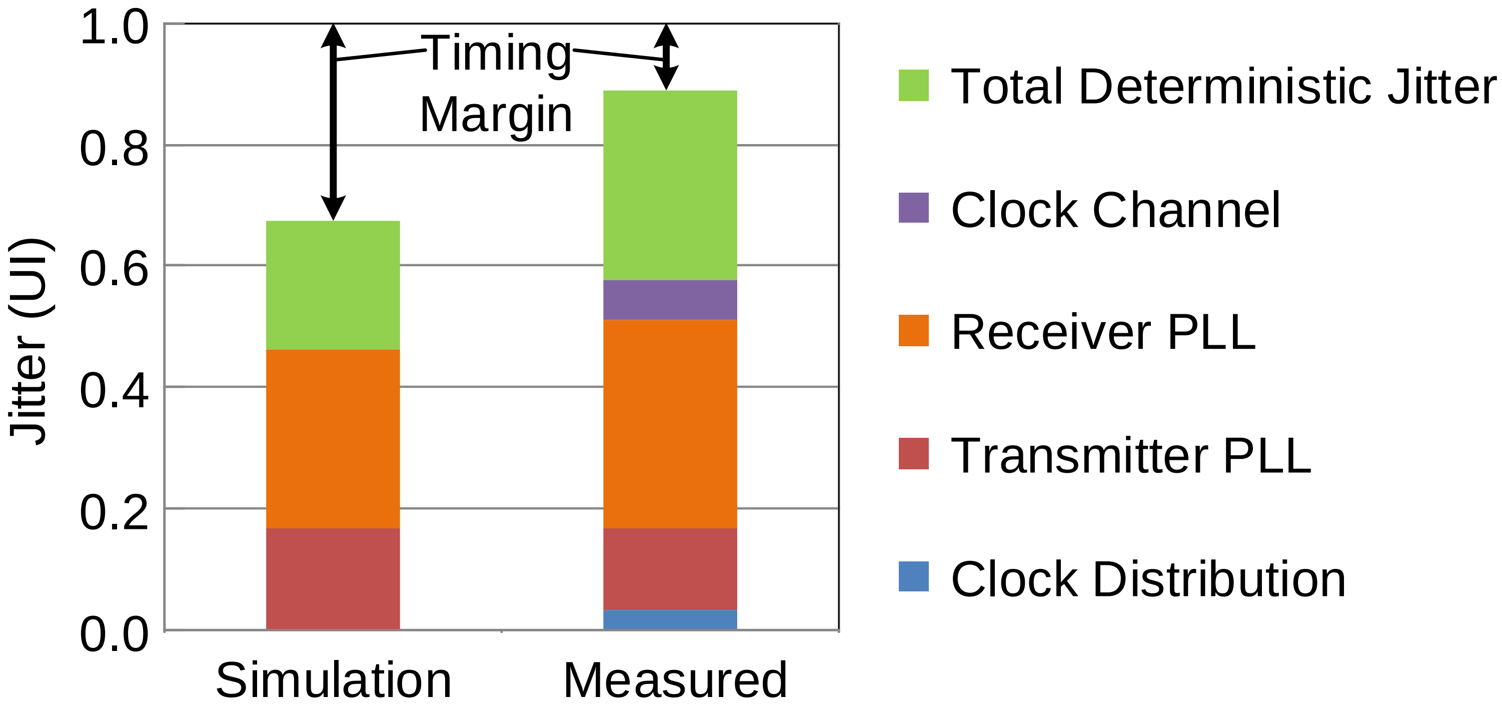
Outline

- Motivation
- Jitter Definitions: What is Jitter?
- Characterizing and Classifying Jitter
- Example: Jitter in Ring Oscillator
- Example: Jitter in Clock and Data Recovery
- Effects of Jitter on Bang-Bang CDR Operation

- **Jitter Monitoring and Jitter Mitigation**

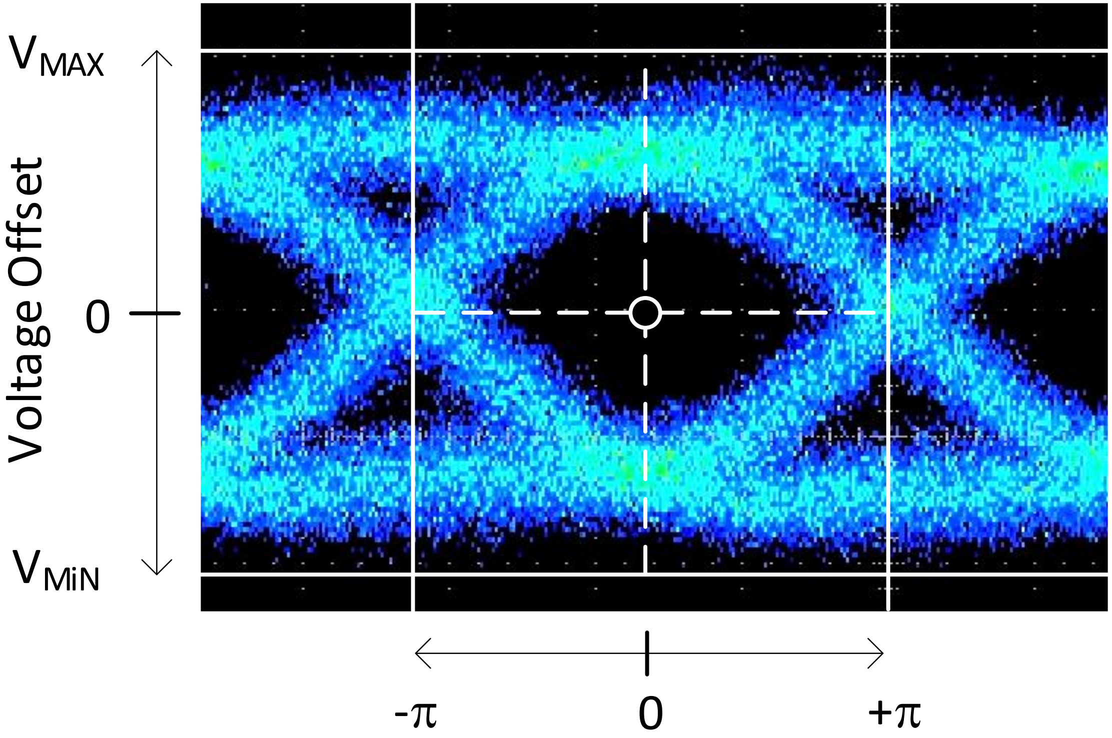
- Intentional Jitter: How Jitter can help
- Summary
- References

Why Jitter Monitoring?



