ESSCIRC 2019 Tutorials

Fundamental Concepts in Jitter and Phase Noise

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Outline

- Motivations

- Jitter Definitions: What is Jitter?
- Characterizing and Classifying Jitter
- Example: Jitter in Ring Oscillator

- From Jitter to Excess Phase
- Phase Noise and Its Relationship to Jitter
- Phase Noise Profiles

- Jitter Measurements and Intentional Jitter

- Summary
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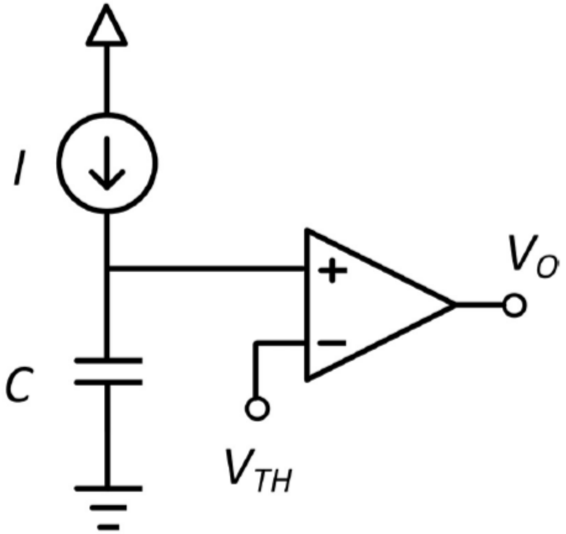
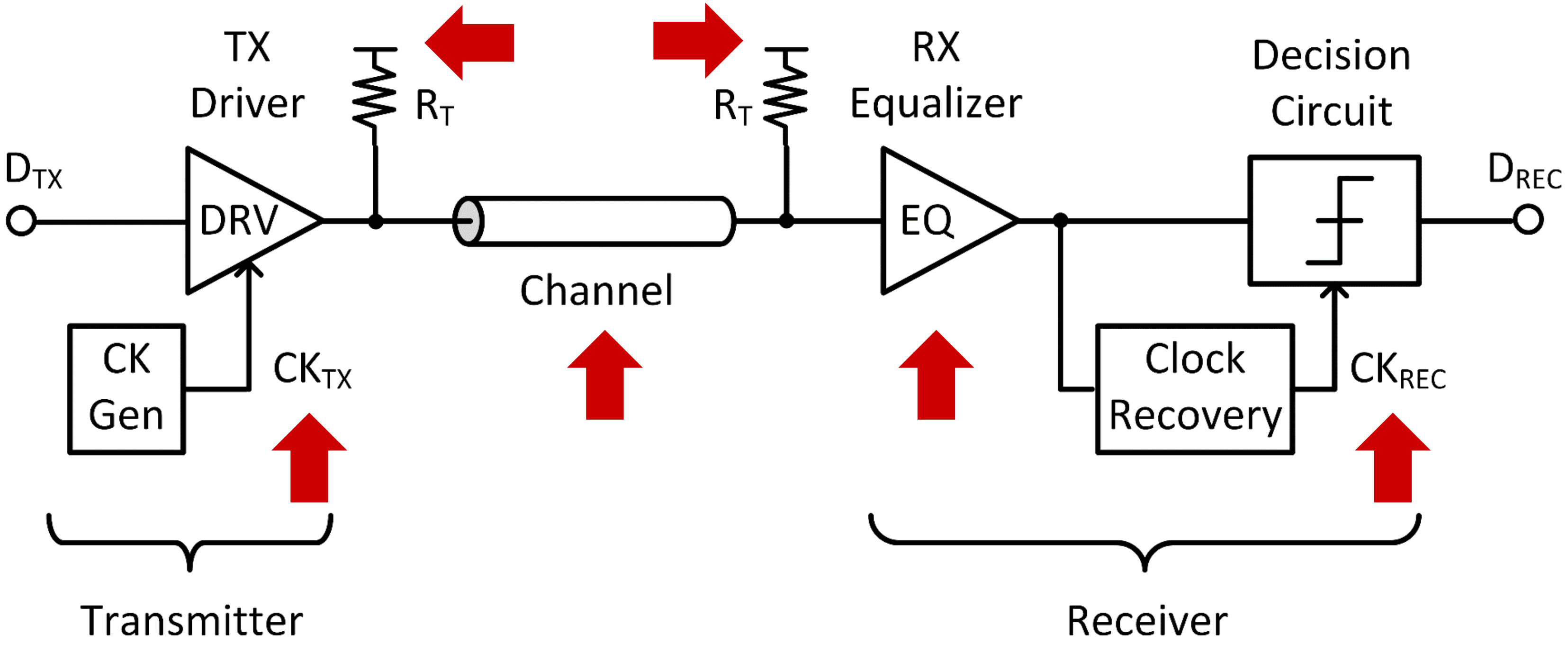
Jitter is Timing Uncertainty



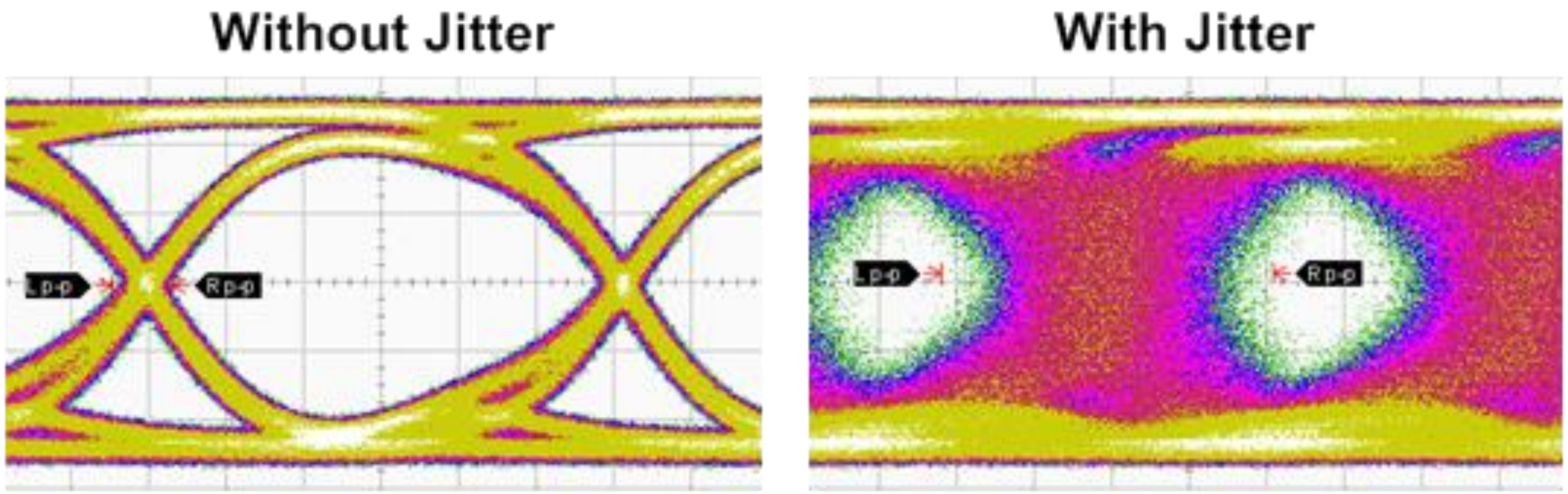
- Hourglass: *nominally* measures 15 mins, but could deviate by a few seconds
- Time to charge C to reach V_{TH} is CV_{TH}/I, but this varies with noise in I
- Expected duration of this tutorial is 1.5 hrs, give or take a few minutes
- Timing uncertainty exists in all these example

Effects of Jitter in Wireline



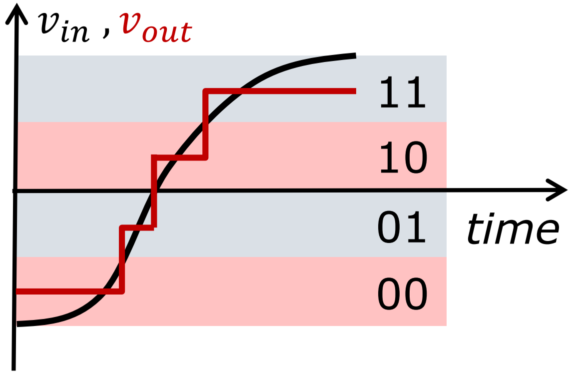
- No clock is perfect: they are either a bit slow or a bit fast
- There is uncertainty as to when they are slow or fast, and by how much
- VDD noise, channel, equalization (EQ), and crosstalk contribute to this
- Timing uncertainty can lead to high bit error rates (BER) in detected bits

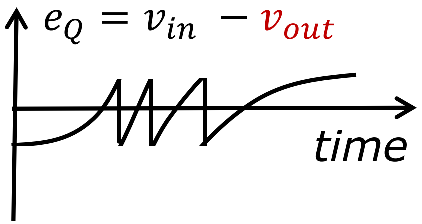
Effects of Jitter on Data Eye



- Data eye at decision point
- Without jitter, data "1"s and "0"s line up well at the center of the eye
- With jitter, the eye is almost closed; "1" and "0" can be confused
- The Bit Error Rate (BER) may become Unacceptable
- What can we do about jitter? Talk #2 will address this question

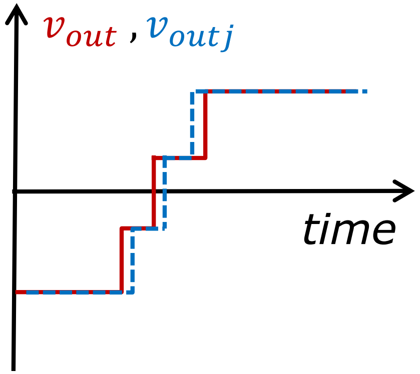
Effects of Jitter on SNR

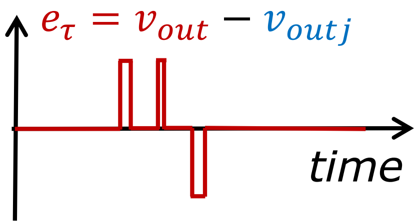




SNR due to quantization error:

$$SNR_Q = P_{signal}/P_{quan.\,noise}$$



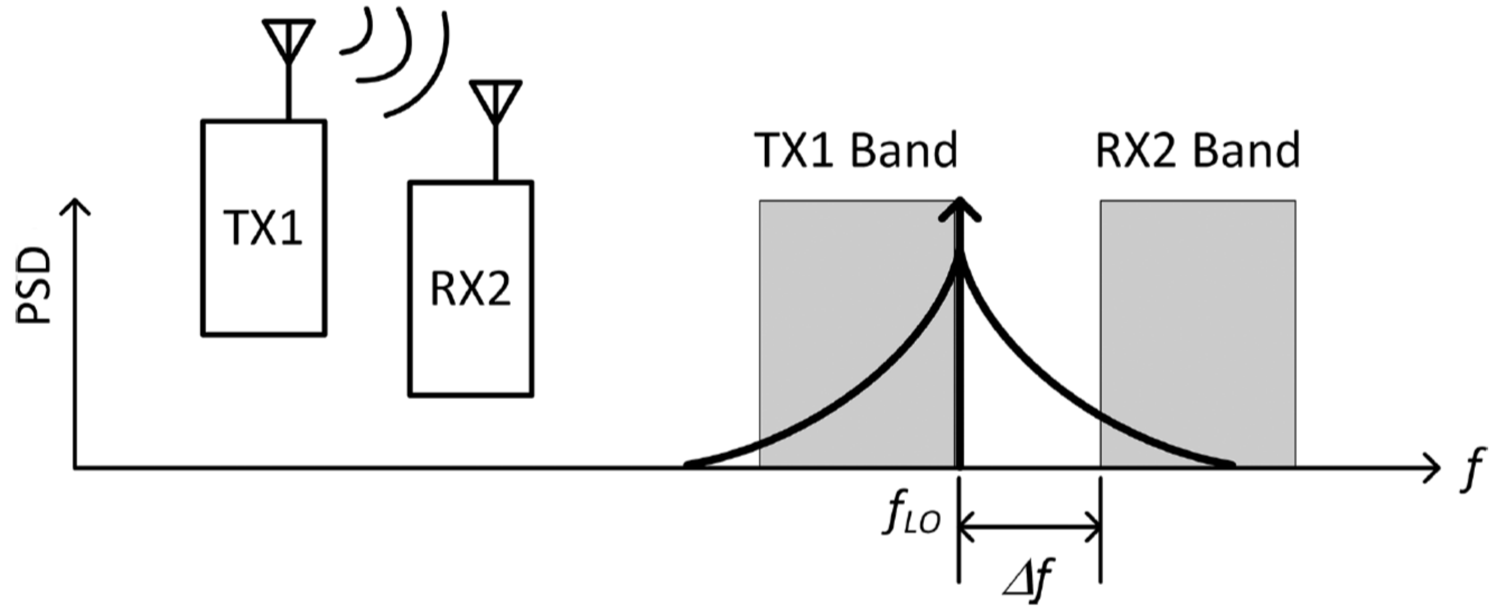


SNR due to timing uncertainty:

$$SNR_\tau = P_{signal}/P_{jitter\ noise}$$

- ADC accuracy is measured by its output signal to noise ratio (SNR)
- Total noise is due to quantization in voltage domain and jitter in time domain
- Final SNR determines the effective number of bits (ENOB)

Phase Noise in Wireless Applications



- A guard band (Δf) is envisioned to avoid signal leaks from TX1 to RX2 bands
- However, some phase noise from local oscillator at TX1 leaks to RX2
- This leakage degrades the SNR at the receiver
- Talks #3 & #4 will cover phase noise in oscillators & wireless applications

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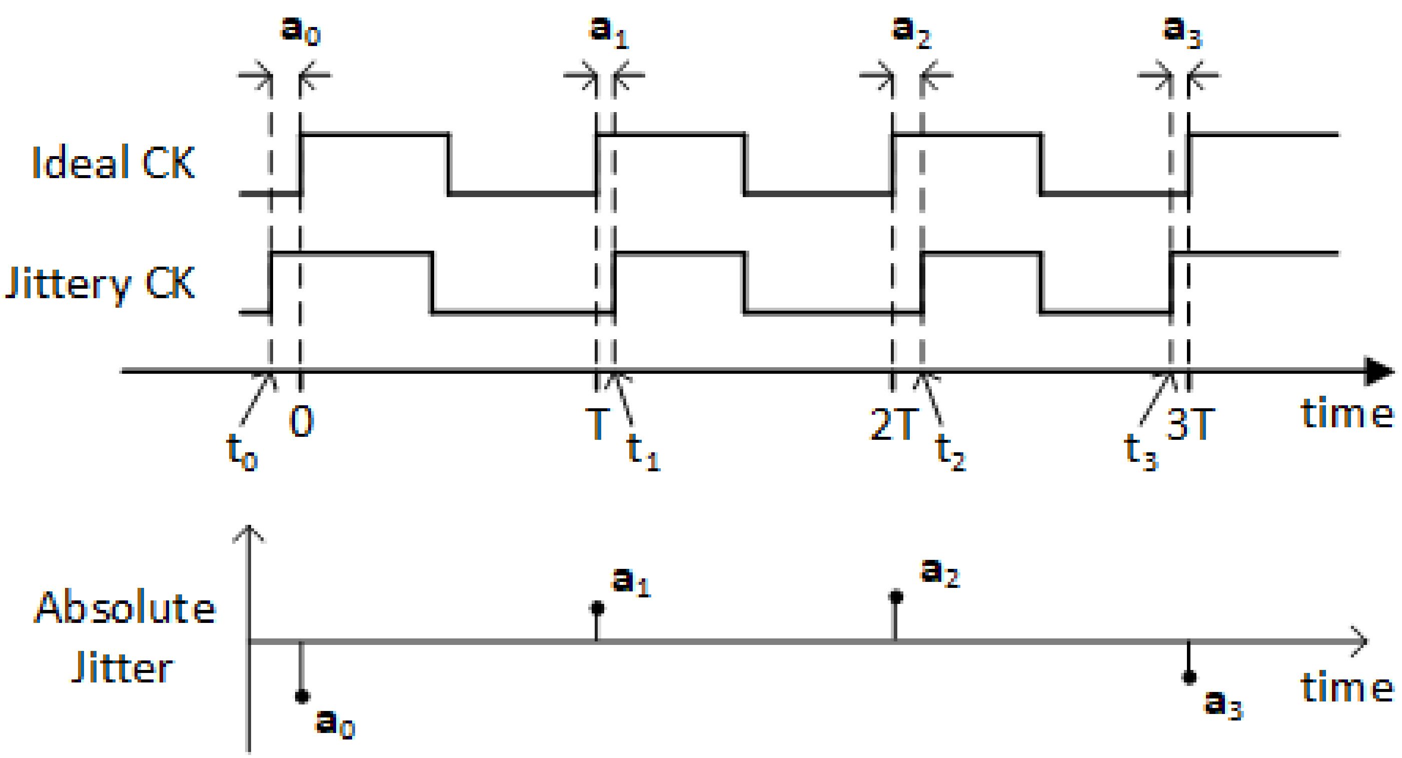
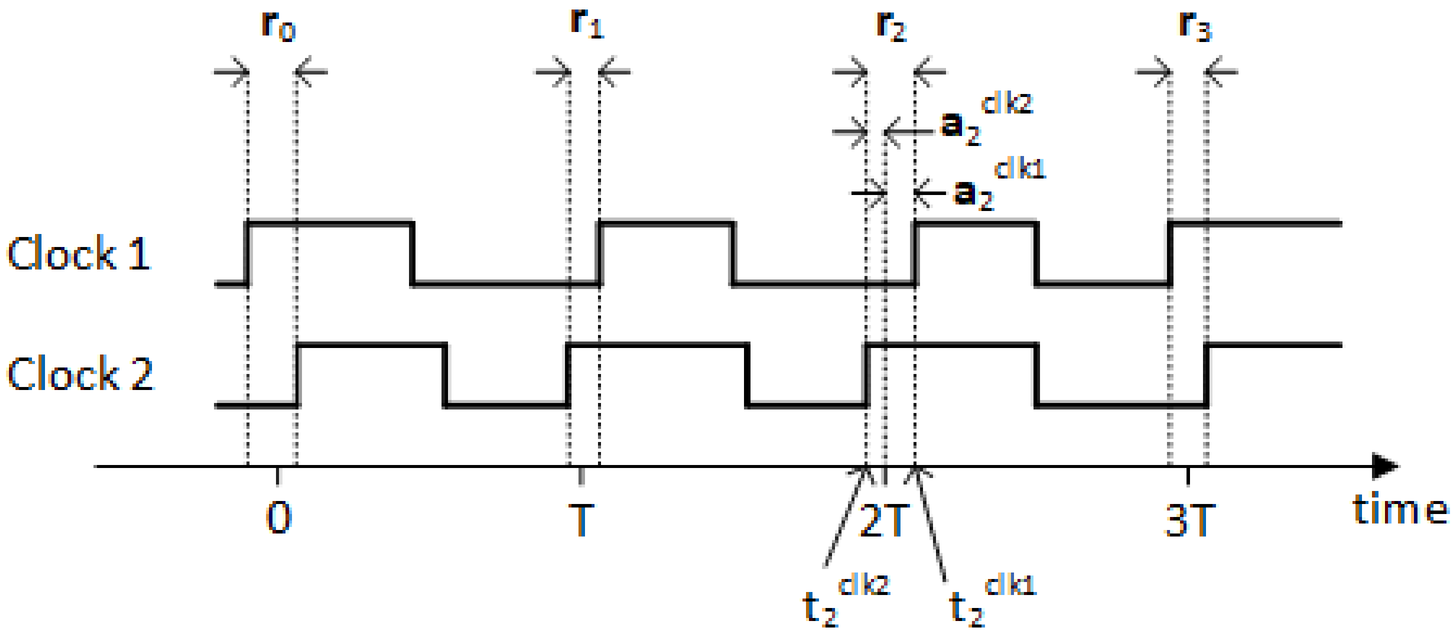
Absolute Jitter