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

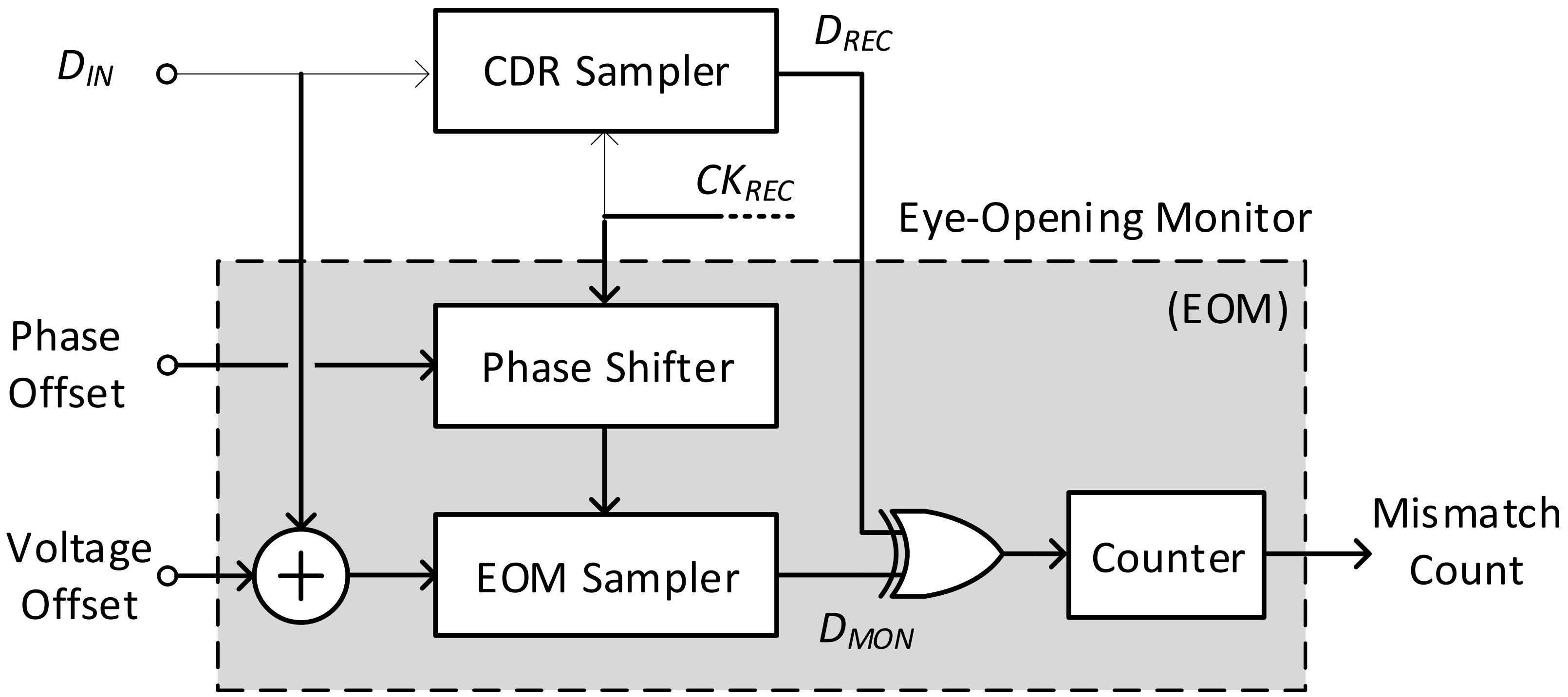
Ideal Sampling Position



- 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

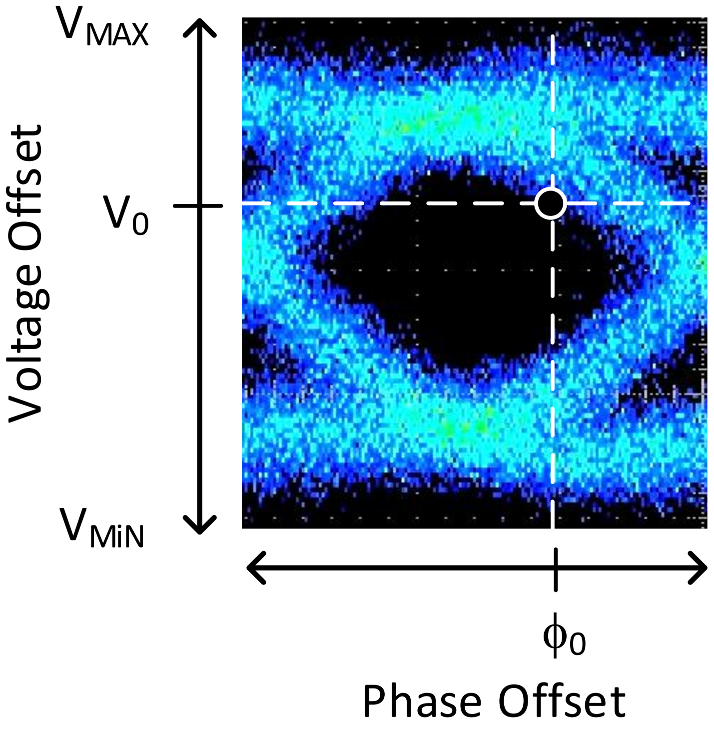
[Noguchi JSSC '08]

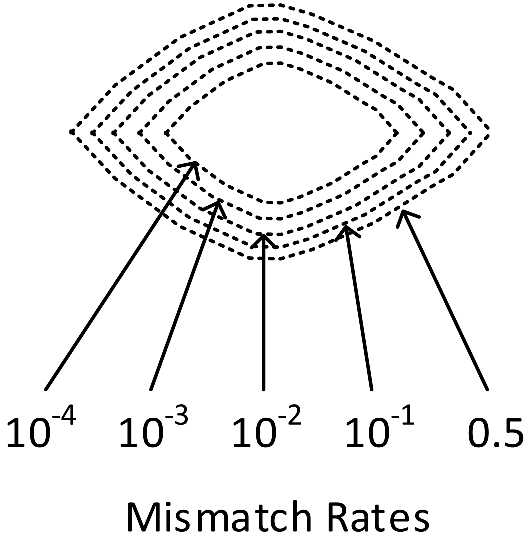


- EOM samples data at a phase/voltage offset away from CDR sampling point
- Comparing the two samples creates an "eye map"

Search for Ideal Sampling Position

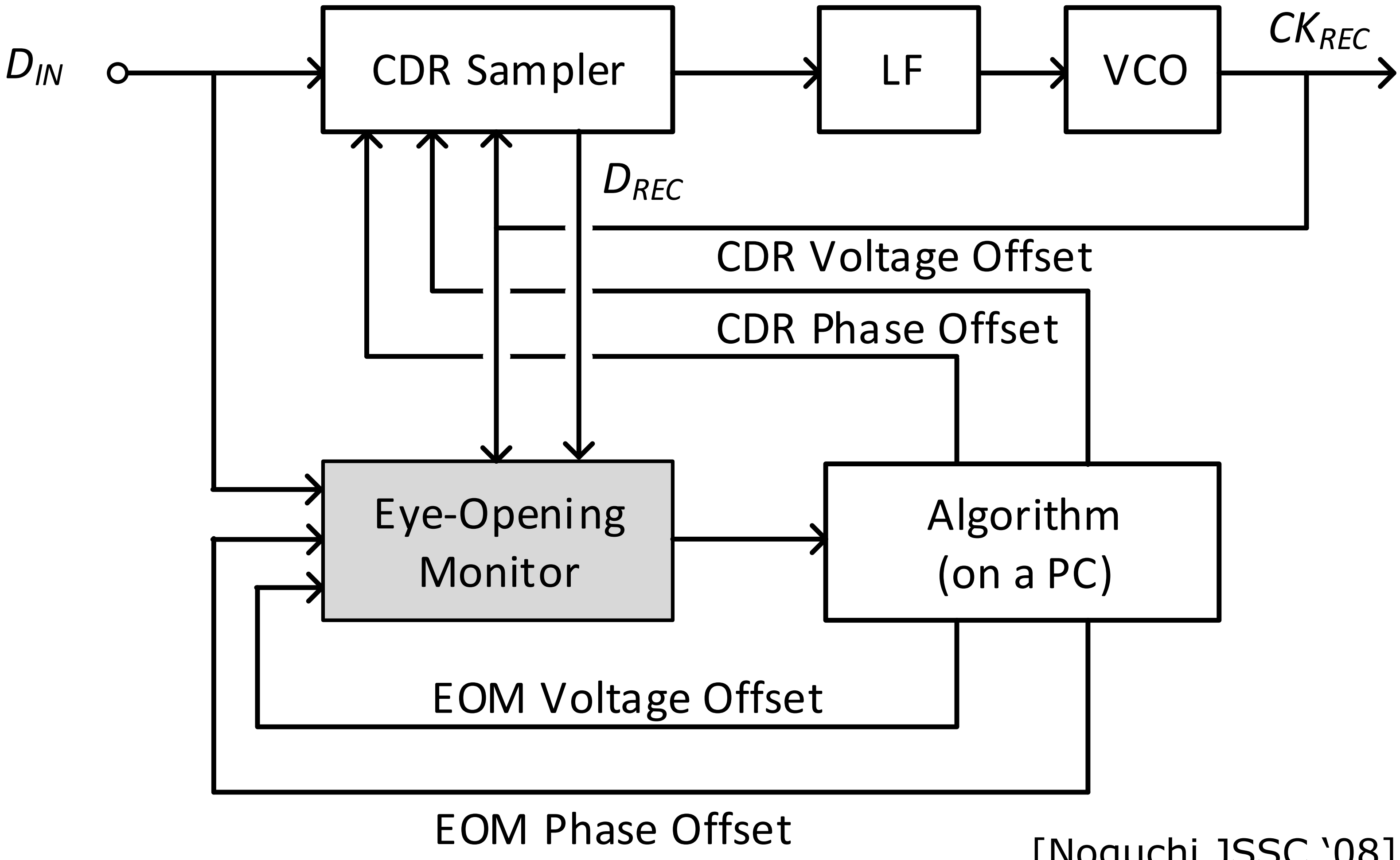
[Noguchi JSSC ‘08]





- Comparing CDR and EOM data creates eye contours
- Adaptive algorithms will position CDR sampling location

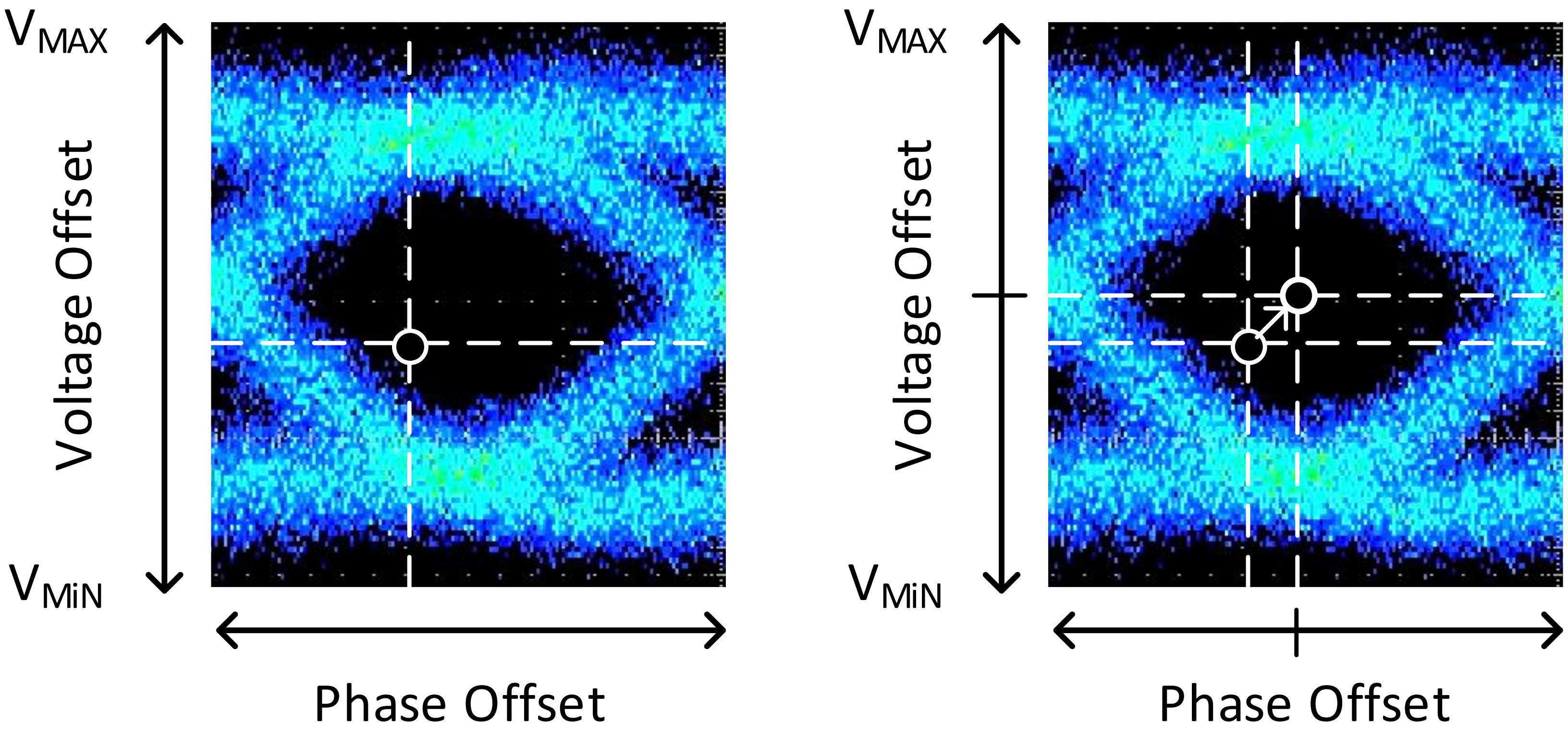
CDR with Eye-Opening Monitor



[Noguchi JSSC '08]

Moving to Ideal Position

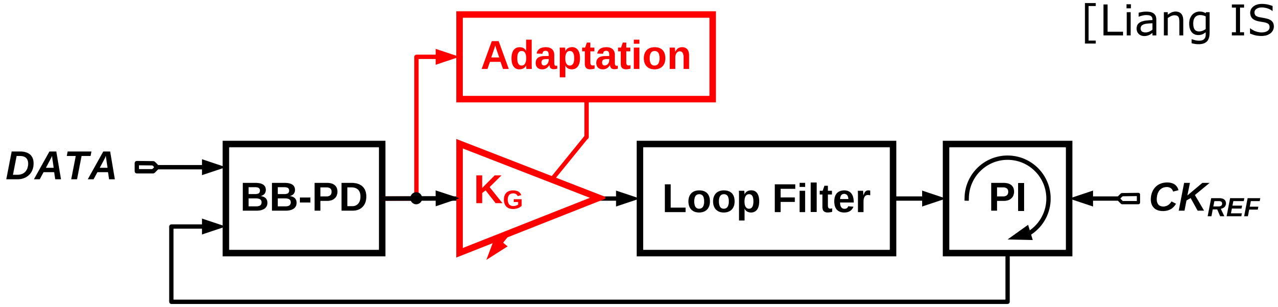
[Noguchi JSSC ‘08]



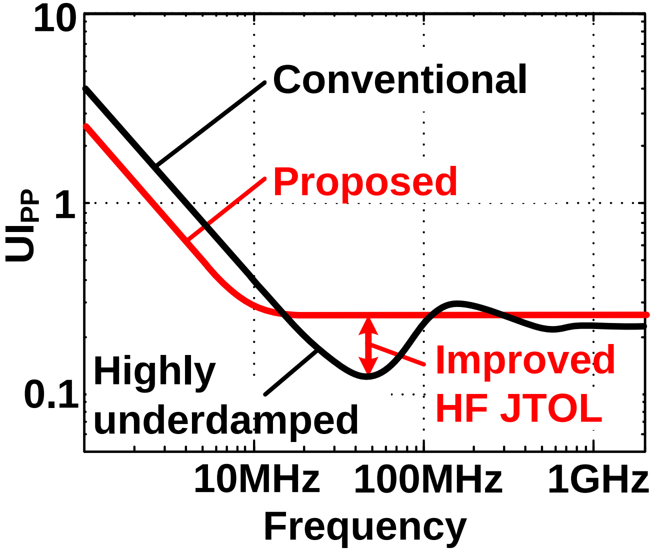
- Initial sampling position of CDR is detected using EOM
- Sampling position is moved to the center of the eye