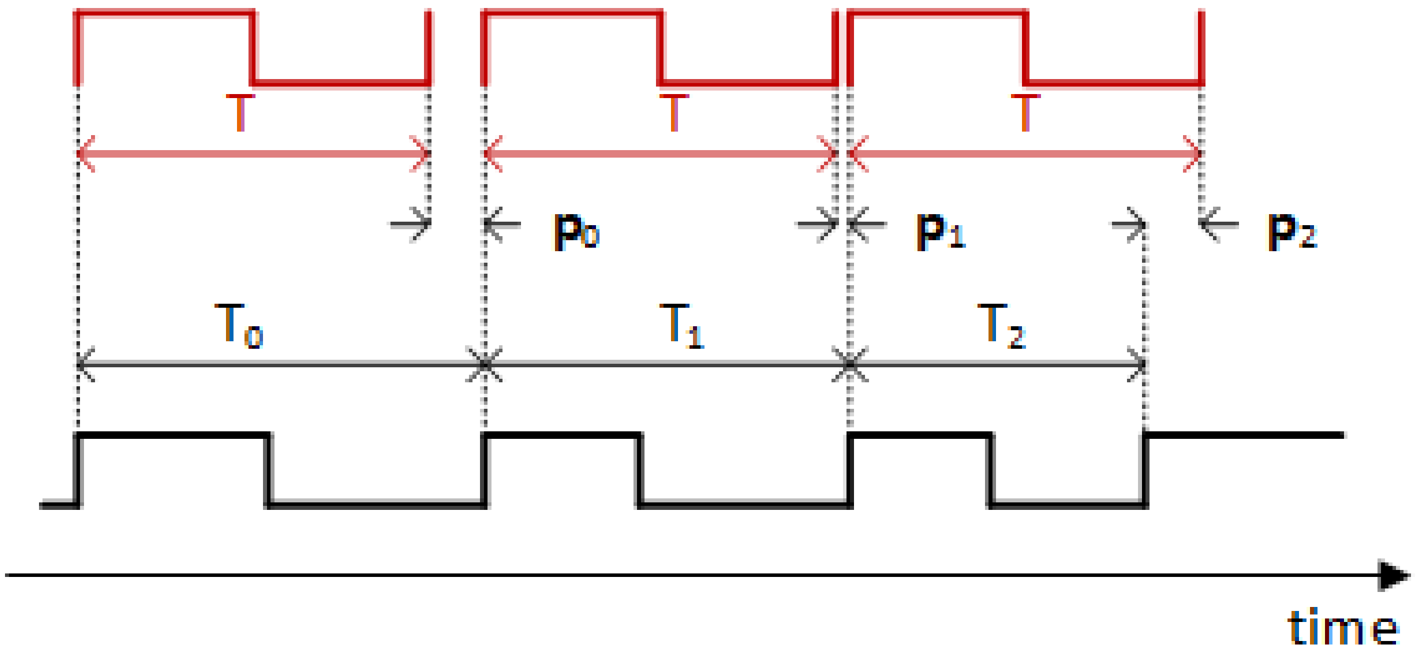
- Timing deviation between a jittery CK and an ideal CK
- A discrete-time random signal, defined as $a_k := t_k - kT$
- Never have an ideal clock; how is this useful?

Relative Jitter



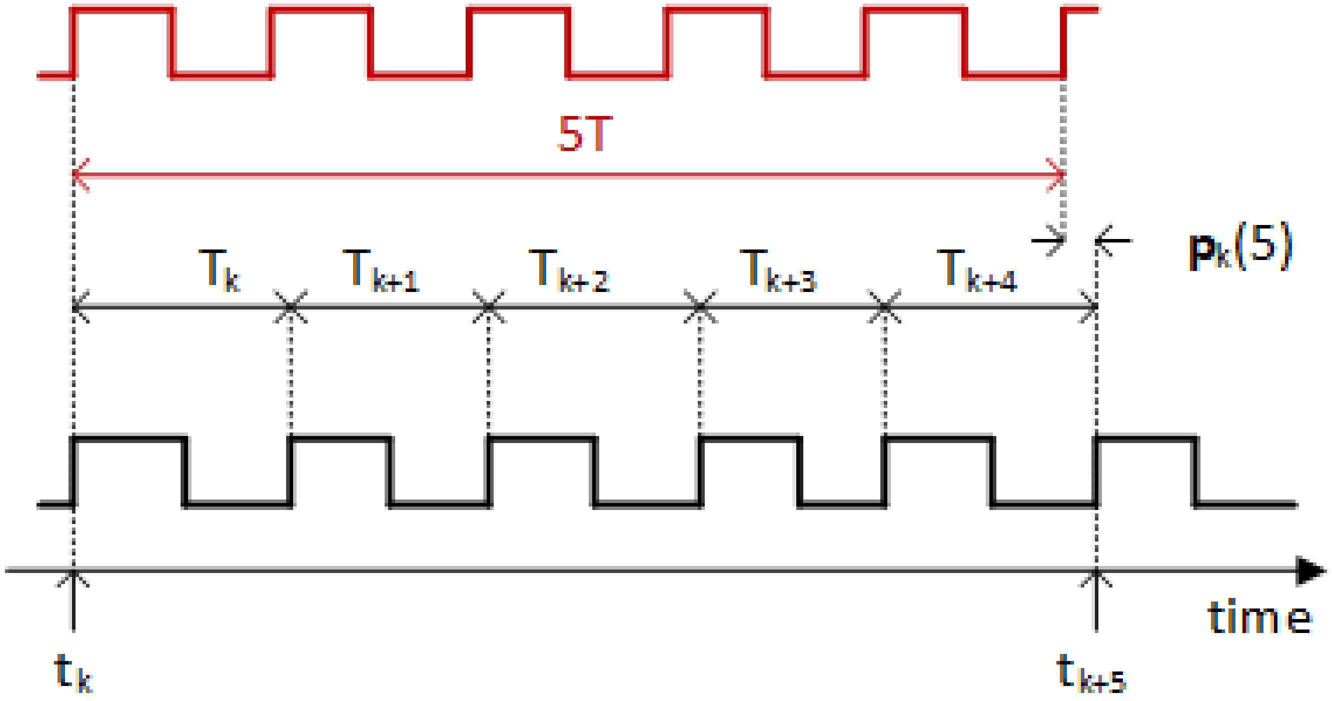
- Timing difference between two non-ideal clocks
- Another discrete-time random signal
- $\boldsymbol{r}_k := t_k\,(CK1) - t_k\,(CK2) = \boldsymbol{a}_k\,(CK1) - \boldsymbol{a}_k\,(CK2)$
- Where do we use this?

Period Jitter



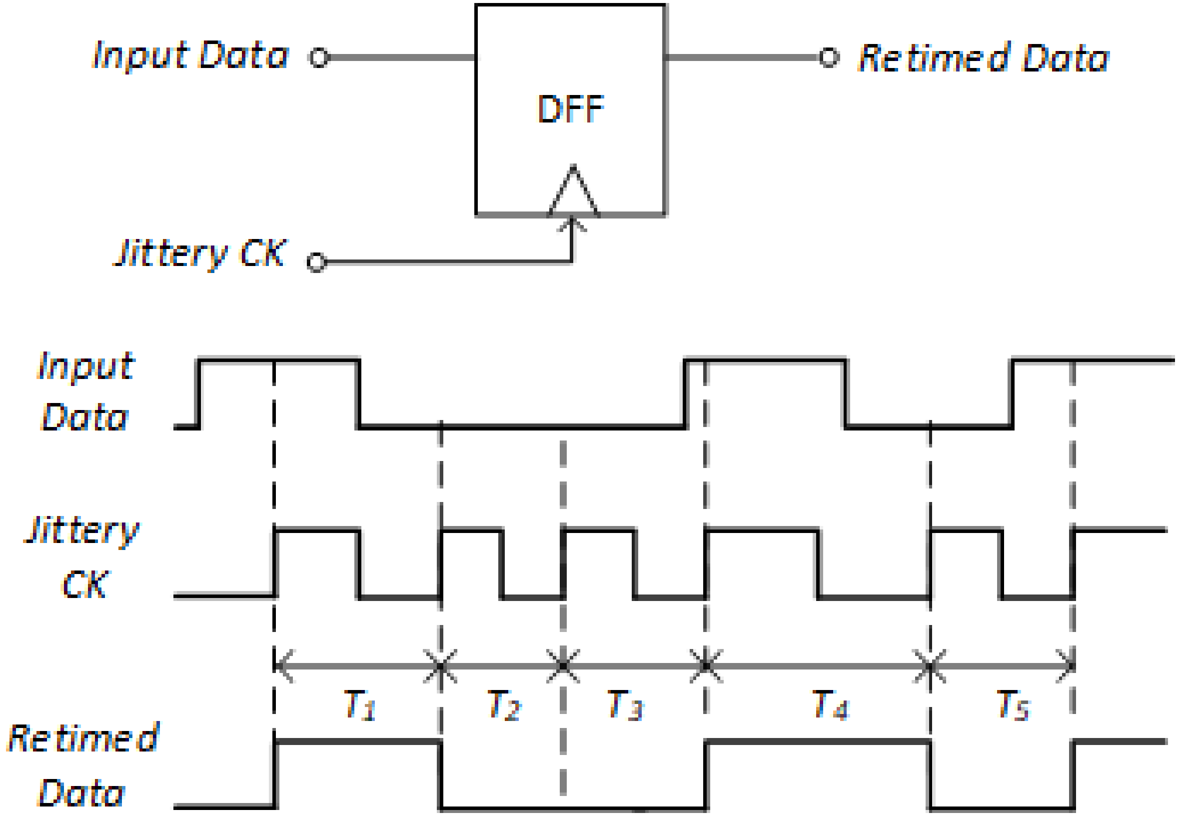
- Also known as Cycle Jitter, defined as difference between edge-to-edge interval ("period") and the nominal period
- $\boldsymbol{p}_k := (t_{k+1} - t_k) - T = T_k - T = \boldsymbol{a}_{k+1} - \boldsymbol{a}_k$
- Period jitter can be derived easily from absolute jitter
- Where do we use this?

N-Period Jitter



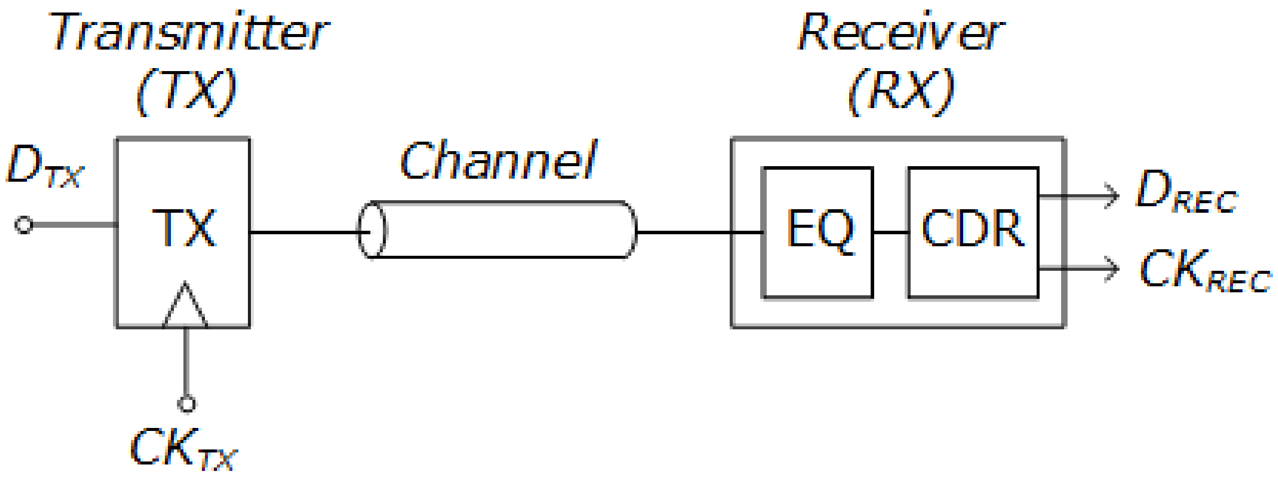
- Also known as Accumulation Jitter, defined as an accumulation of period jitter over N consecutive intervals
- $\boldsymbol{p}_k\ (N) := (t_{k+N} - t_k) - NT = \boldsymbol{a}_{k+N} - \boldsymbol{a}_k$
- Where do we use this?