Jitter Monitoring for Jitter Tolerance

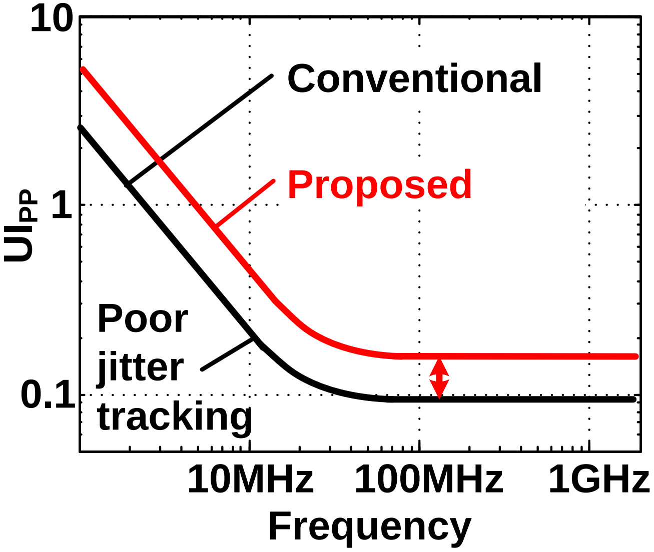
[Liang ISSCC’17]



JTOL when jitter is too small

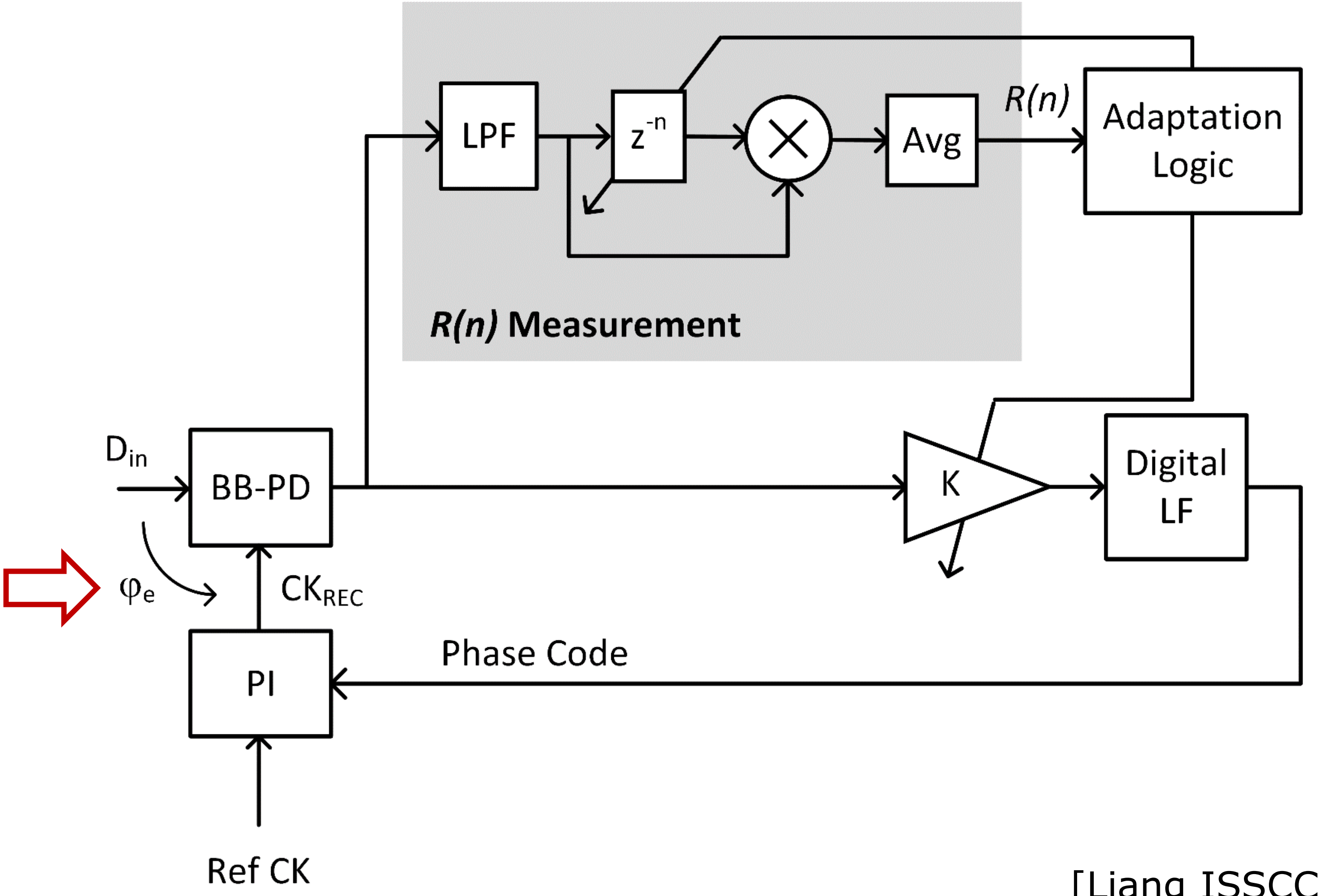


JTOL when jitter is too high



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

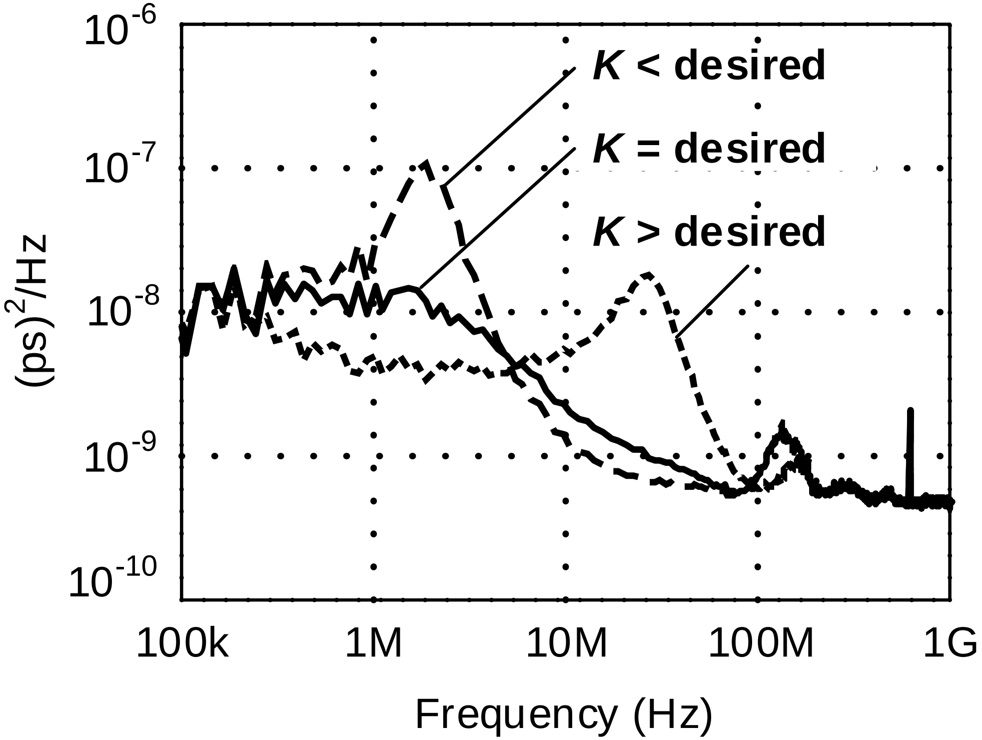
Monitoring Jitter at BB-PD Output



[Liang ISSCC'17]

PSD of Relative Jitter

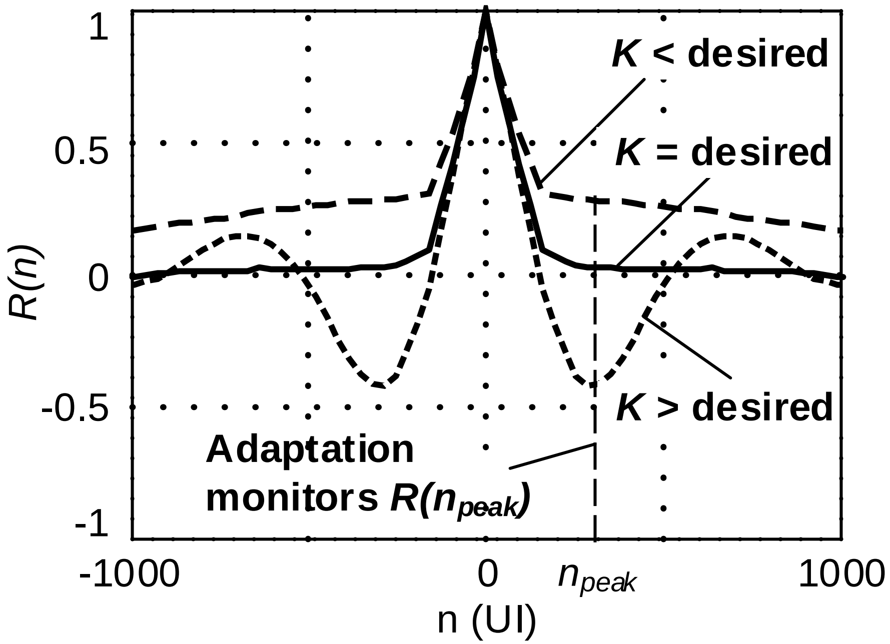
[Liang ISSCC'17]



- Power Spectral Density (PSD) versus loop gain (K)
  - The total power is in units of $(ps)^2$
  - Desired K corresponds to no overshoot or undershoot
  - Hard to measure

Measure Autocorrelation

[Liang ISSCC'17]

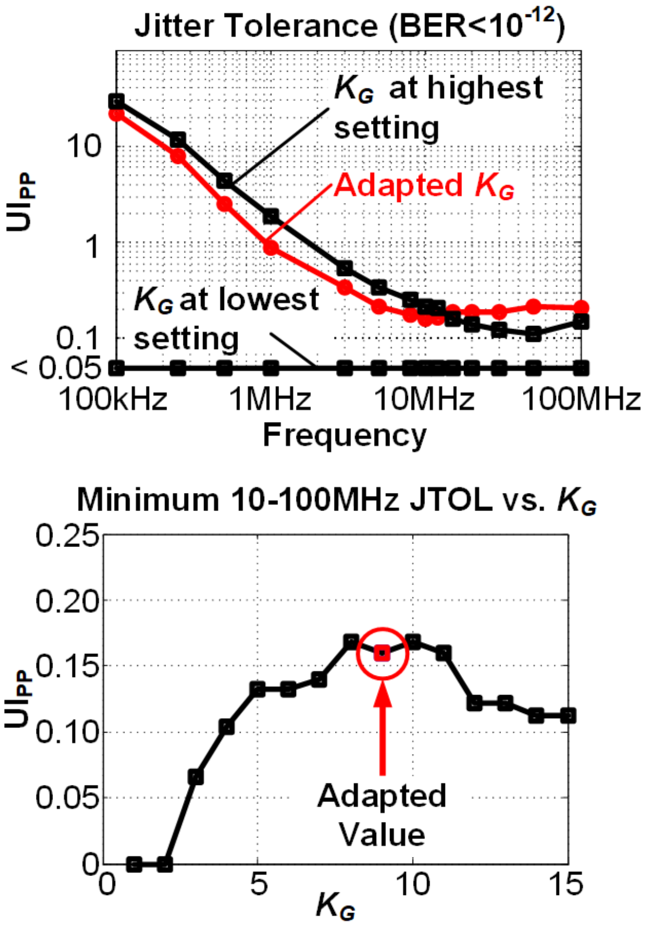


- Use autocorrelation of PD output, R(n), instead
  - Reveals similar behavior as PSD
  - Adjust K to arrive at "critically damped" condition
  - How? Start with max K, measure n_{peak}
  - Reduce K gradually to force $R(n_{peak})$ to zero.

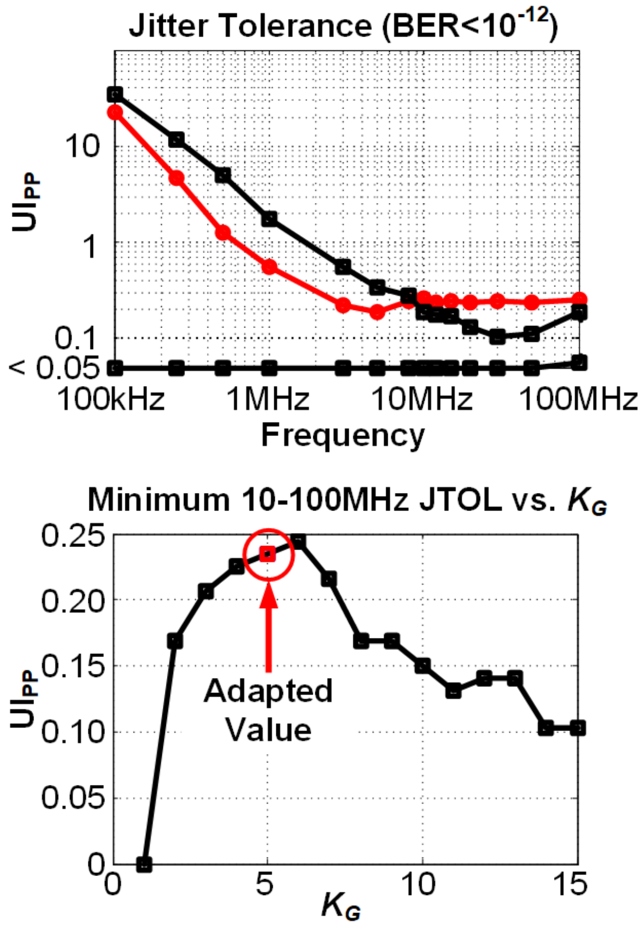
Measured Jitter Tolerance

[Liang ISSCC’17]

Test Case 1

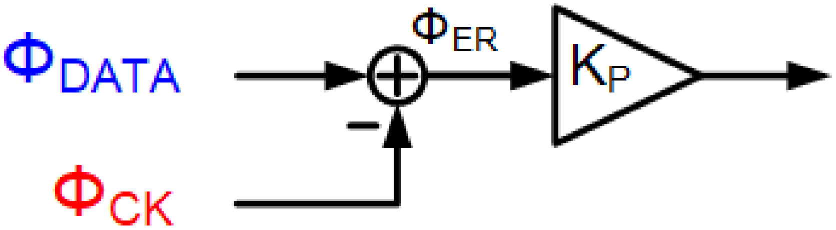


Test Case 2



Measuring Absolute Jitter

[Liang JSSC '15]