Data Jitter



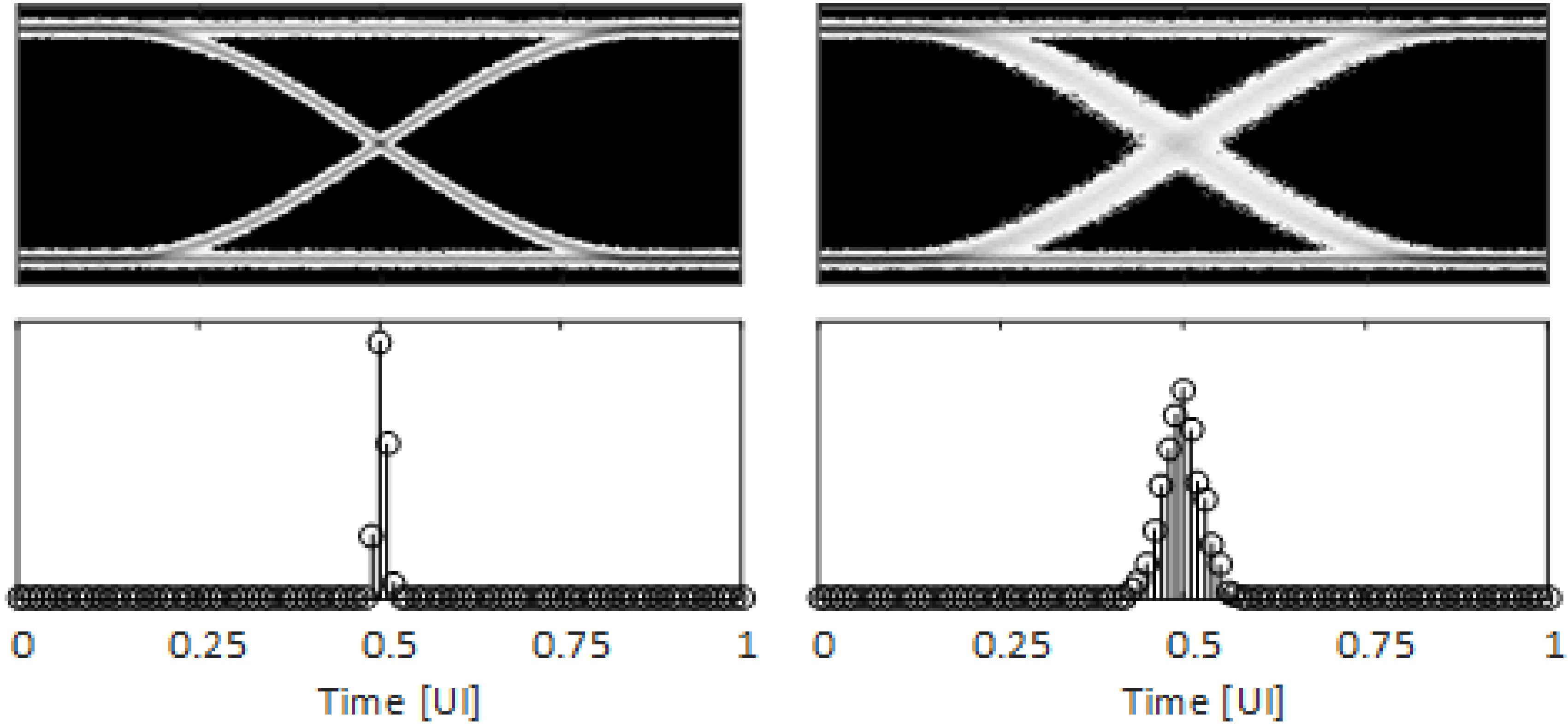
- Jittery CK retimes random binary input data
- Due to random nature of data sequence (i.e. lack of transitions), jitter not fully observable at the output

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

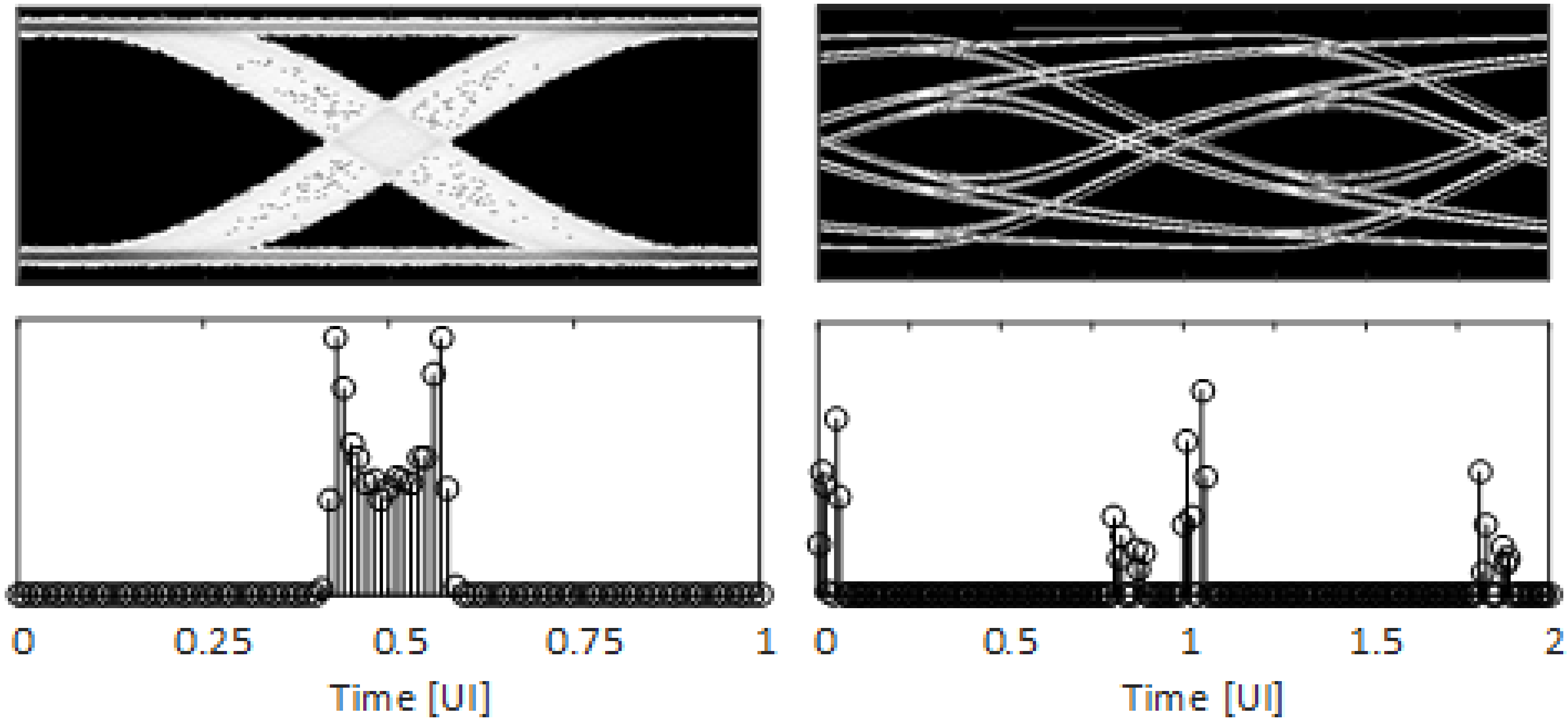
No Jitter versus Random Jitter (RJ)



- 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

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Characterizing Jitter

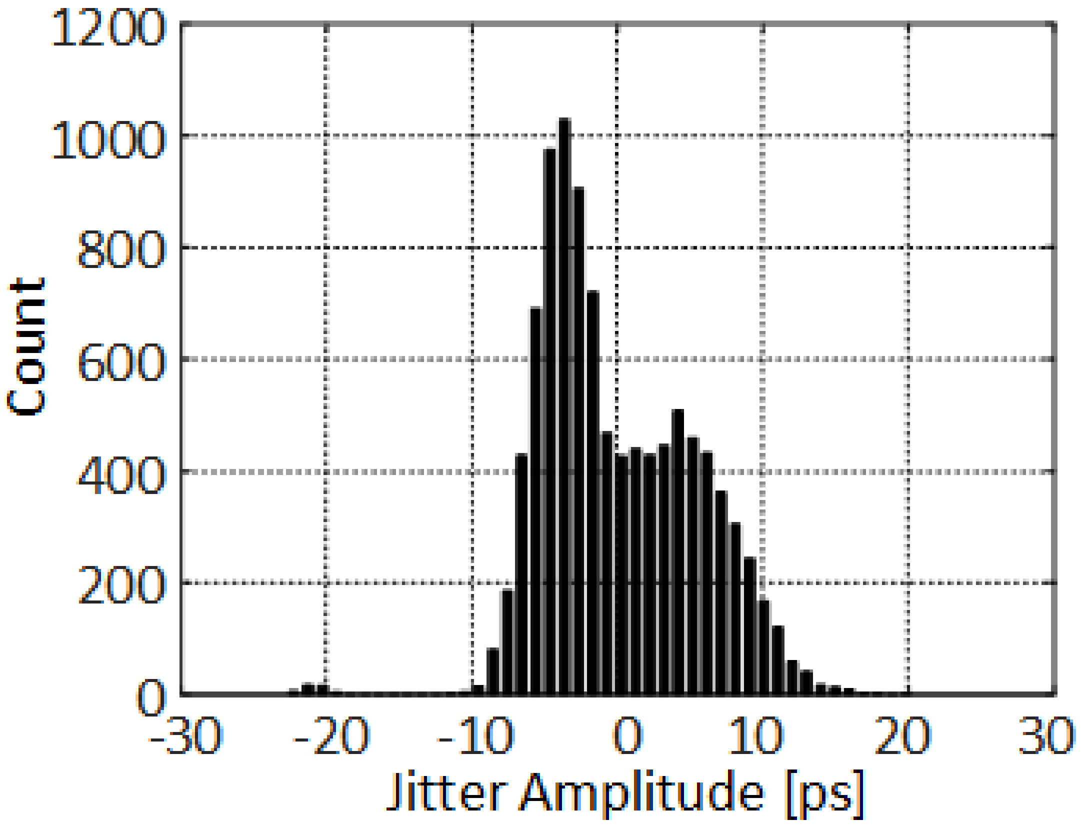
- Jitter (absolute, relative, period, N-period) is a discrete-time random signal
- How do we characterize a random signal?

- Statistics:
  - Histogram, Probability Density Function (PDF)
  - mean, rms, signal power, peak-to-peak value

- Time Domain:
  - How the signal statistics changes with time
  - Autocorrelation function

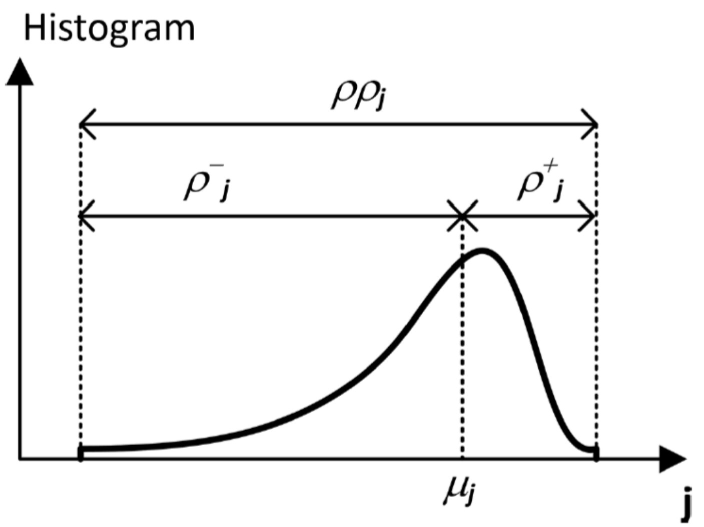
- Frequency Domain:
  - Fourier of Autocorrelation function: Power Spectral Density (PSD)

Jitter Histogram



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

Jitter Mean, Median, RMS, and Peak



sample mean $$\hat{\mu}_{\mathbf{j}} = \frac{1}{n}\sum_{k=1}^{n}\mathbf{j}_k$$

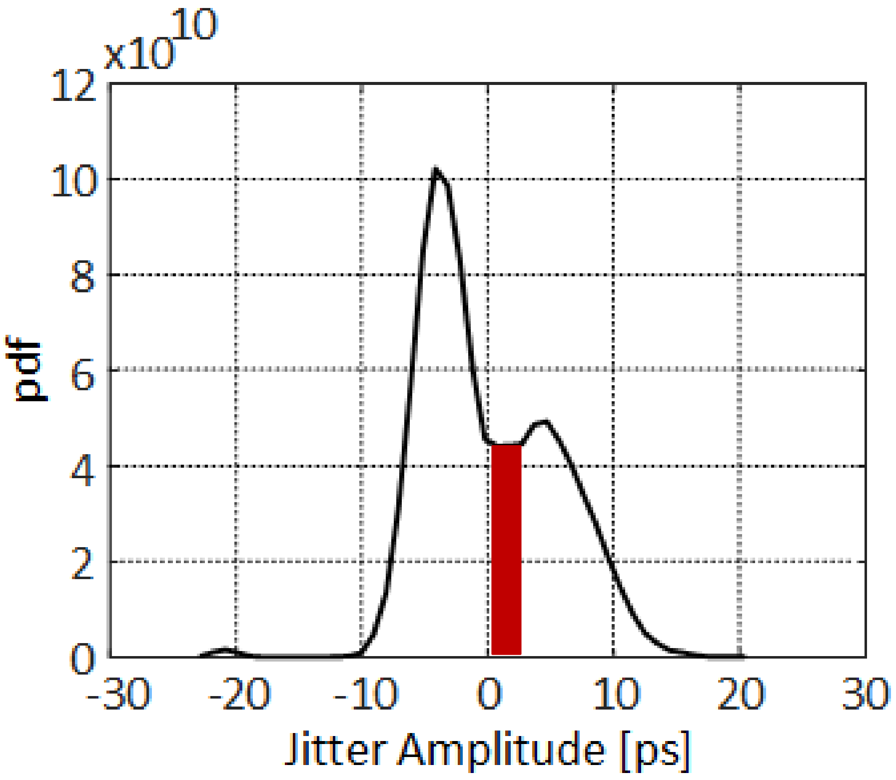
sample median $$P[\mathbf{j}_k < j] = P[\mathbf{j}_k > j] = 0.5$$

Sample variance $$\hat{\sigma}_{\mathbf{j}}^2 = \frac{1}{n-1}\sum_{k=1}^{n}(\mathbf{j}_k - \mu_{\mathbf{j}})^2$$

Sample peak-to-peak $$\rho\rho_{\mathbf{j}} := \max_k(\mathbf{j}_k) - \min_k(\mathbf{j}_k)$$

- Choose a total of n samples
- Calculate estimated mean, median, variance, and peak-to-peak of jitter
- Estimated values referred to as *sample* values as they are sample dependent

Jitter Probability Density Function



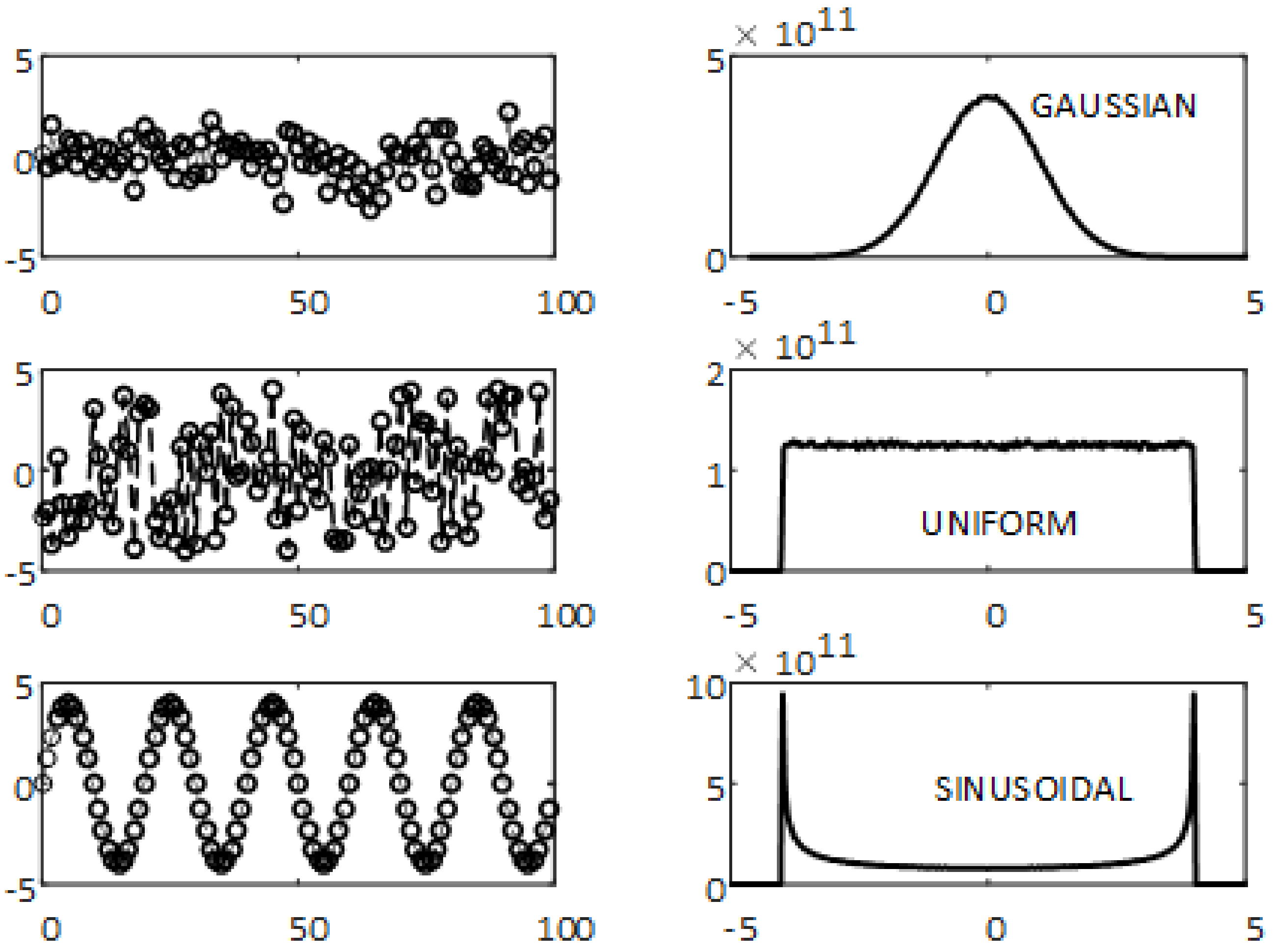
Difference between histogram and pdf:

- Histogram: based on one realization over time (time average)
- PDF: based on many realizations at one time (ensemble average)

- In ergodic processes, time and ensemble averages are the same, hence histogram and pdf carry the same information