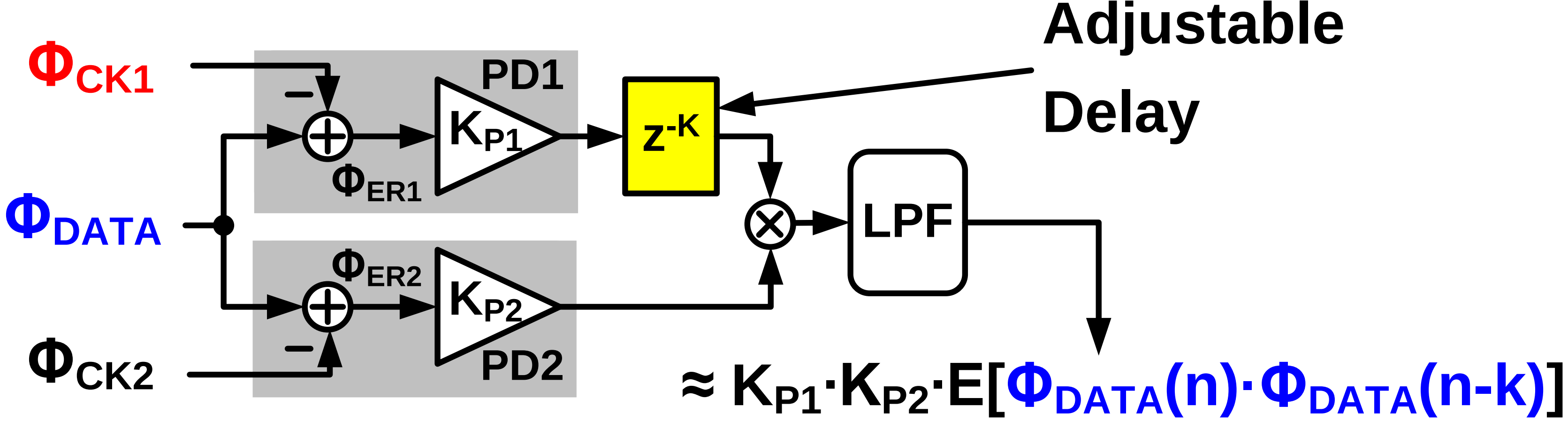


$$K_P \cdot \Phi_{ER} = K_P \cdot (\Phi_{DATA} - \Phi_{CK})$$

- 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

[Liang JSSC '15]

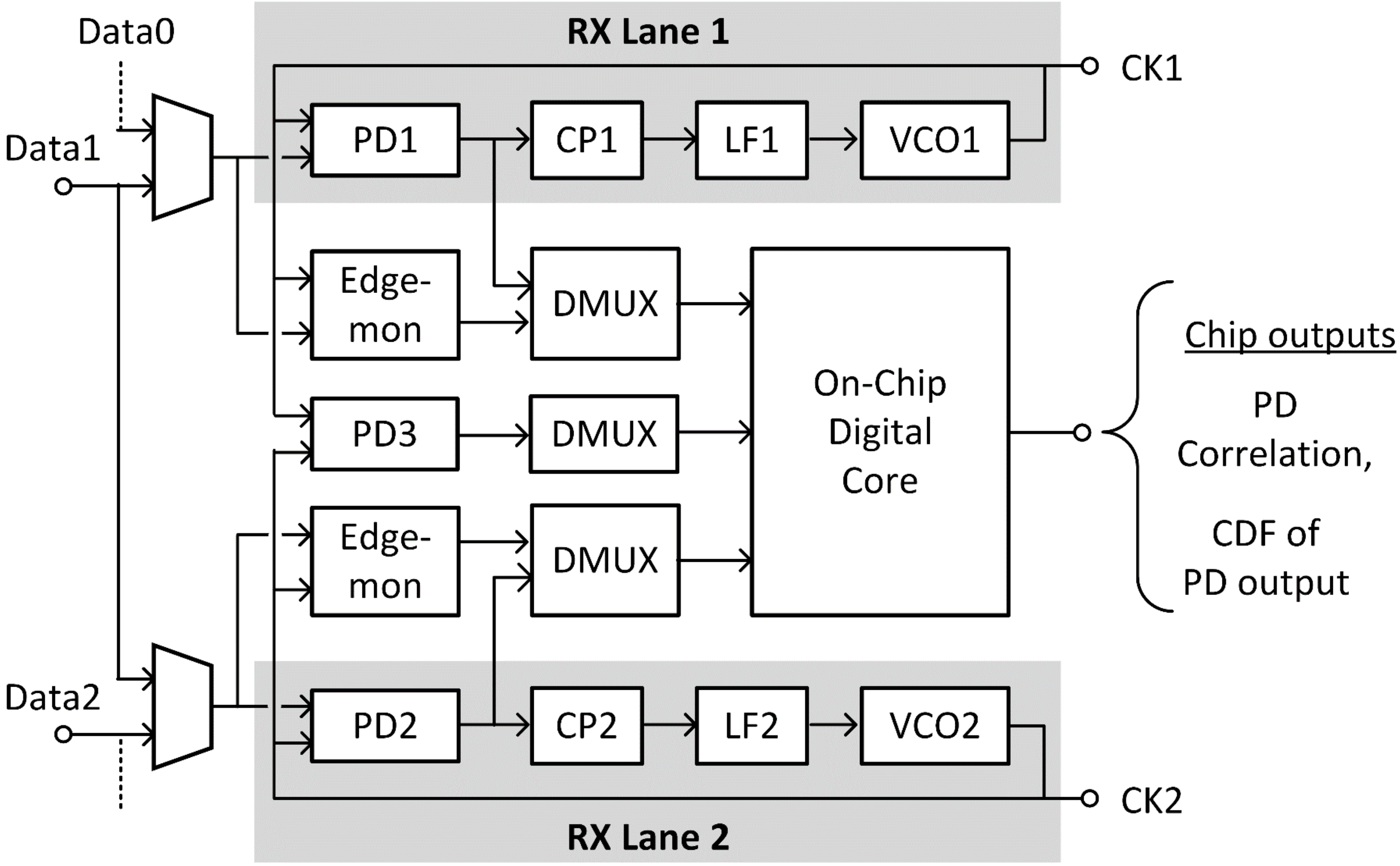


$$\approx K_{P1} \cdot K_{P2} \cdot E[\Phi_{DATA}(n) \cdot \Phi_{DATA}(n-k)]$$

- Assumes Φ_{CK1} and Φ_{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
- Fourier Transform of $R_{DATA}(k)$ gives the PSD of Φ_{DATA}

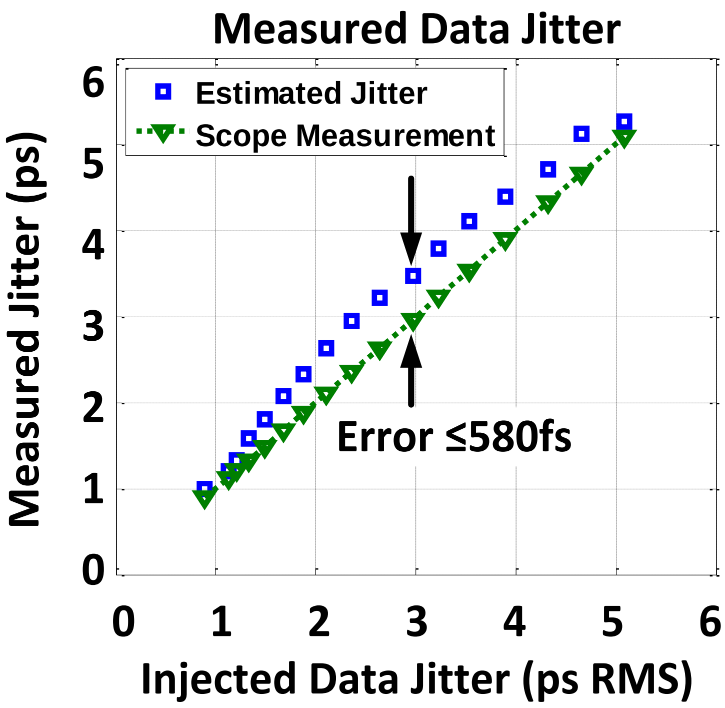
Implementation in Multi-Lane CDR

[Liang JSSC ‘15]