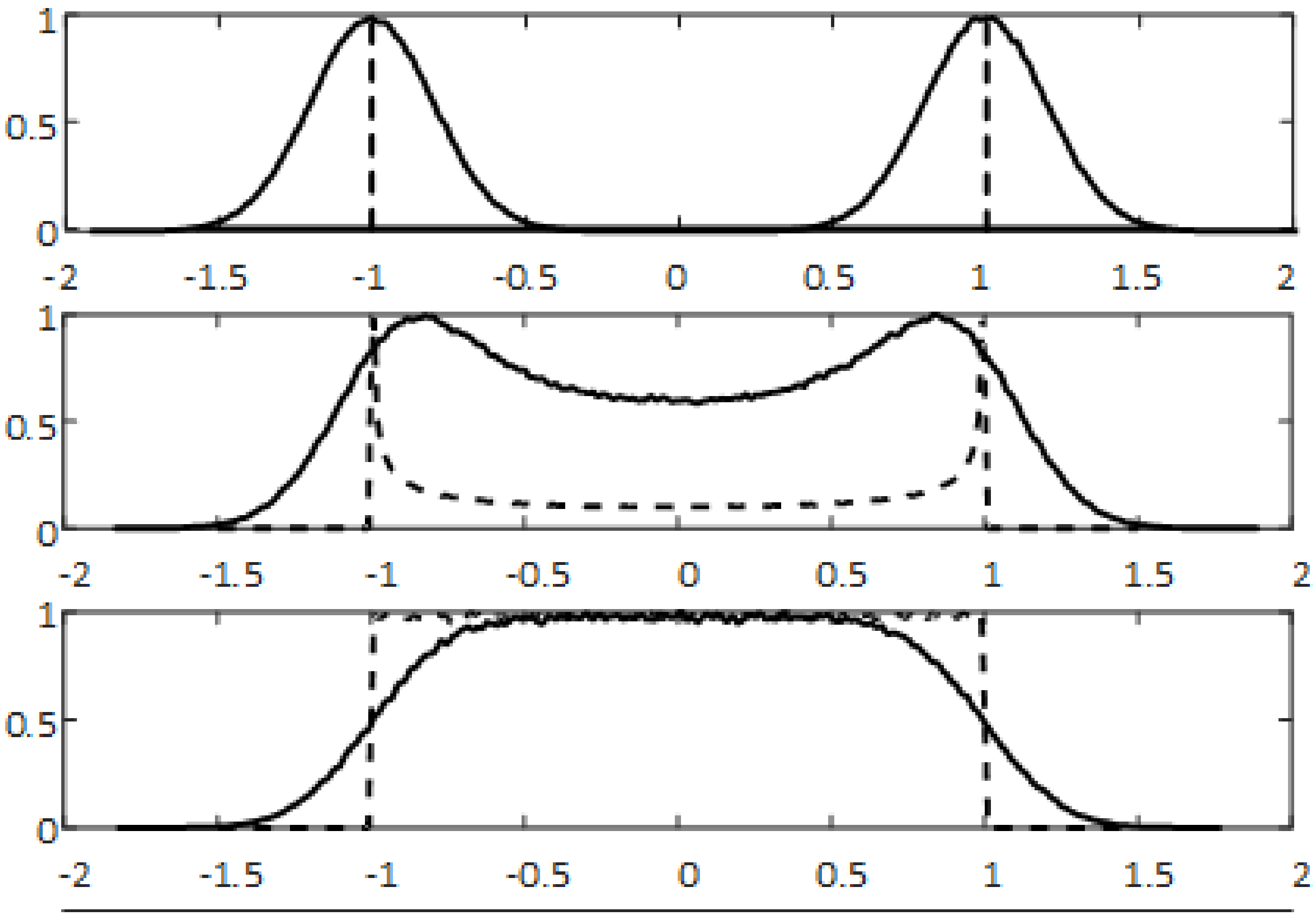
- Normalize vertical axis of histogram to have unit area under the curve
- Red area indicates probability of jitter in the interval shown

Histogram Examples



- Gaussian: unbounded
- Uniform: bounded; easy to produce
- Sinusoid: bounded
- Used in jitter tolerance measurement

Sum of two jitter: Convolve PDFs

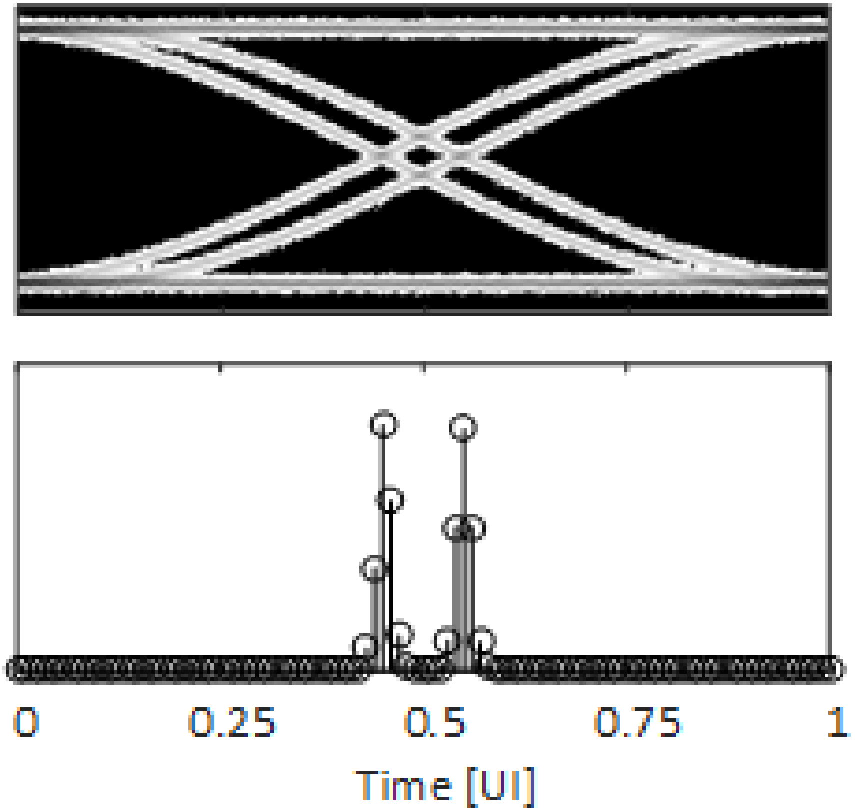


Dirac + Gaussian

SJ + Gaussian

Uniform + Gaussian

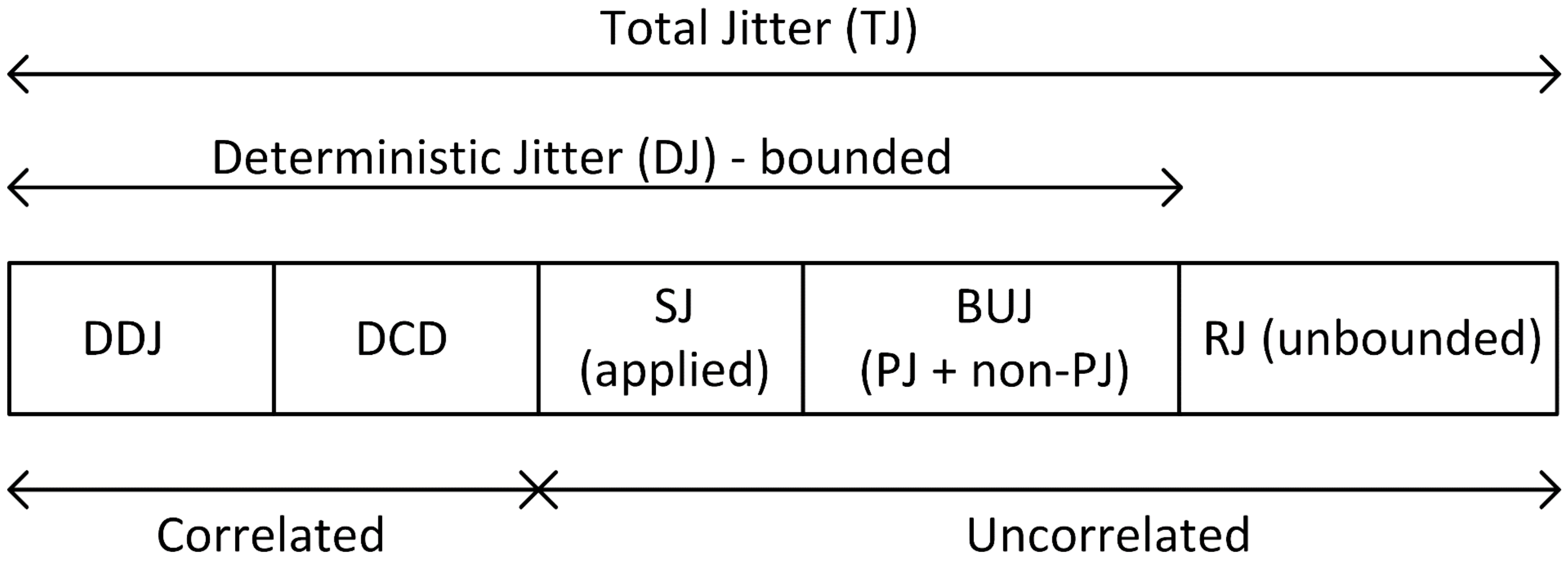
Combined Jitter in Eye Diagram



- Combined DCD & RJ
- Convolution of two PDFs

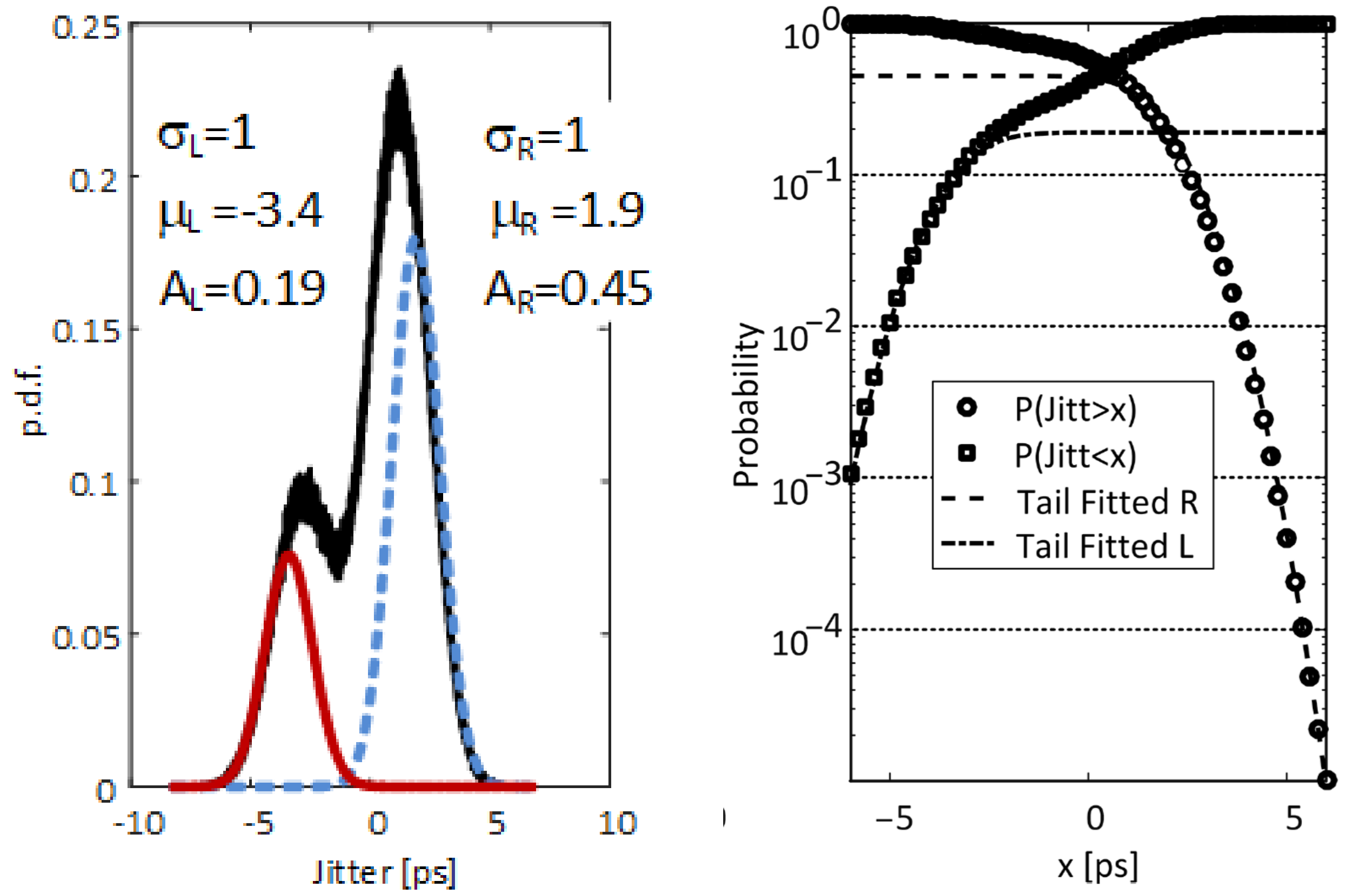
- Combined jitter is sum of individual jitter signals
- Combined jitter PDF is convolution of individual PDFs

Classifying Jitter

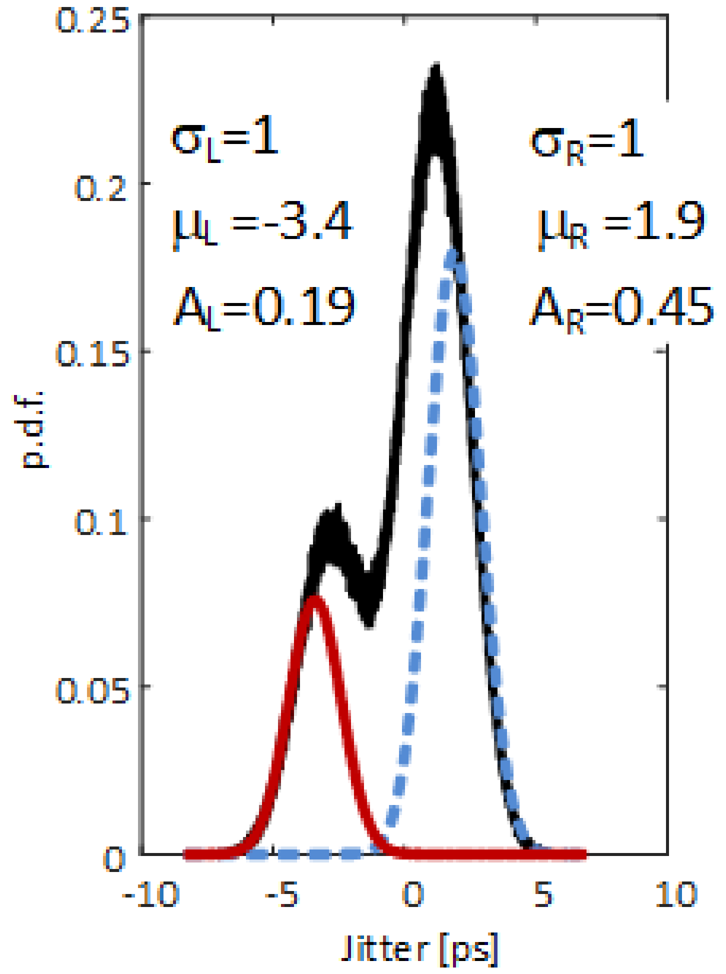


- Total Jitter is sum of DJ and RJ
- DJ includes:
  - Data-Dependent, Duty-Cycle-Distortion (DCD) Jitter
  - Sinusoidal, any other bounded periodic/non-periodic jitter
- RJ is unbounded and uncorrelated

Jitter Decomposition (1 of 2)



Jitter Decomposition (2 of 2)



- 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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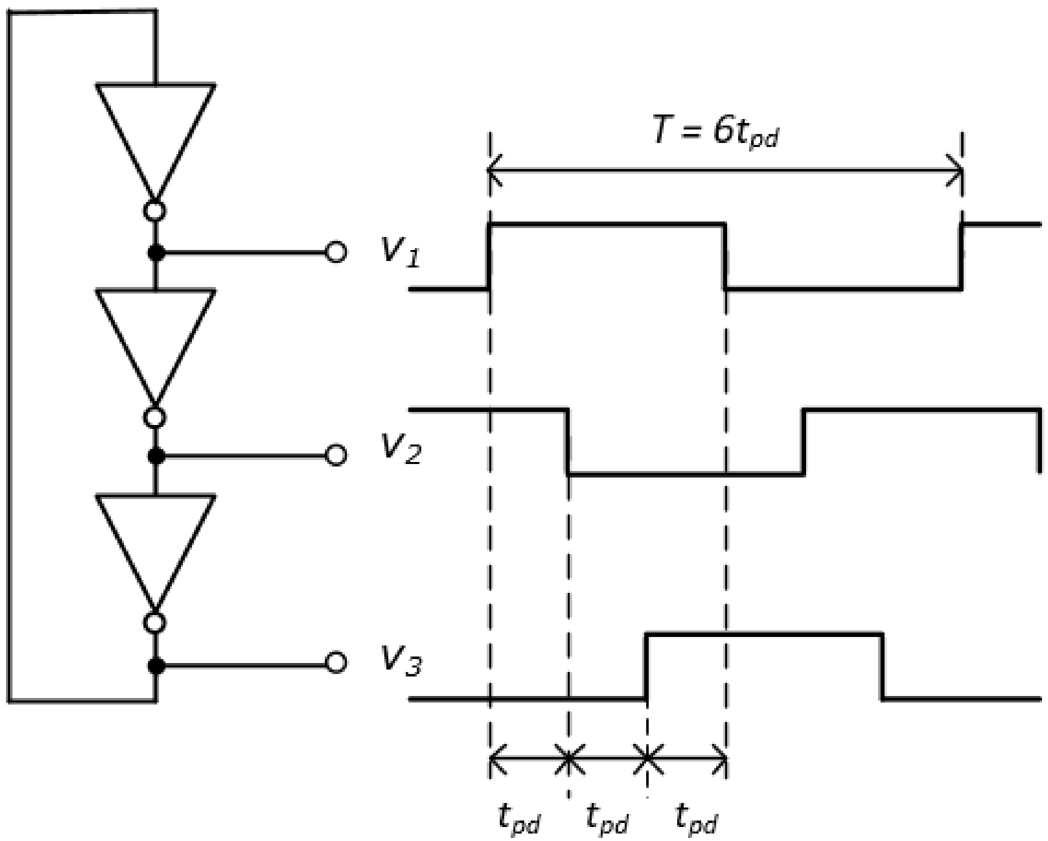
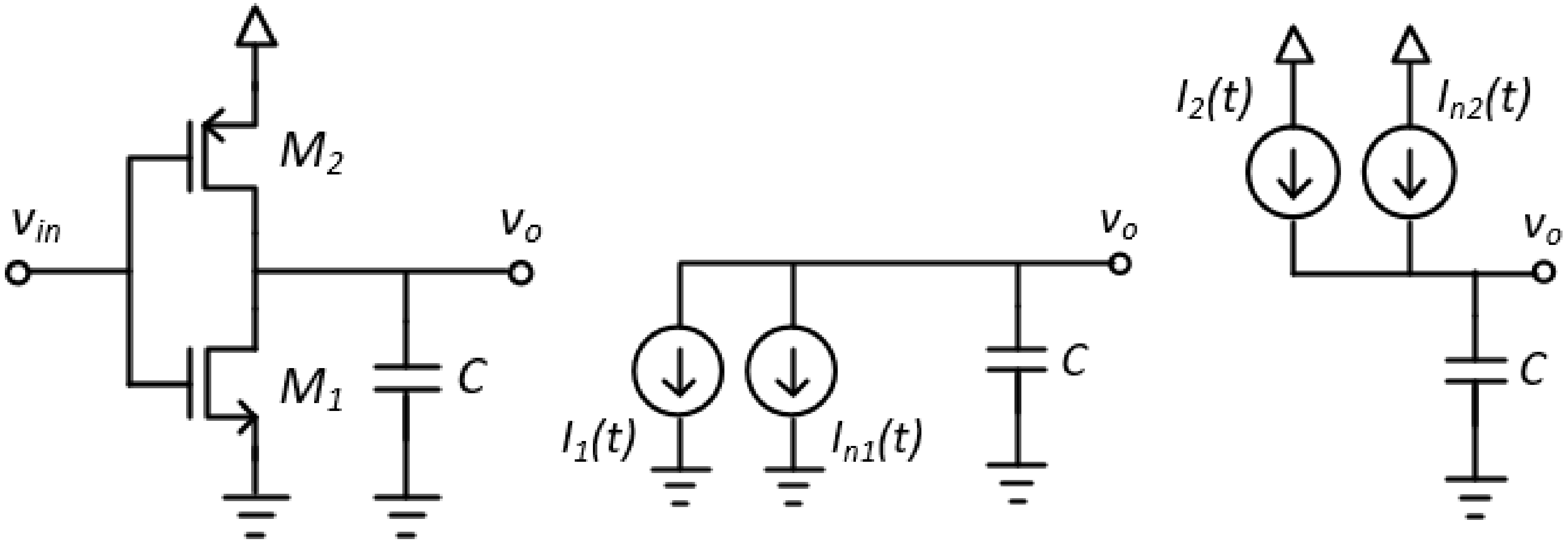
Example: A Ring Oscillator



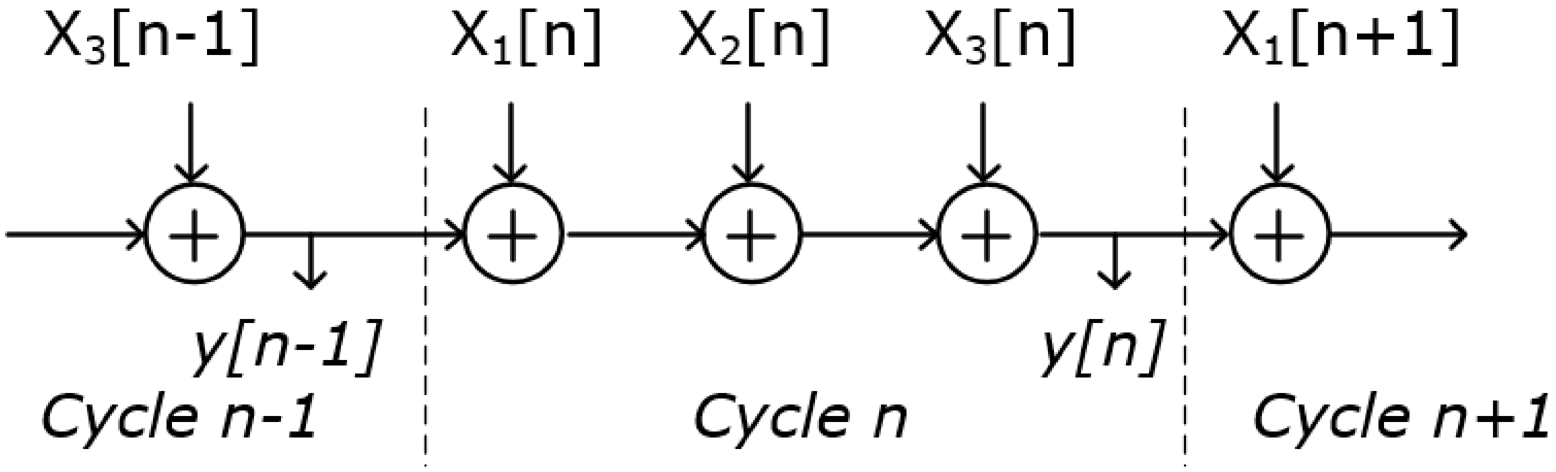
- For any output, say v_1, the period is $6t_{pd}$
- But t_{pd} is random variable (signal) changing with time

Excess Delay of an Inverter



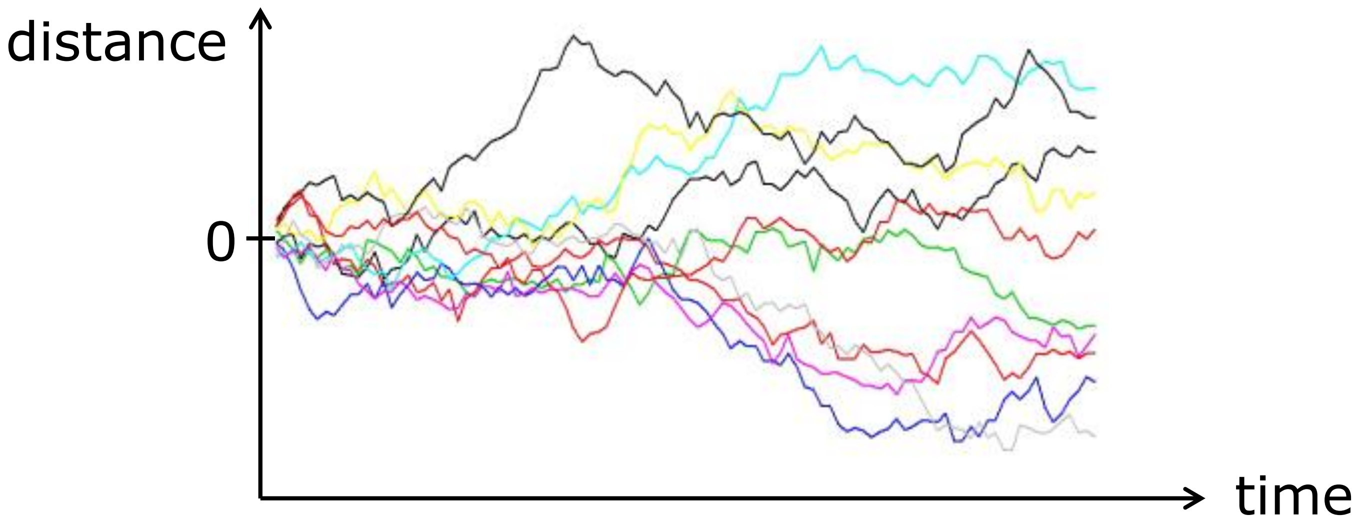
- $I_{n1}(t)$ and $I_{n2}(t)$ represent the thermal (and other) noise currents of M_1 and M_2, respectively
- $I_{n1}(t)$ and $I_{n2}(t)$ will cause v_o to reach a threshold ($V_{DD}/2$) faster or slower than nominal; causing delay of each stage to be a random variable

Modeling Jitter in Ring Oscillator



- Let $X_i[n]$ represent the random *excess delay* introduced by inverter i in cycle n
- $X_i[n]$ 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

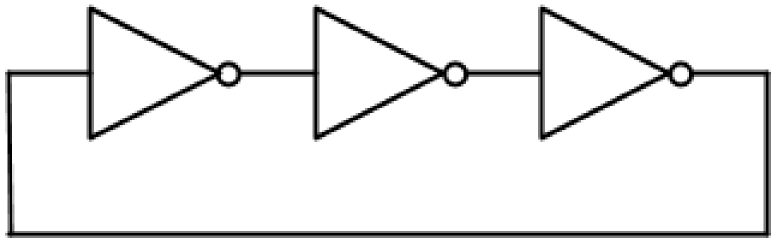
Random Walk Process

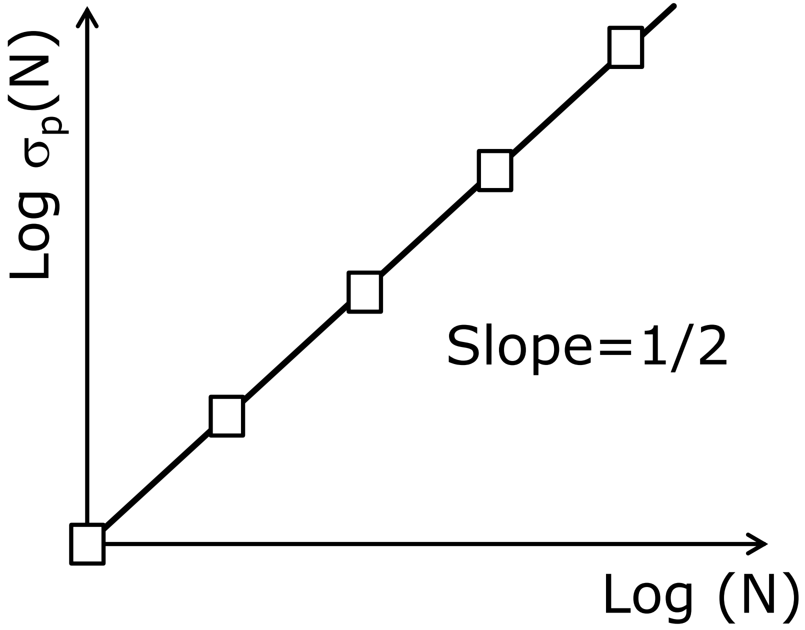


- Start at 0 and toss a coin
  - If head, move one step forward, then repeat
  - If tail, move one step backward, then repeat
- Graph shows 10 difference trials (imagine for 10 people)
- The *expected* distance for all trials are zero
- But the variation around 0 grows over time

Jitter Variance over Time

[McNeill JSSC 1997]



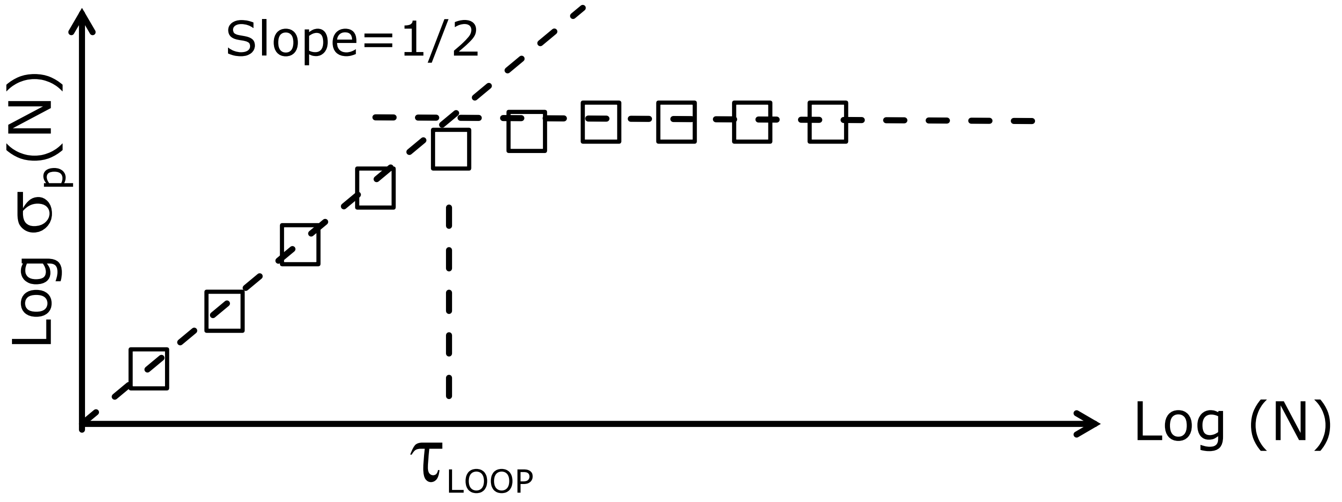


$$\sigma_p(N) = \sqrt{N}\,\sigma_p(1)$$

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

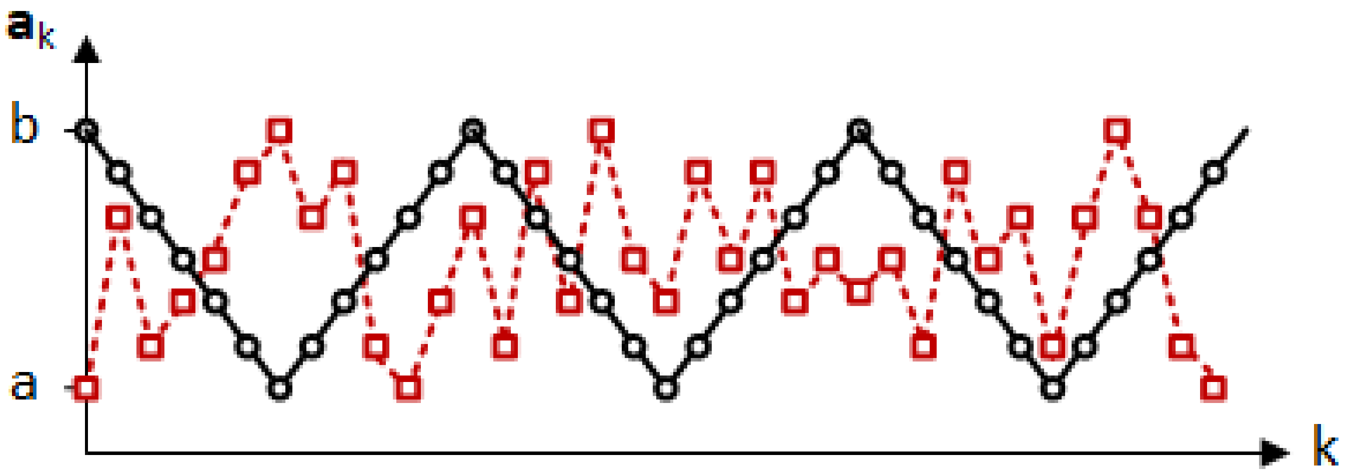
- Jitter variance increases linearly with time
- Jitter rms increases with root square of time

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

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!