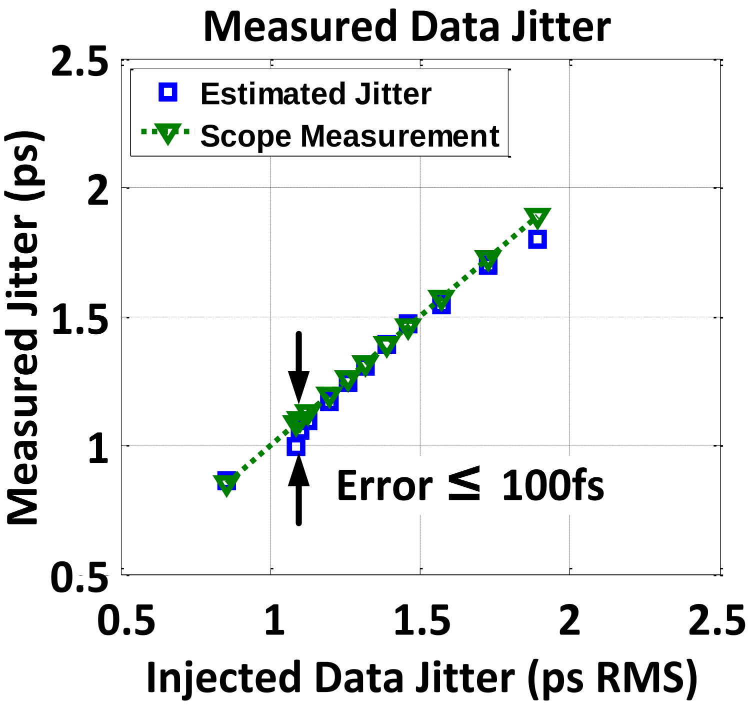


Measured Results [Liang JSSC'15]

100MHz SJ Applied



20-100MHz RJ Applied



□ **Estimated Jitter**

▽ **Measurement from 80GS/s real-time scope**

Outline

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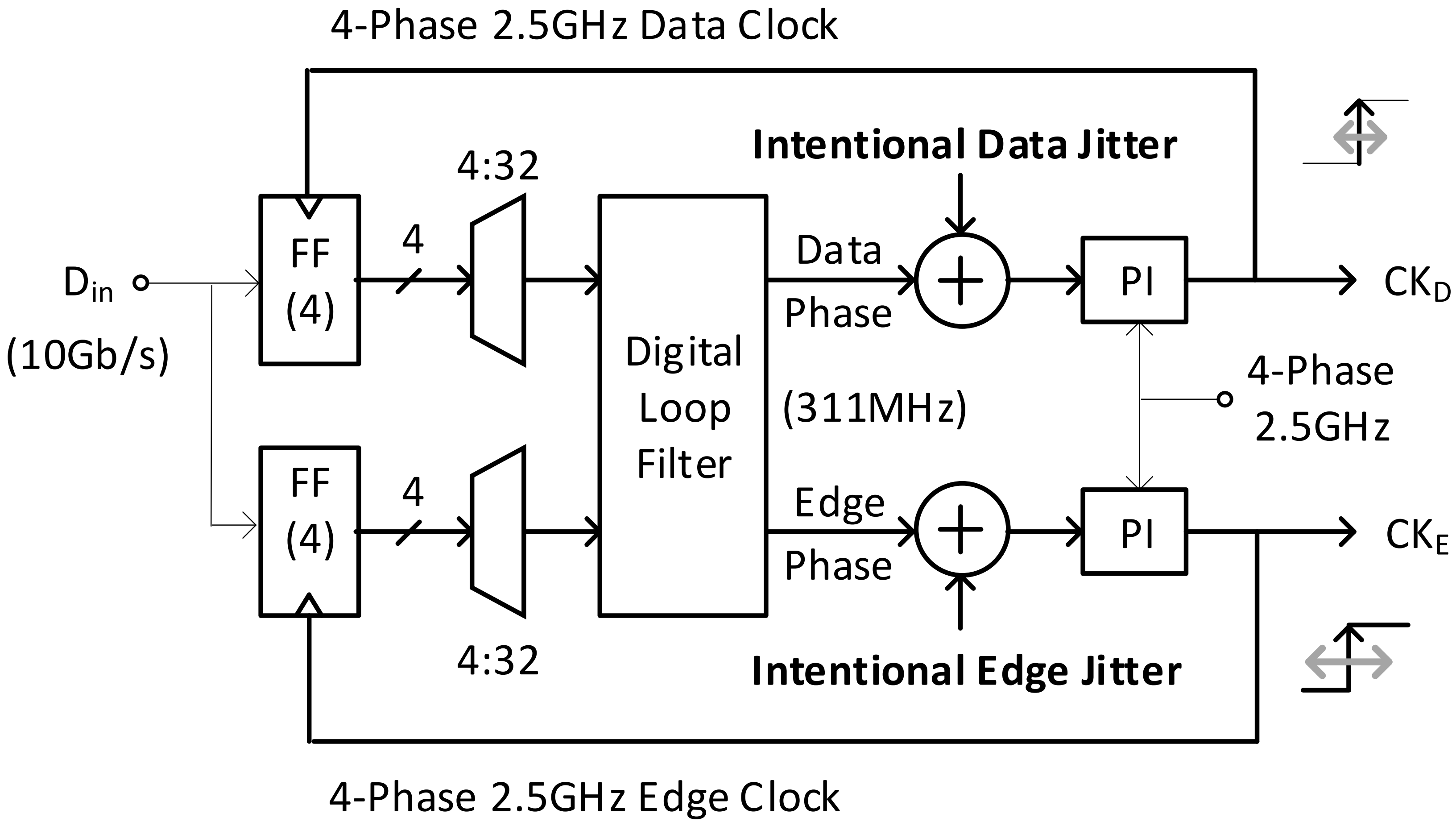
- ☐ Effects of Jitter on Bang-Bang CDR Operation
- ☐ Jitter Monitoring and Jitter Mitigation