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From Jitter to Excess Phase

- Jitter is a discrete-time random process, defined only at CK transitions
- Now consider a periodic signal such as a sinusoid as a clock
- The signal is affected by noise at any time, not just at zero crossings
- The noise effectively shifts the signal phase at any time

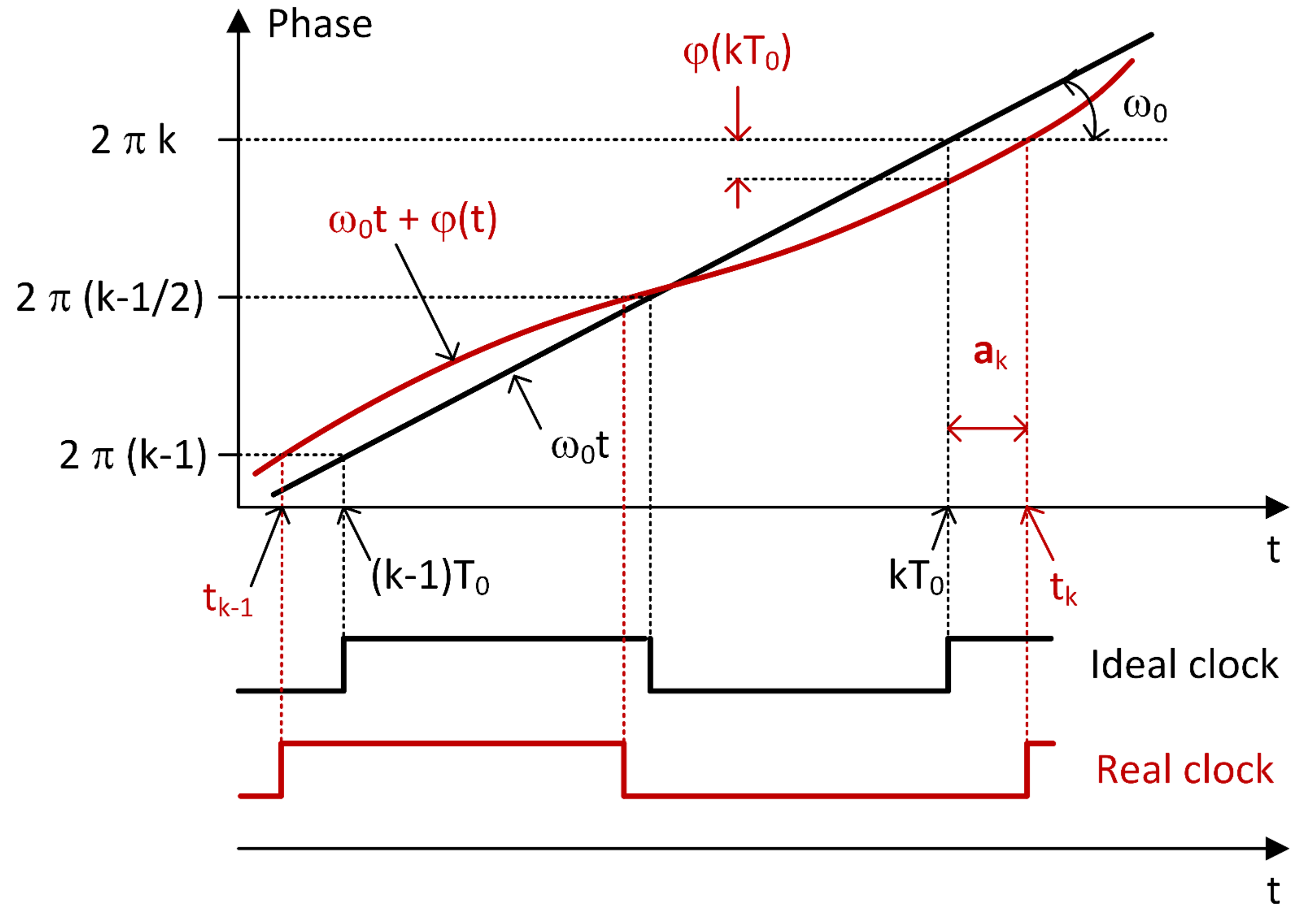
$$v(t) = A_0 \sin(\omega_0 t) + n(t)$$

$$v(t) = A_0 \sin\big(\omega_0 t + \varphi(t)\big) \cong A_0 \sin(\omega_0 t) + A_0 \cos(\omega_0 t)\varphi(t)$$

- We define the deviation from an ideal phase as the excess phase

- Unlike jitter, excess phase is a continuous-time random process
- Jitter can be considered as a sampled version of excess phase

Excess Phase versus Jitter



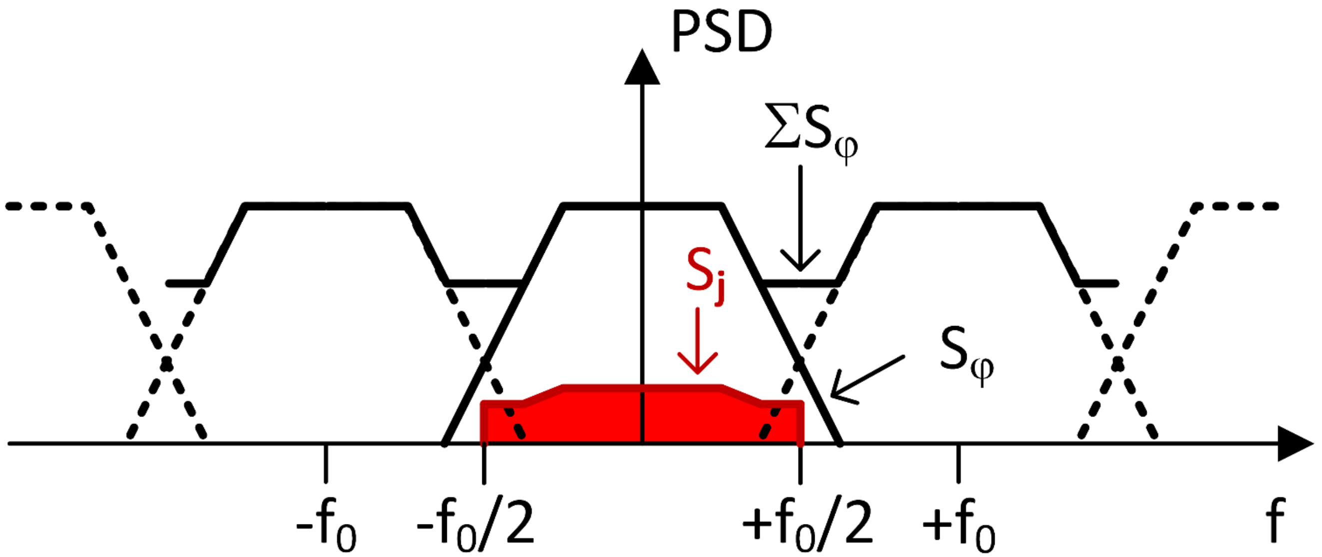
- $\boldsymbol{\varphi}(kT_0) = -\omega_0 \boldsymbol{a}_k$
- $\boldsymbol{a}_k$ are scaled samples of $\boldsymbol{\varphi}(t)$
- $\boldsymbol{\varphi}(kT_0) = -2\pi/T_0\, \boldsymbol{a}_k$
- $\dfrac{\boldsymbol{\varphi}(kT_0)}{2\pi} = -\dfrac{\boldsymbol{a}_k}{T_0}$

Jitter can be considered as a sampled version of excess phase

Excess Phase versus Jitter

$$\mathbf{a}_k = \frac{-\varphi(kT_0)}{\omega_0}$$

$$R_{\mathbf{a}}(kT_0) = \frac{R_\varphi(kT_0)}{\omega_0^2}$$



$$S_{\mathbf{a}}(f) = \frac{1}{\omega_0^2}\sum_{n=-\infty}^{+\infty} S_\varphi(f + nf_0)$$

$$-f_0/2 < f < +f_0/2$$

$$S_{\mathbf{a}}(f) = \begin{cases} \dfrac{S_\varphi(f)}{\omega_0^2} & \text{for} \quad \dfrac{-f_0}{2} \leq f \leq \dfrac{+f_0}{2} \\ 0 & \text{otherwise} \end{cases}$$

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Clock PSD (when $\varphi(t)$ <<1)

$$v(t) = A(t)\sin(\omega_0 t + \varphi(t))$$

$$v(t) = A\left[\sin(\omega_0 t)\cos\varphi(t) + \cos(\omega_0 t)\sin\varphi(t)\right]$$

$$v(t) \approx A\sin(\omega_0 t) + A\varphi(t)\cos(\omega_0 t)$$

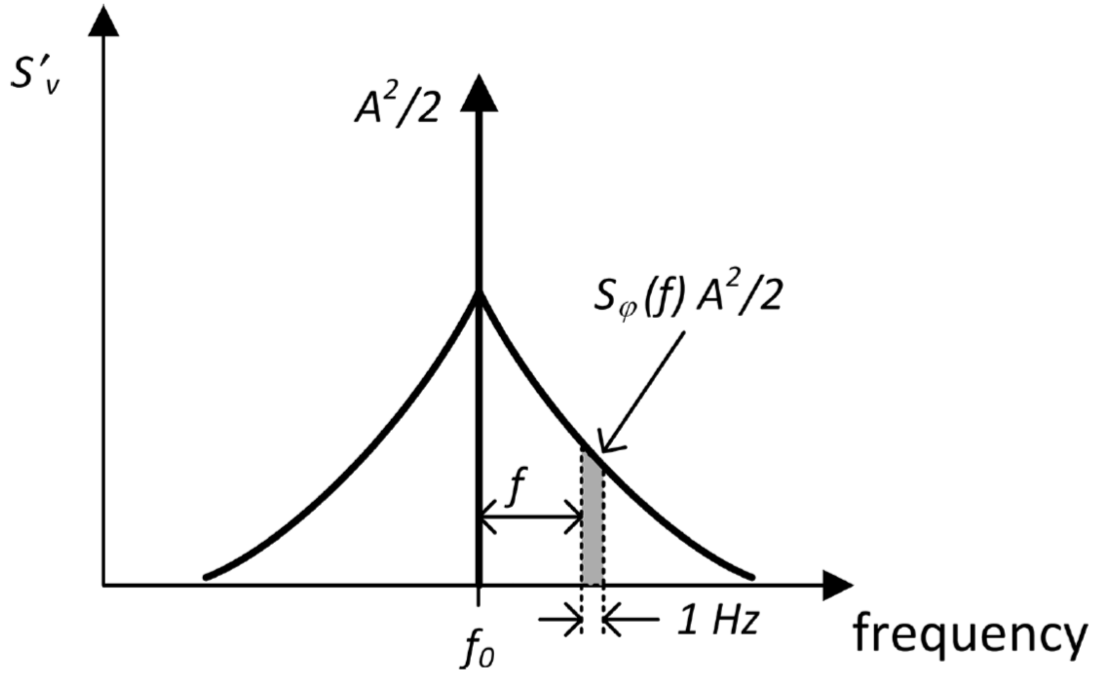
$$R_v(t,\tau) = \frac{A^2}{2}\left\{\cos(\omega_0\tau) - \cos(2\omega_0 t + \omega_0\tau) + [\cos(2\omega_0 t + \omega_0\tau + \cos(\omega_0\tau)]\,R_\varphi(\tau)\right\}$$

$$\bar{R}_v(\tau) = \frac{\omega_0}{\pi}\int_0^{\pi/\omega_0} R_v(t,\tau)dt = \frac{A^2}{2}\cos(\omega_0\tau)\left[1 + R_\varphi(\tau)\right]$$

$$S_v(f) = \frac{A^2}{4}\left[\delta(f - f_0) + \delta(f + f_0) + S_\varphi(f - f_0) + S_\varphi(f + f_0)\right]$$

$$S'_v(f) = \frac{A^2}{2}\left[\delta(f - f_0) + S_\varphi(f - f_0)\right]$$

Clock PSD and Excess Phase PSD



$$S_v'(f) = \frac{A^2}{2}\left[\delta(f - f_0) + S_\varphi(f - f_0)\right]$$

Alternatively,
if define *f* as offset from f_0:

$$S_\varphi(f) = \frac{S_v(f_0 + f)}{A^2/4} = \frac{S_v'(f_0 + f)}{A^2/2}$$

- The excess phase spectrum (baseband) is upconverted to around f_0

Harmonics in Clock Signal

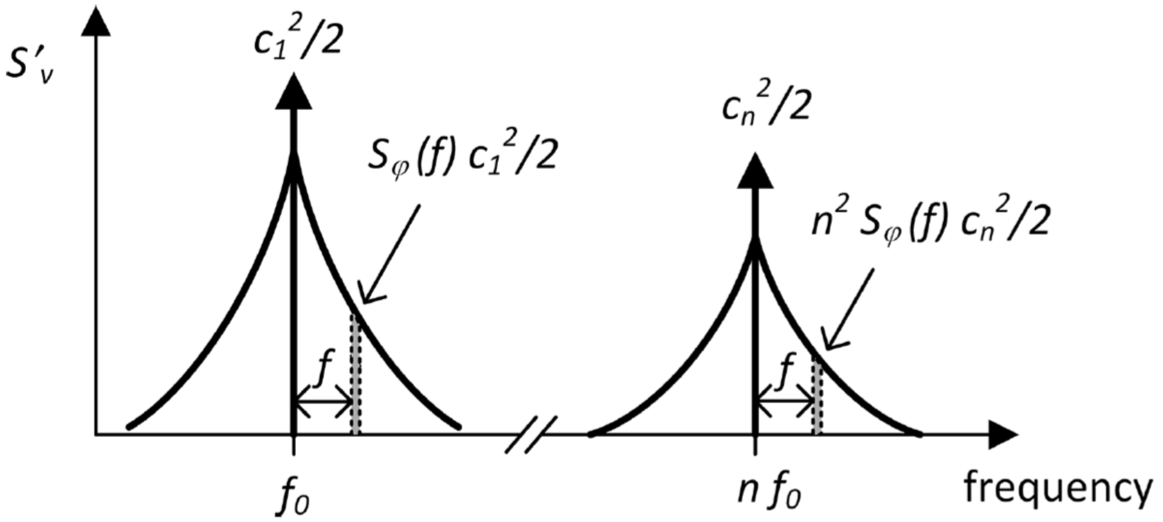
- Assume a generic period signal x(t) as the clock signal

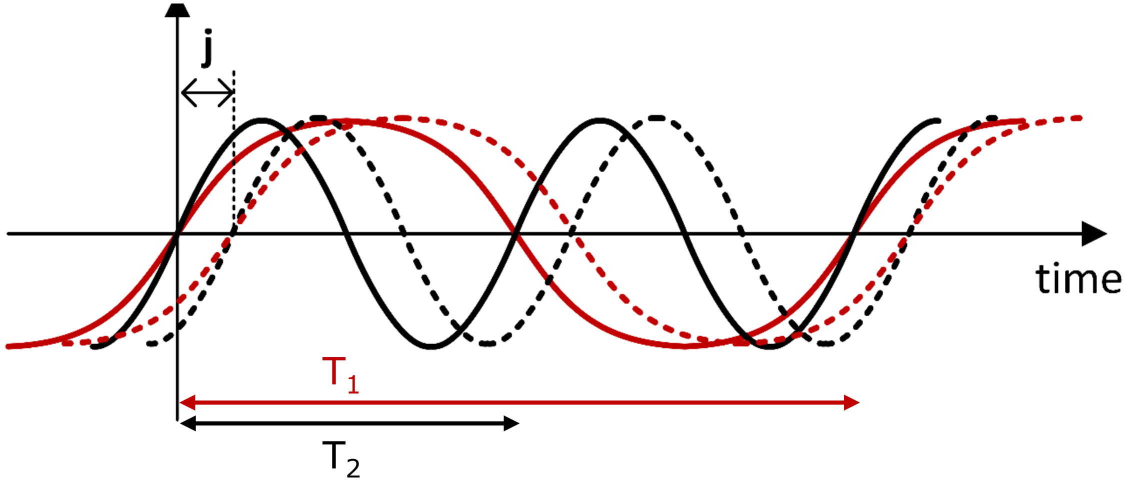
- For simplicity, x(t) has odd symmetry, i.e. x(-t)=-x(t)

$$x(t) = \sum_{n=1}^{+\infty} c_n \sin(n\omega_0 t).$$

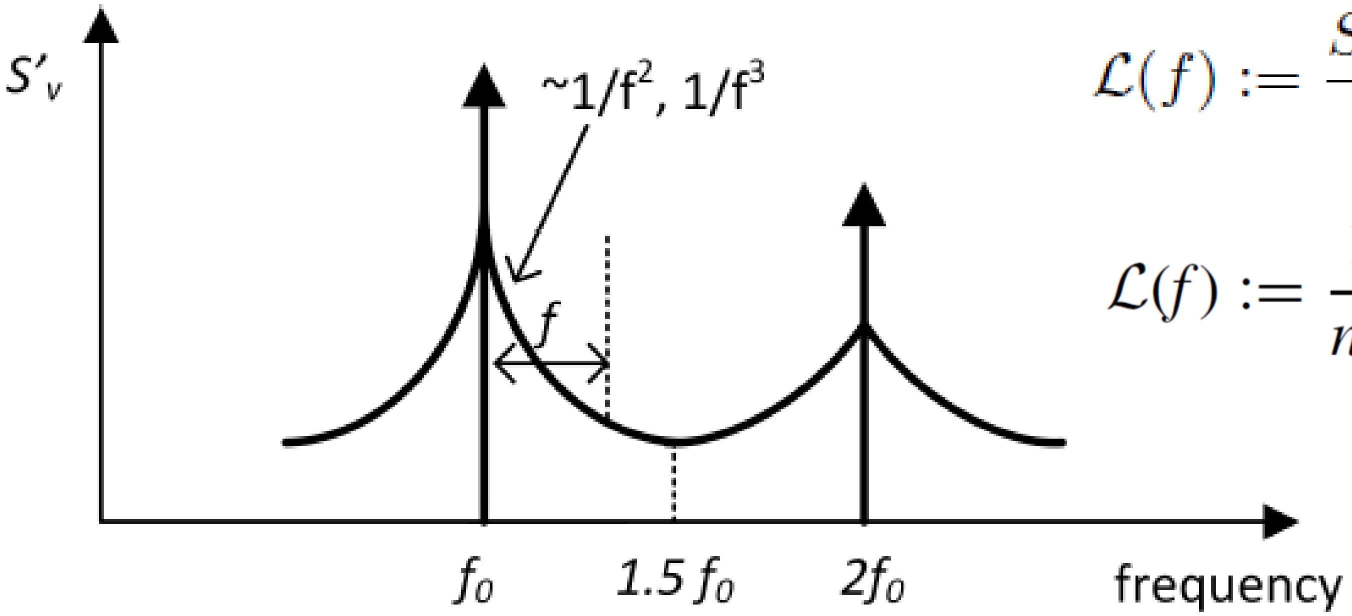
$$x(t - \mathbf{a}(t)) = \sum_{n=1}^{+\infty} c_n \sin\left(n\omega_0 t - n\omega_0 \mathbf{a}(t)\right)$$

$$\varphi_n = n\varphi \qquad S_{\varphi_n}(f) = n^2 S_\varphi(f).$$





Phase Noise Definition

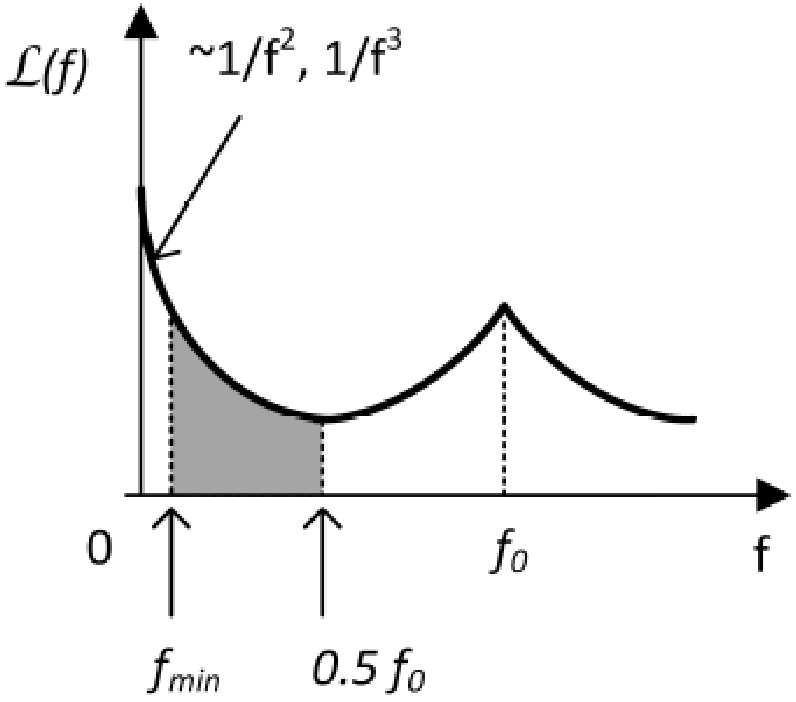


$$\mathcal{L}(f) := \frac{S'_v(f_0 + f) \text{ in 1 Hz bandwidth}}{P}$$

$$\mathcal{L}(f) := \frac{1}{n^2} \frac{S'_v(nf_0 + f) \text{ in 1Hz bandwidth}}{\text{power of the } n\text{-th harmonic}}$$

- Phase noise is defined for positive frequencies only!
- f in phase noise expression represents offset from carrier frequency f_0
- Phase noise can also be derived from skirts around the n-th harmonic

From Phase Noise to Jitter rms



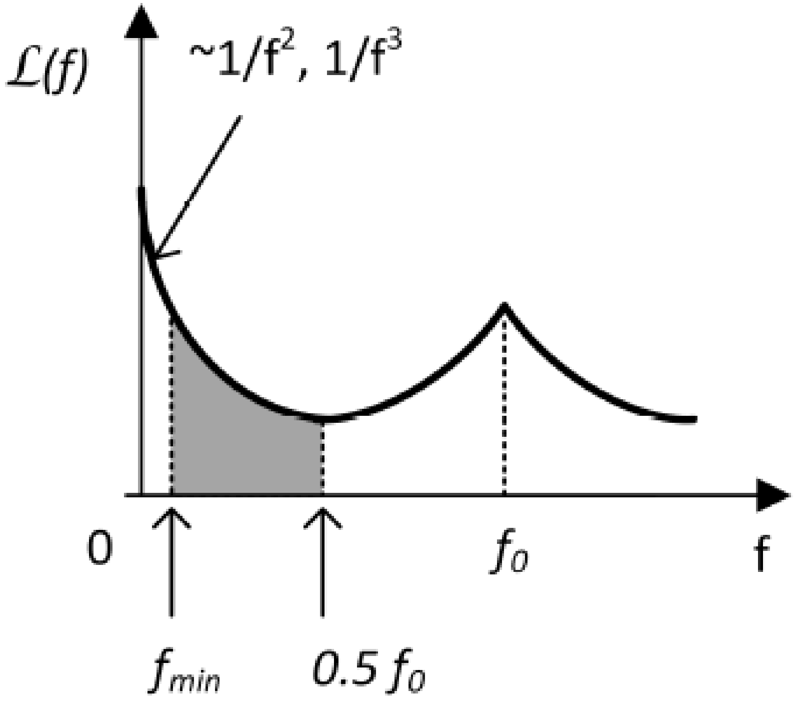
$$\varphi = \omega_0\, a \qquad \sigma_\varphi = \omega_0 \sigma_a$$

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

$$\sigma_a^2 = \int_{-f_0/2}^{+f_0/2} S_a(f)\, df$$

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

Integration Limits

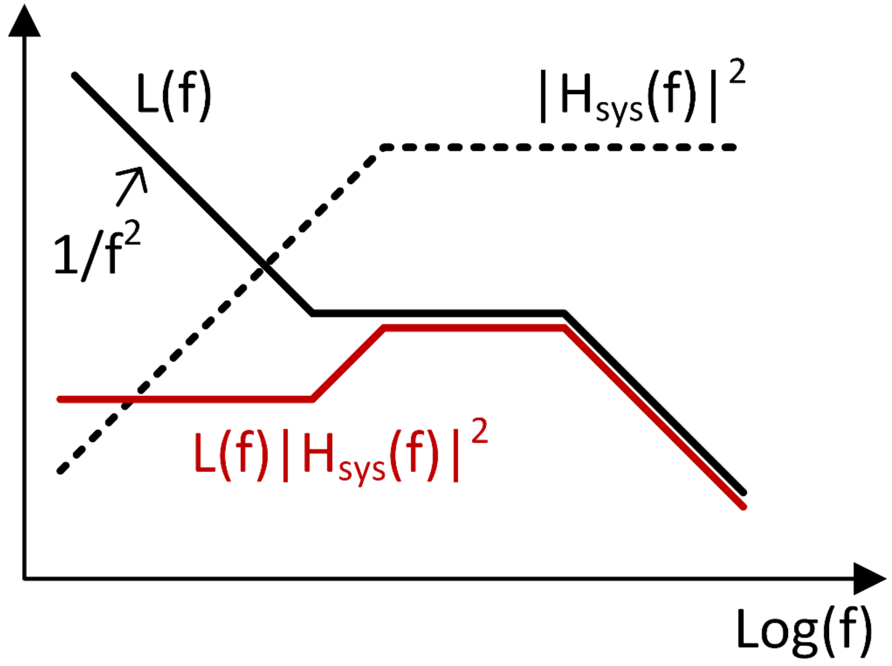


$$\sigma_{\mathrm{a}} = \sqrt{\frac{2}{\omega_0^2}\int_0^{+\infty} \mathcal{L}(f)\,df}$$

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

- Upper limit is set to $f_0/2$ not to double count phase noise around 2^{nd} harmonic
- Lower limit is set to f_{min}, often set by limited observation time
- If lower limit is left at 0, the rms jitter will go to infinity
- Consistent with our observations about the ring oscillator

Jitter RMS after Transfer



$$\sigma_{\mathbf{a}} = \sqrt{\frac{2}{\omega_0^2} \int_0^{f_0/2} \mathcal{L}(f) \left|H_{sys}(f)\right|^2 \, df}$$

- Jitter PSD is multiplied by the square of the jitter transfer function
- A high-pass jitter transfer attenuates jitter at low frequencies
- Lower integration limit can be set back to 0; more accurate results

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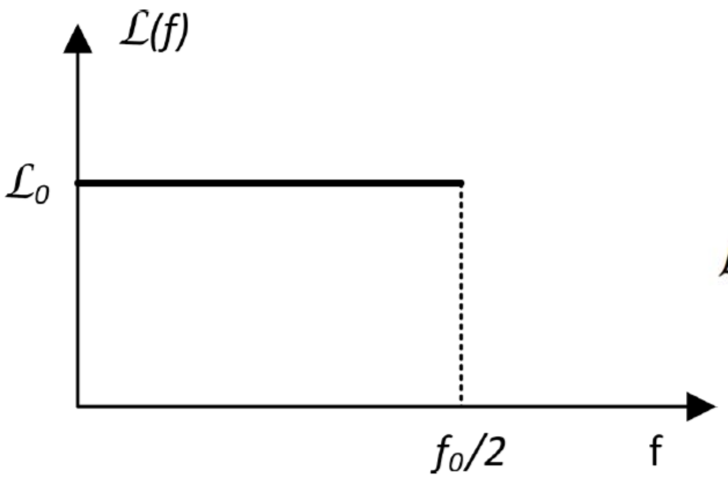
Example 1: Flat Phase Noise Profile

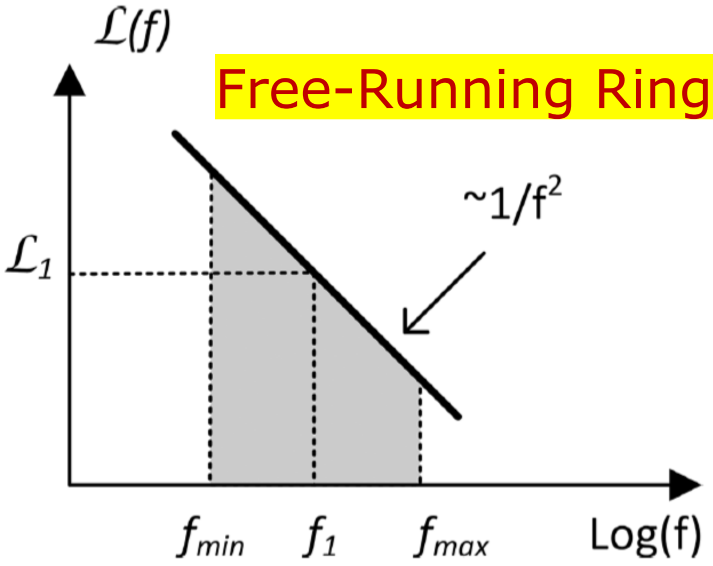


$$\mathcal{L}(f) = \begin{cases} \mathcal{L}_0 & \text{if } 0 < f < f_{max} \\ 0 & \text{otherwise} \end{cases}$$

$$\sigma_{\mathbf{a}} = \sqrt{\frac{2}{\omega_0^2} \int_{f_{min}}^{+f_0/2} \mathcal{L}(f)\, df} \qquad \sigma_{\mathbf{a}} = \frac{1}{\omega_0}\sqrt{2\mathcal{L}_0 f_{max}} \qquad \frac{\sigma_{\mathbf{a}}}{T_0} = \frac{\sqrt{\mathcal{L}_0 f_0}}{2\pi}$$

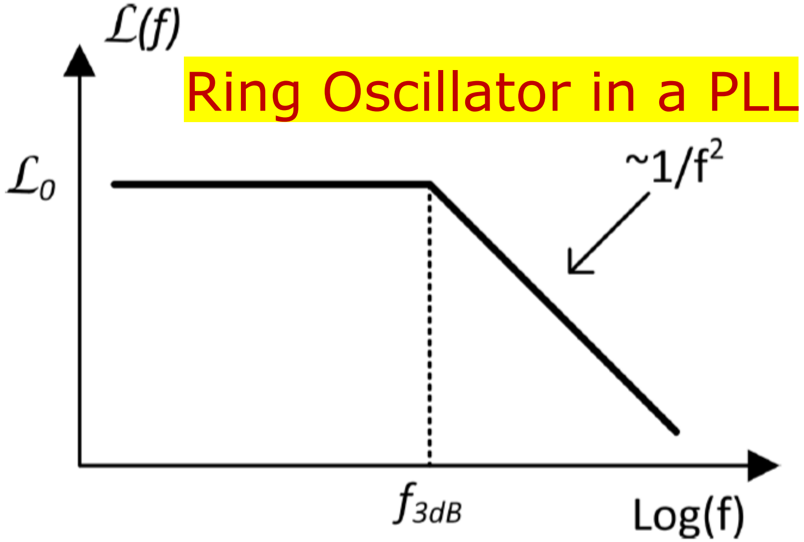
- Numerical Example: f_0 = 1GHz, and L_0 = 130dBc/Hz (=10^{-13})
- RMS of absolute jitter is 0.16% of the clock period, namely 1.6ps.

Example 2: $1/f^2$ Jitter Profile



$$\mathcal{L}(f) = \frac{\mathcal{L}_1 f_1^2}{f^2}$$

$$\frac{\sigma_{\mathbf{a}}}{T_0} = \sqrt{\frac{\mathcal{L}_1 f_1^2}{2\pi^2}\left(\frac{1}{f_{min}} - \frac{1}{f_{max}}\right)}$$

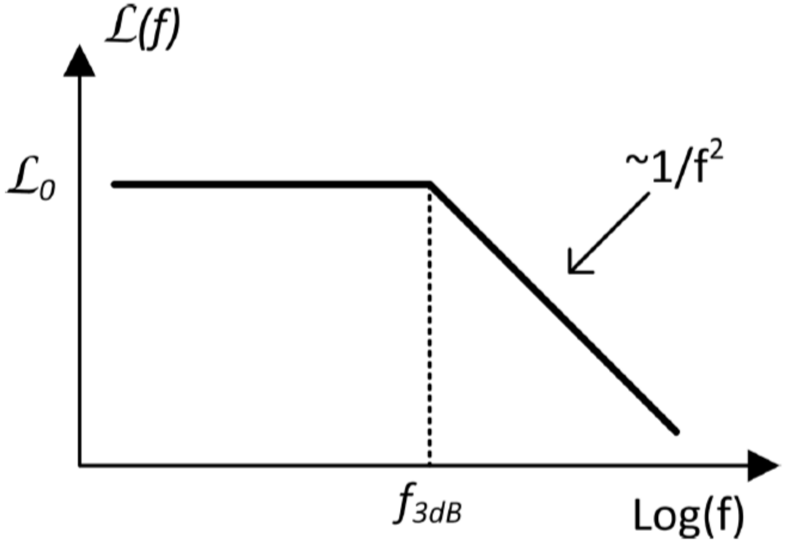


$$\mathcal{L}(f) = \frac{\mathcal{L}_0}{1 + (f/f_{3dB})^2}$$

$$\frac{\sigma_{\mathbf{a}}}{T_0} = \sqrt{\frac{\mathcal{L}_0 f_{3dB}}{4\pi}}$$

Numerical Examples

[Marzin ISSCC '14]



$$\frac{\sigma_a}{T_0} = \sqrt{\frac{\mathcal{L}_0 f_{3dB}}{4\pi}}$$

Design #	f_{3dB} (Hz)	L_0 (dBc/Hz)	σ_a Calculated	σ_a Measured
1	300k	-100	428fs	440fs
2	2M	-102	621fs	660fs
3	4M	-104	697fs	680fs

Jitter Generation in Matlab [1 of 3]

- Generate jitter numbers for a clock so as to have a target phase noise
- Useful for simulation & performance analysis of circuits involving jittery clocks

- Jitter can be considered as a vector (1xN matrix) of timing deviations

- Example in matlab: Generate a jitter vector that includes 1 million samples for a 1GHz clock with flat phase noise of -110dBc/Hz

```
F0=1e9;
L0=-110;
npoints=1e6;
sigma=sqrt(10^(L0/10)/F0)/(2*pi);
t_id=1/F0*(0:npoints-1);
j=sigma*randn(1,npoints);
t=t_id+j;
```

[Available for download at www.understandingjitter.com]

Jitter Generation in Matlab [2 of 3]

- Generate jitter samples with high-pass, low-pass, bandpass profiles
- Generate a jitter vector with 10^7 samples with:
  - Simple PLL spectrum
  - inband phase noise = −110dBc/ Hz, f_{3dB} = 1MHz, carrier frequency (f_0 = 1 GHz)