- ☐ Intentional Jitter: How Jitter can help

- ☐ Summary
- ☐ References

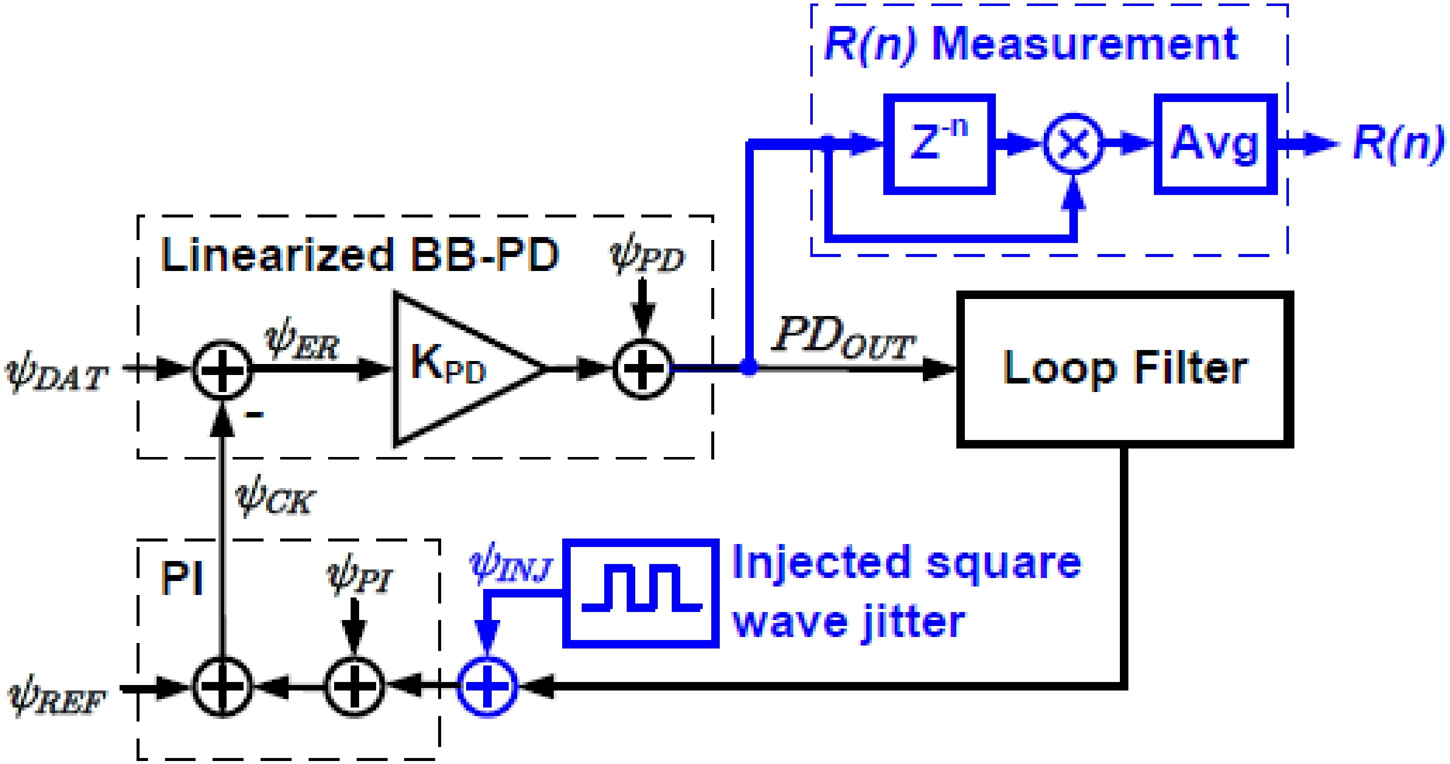
Intentional Jitter to Improve Linearity

[Takauchi JSSC '03]



Jitter Injection for Measurement

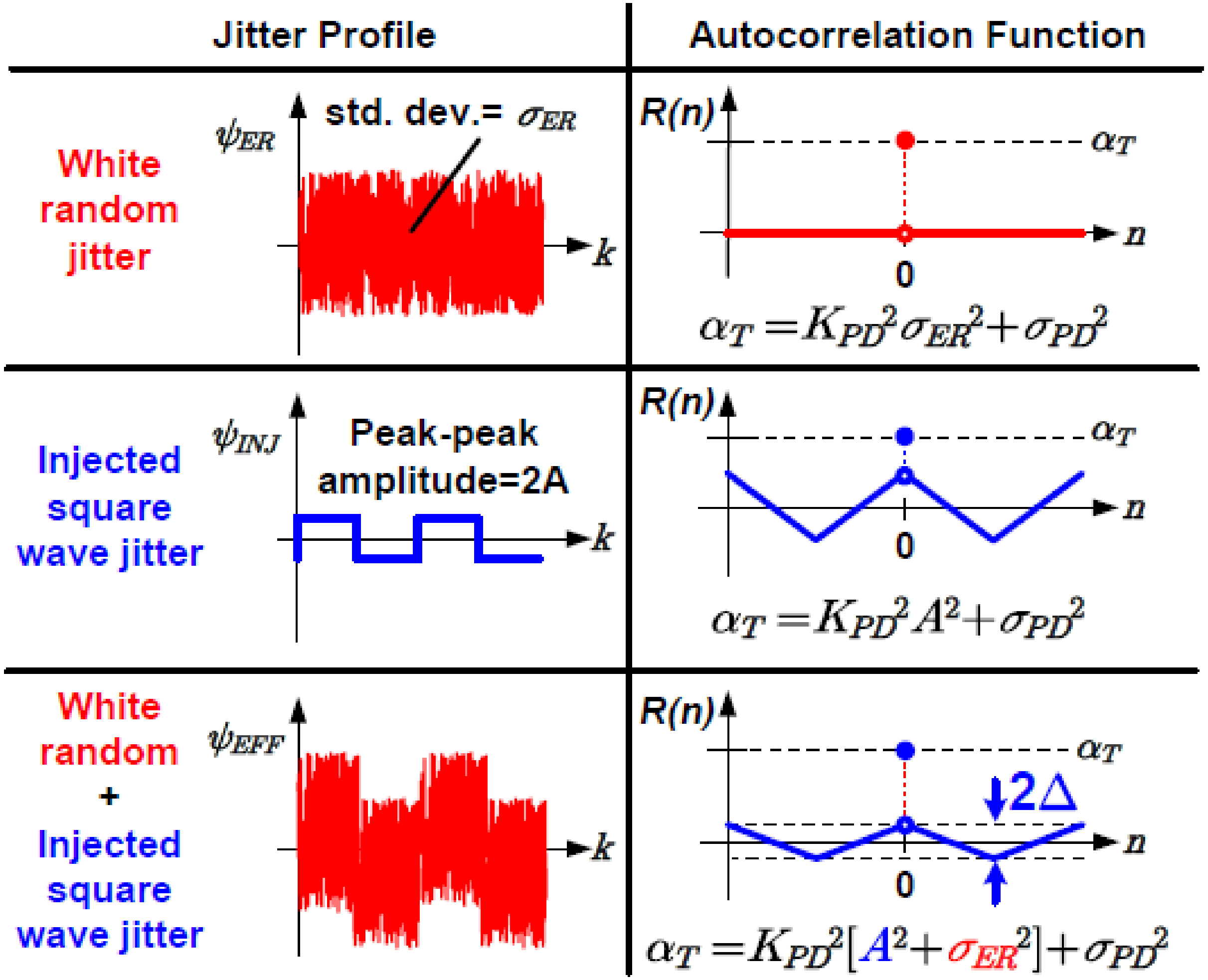
[Liang CICC’17]



- 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]



$$\alpha_T = K_{PD}^2 \sigma_{ER}^2 + \sigma_{PD}^2$$

$$\alpha_T = K_{PD}^2 A^2 + \sigma_{PD}^2$$

$$\alpha_T = K_{PD}^2 [A^2 + \sigma_{ER}^2] + \sigma_{PD}^2$$

*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 ΔΣ 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

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- ☐ N. Da Dalt and A. Sheikholeslami, "Understanding Jitter and Phase Noise - A Circuits and Systems Perspective" by Cambridge University Press, 2018

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- ☐ J. Lee et al., "Analysis and Modeling of Bang-Bang Clock and Data Recovery Circuits," JSSC, pp. 1571-2004, Sep. 2004

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- ☐ 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

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Intentional Jitter

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- 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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