- We use Matlab built-in functions `butter` and `filter`

```
F0=1e9; L0=-110;f3dB=1e6;
npoints=1e7;
sigma=sqrt(10^(L0/10)/F0)/(2*pi)
t_id=1/F0*(0:npoints-1);
j=sigma*randn(1,npoints);
[B,A] = butter(1,2*f3dB/F0);
j_filtered=filter(B,A,j);
t=t_id+j_filtered;
```

[Available for download at www.understandingjitter.com]

Jitter Generation in Matlab [3 of 3]

- Generate jitter samples with
  - $1/f^2$ phase noise profile
  - −110dBc/Hz at 5MHz offset frequency for a 1GHz clock (f_0 = 1 GHz)

```
F0=1e9;
L1=-110;
f1=5e6;
npoints=1e6;
sigma_l=(f1/F0)*sqrt(10^(L1/10)/F0)
t_id=1/F0*(0:npoints-1);
l=sigma_l*randn(1,npoints);
j=cumsum(l);
t=t_id+j;
```

[Available for download at www.understandingjitter.com]

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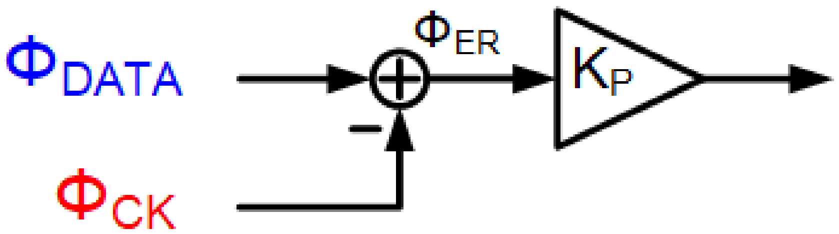
Measuring Absolute Jitter

[Liang JSSC '15]



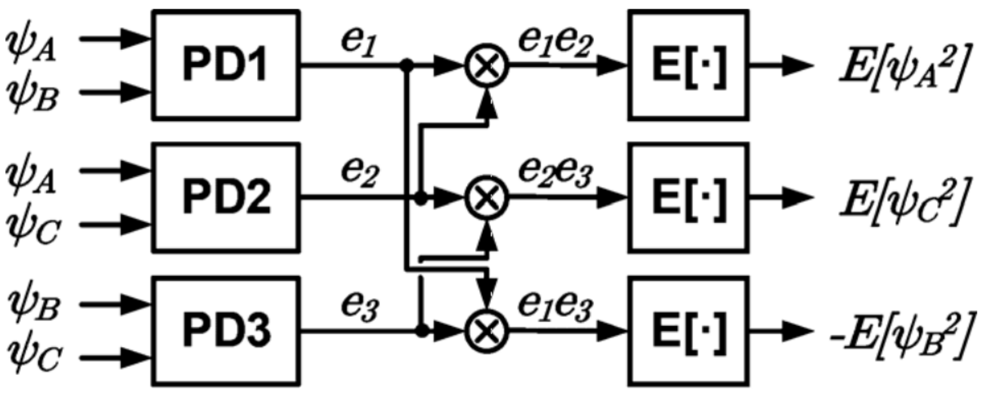
$$K_P \cdot \Phi_{ER} = K_P \cdot (\Phi_{DATA} - \Phi_{CK})$$

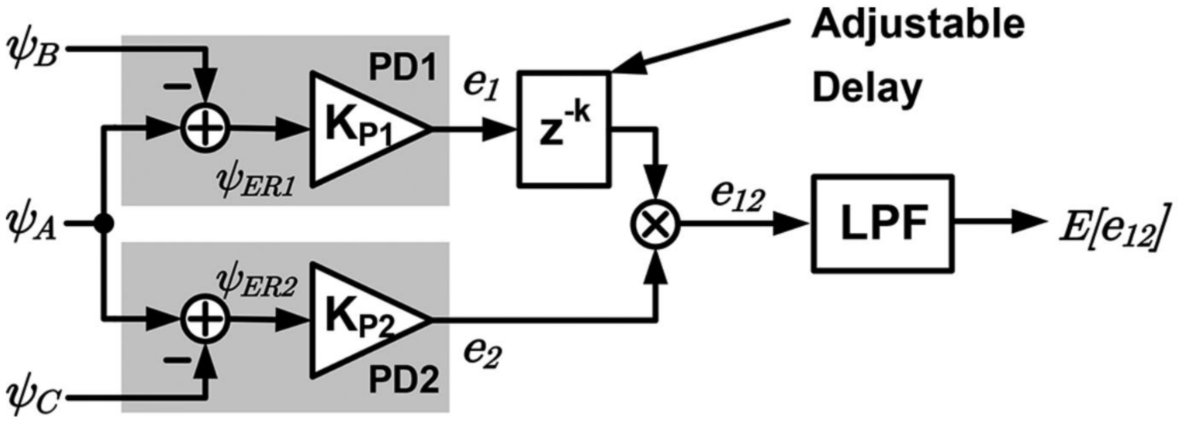
- This diagram models the operation of a linear phase detector
- Clock jitter is subtracted from data jitter to produce relative jitter
- Interested in distinguishing between jitter in data and recovered clock
- Only relative jitter (difference between two absolute jitters) is observable

- Without ideal clock, how to measure absolute jitter?

Add a Third Signal

[Liang JSSC ‘15]

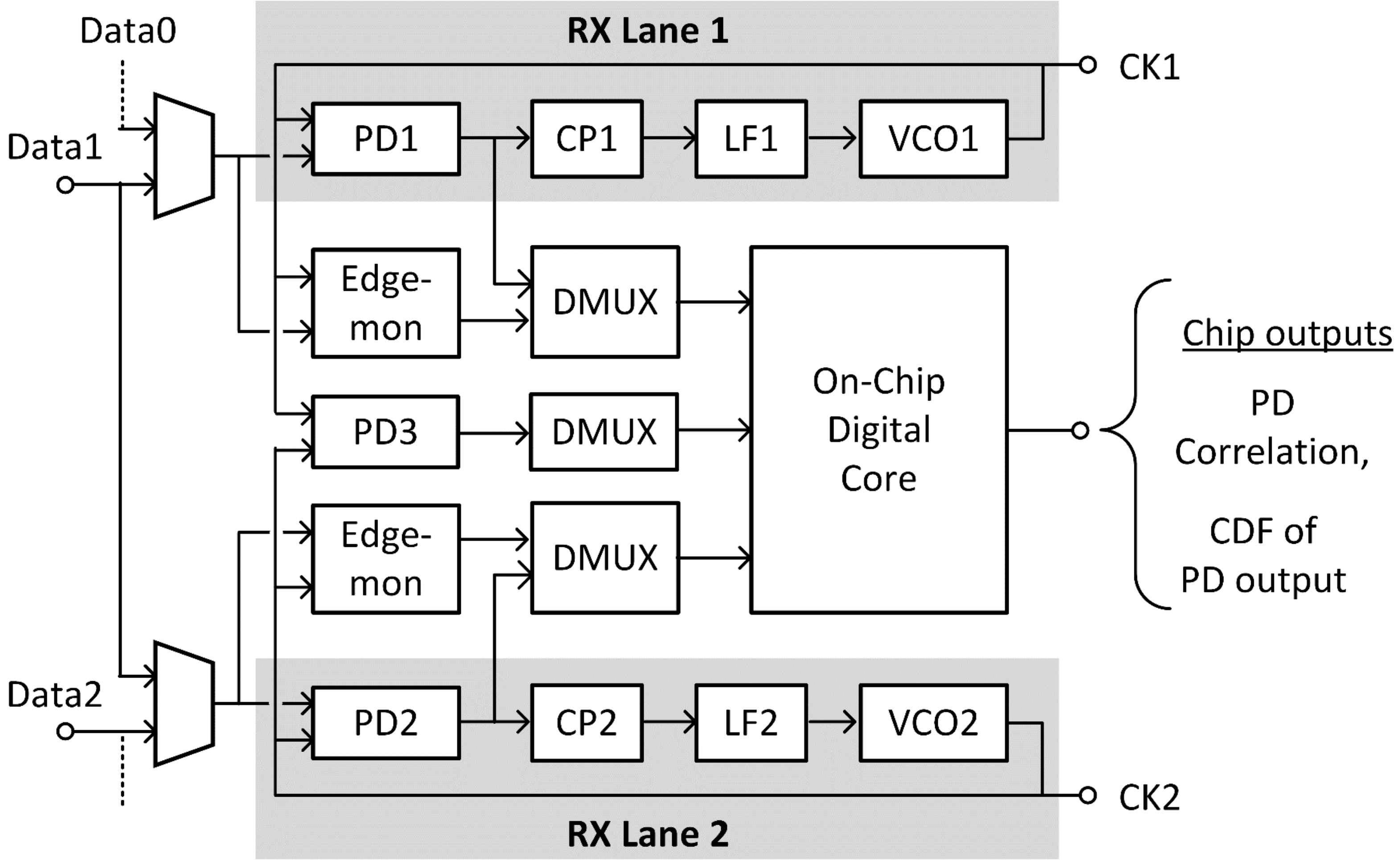




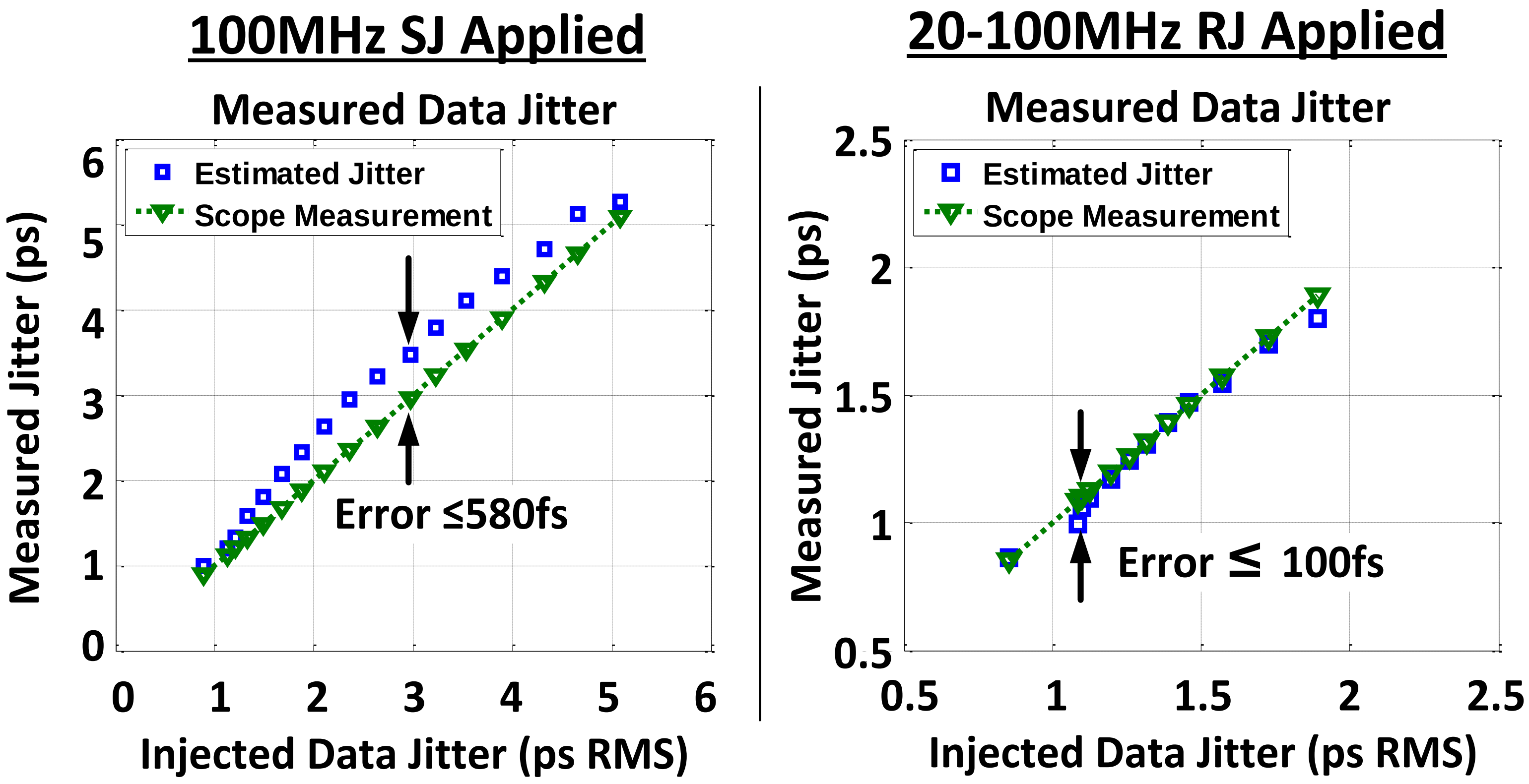
- ψ_A, ψ_B, and ψ_C are absolute jitters of A, B, & C with zero mean, uncorrelated
- Feed pairwise signals to three linear phase detectors (PD)
- Correlate two relative jitters to estimate rms of absolute jitter
- Block diagram on the right implements autocorrelation of jitter
- $E[\Phi_{DATA}(n)\cdot\Phi_{DATA}(n-k)] = R_{DATA}(k)$
- 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]



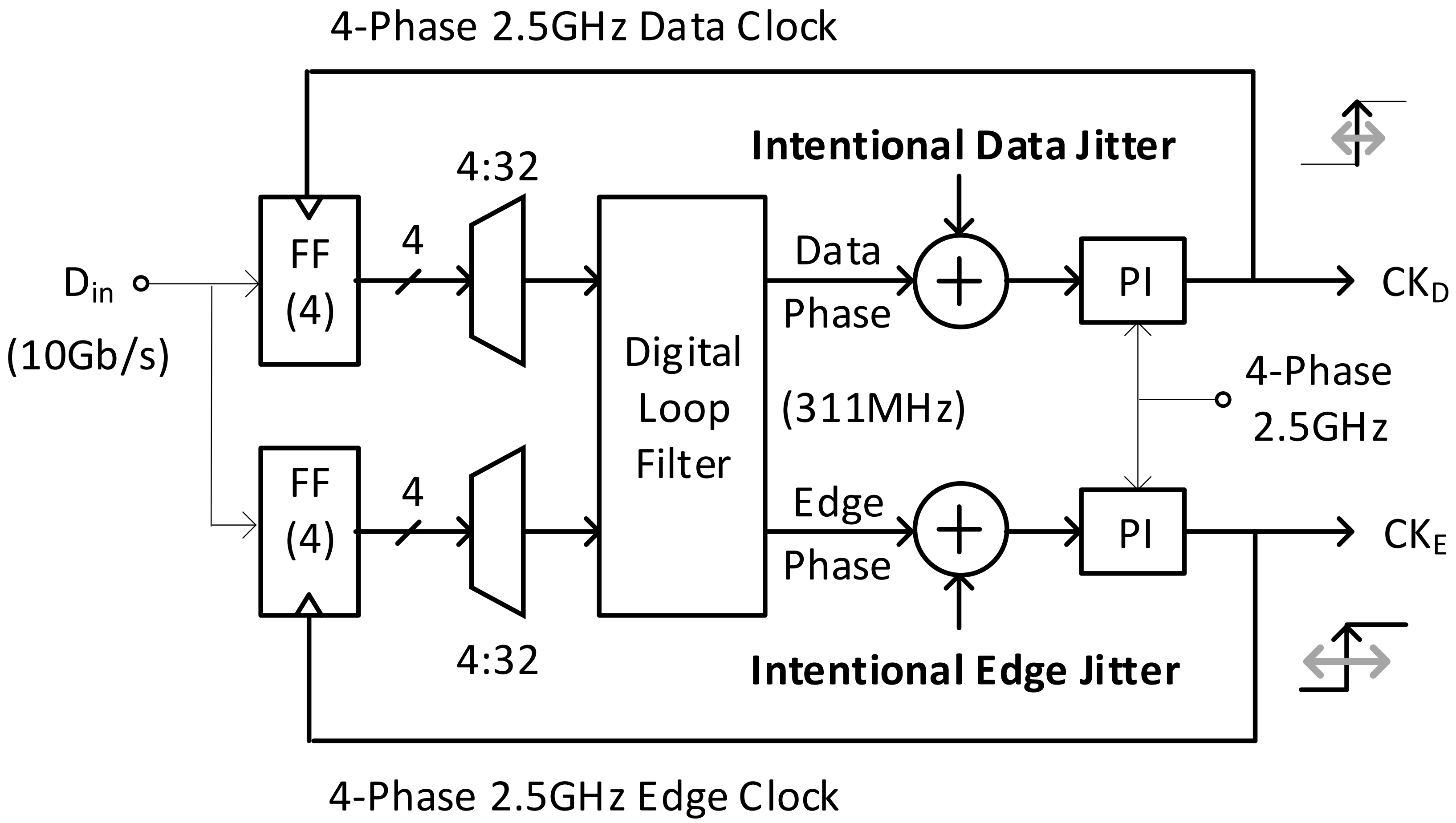
Measured Results [Liang JSSC'15]



- □ Estimated Jitter
- ▽ Measurement from 80GS/s real-time scope

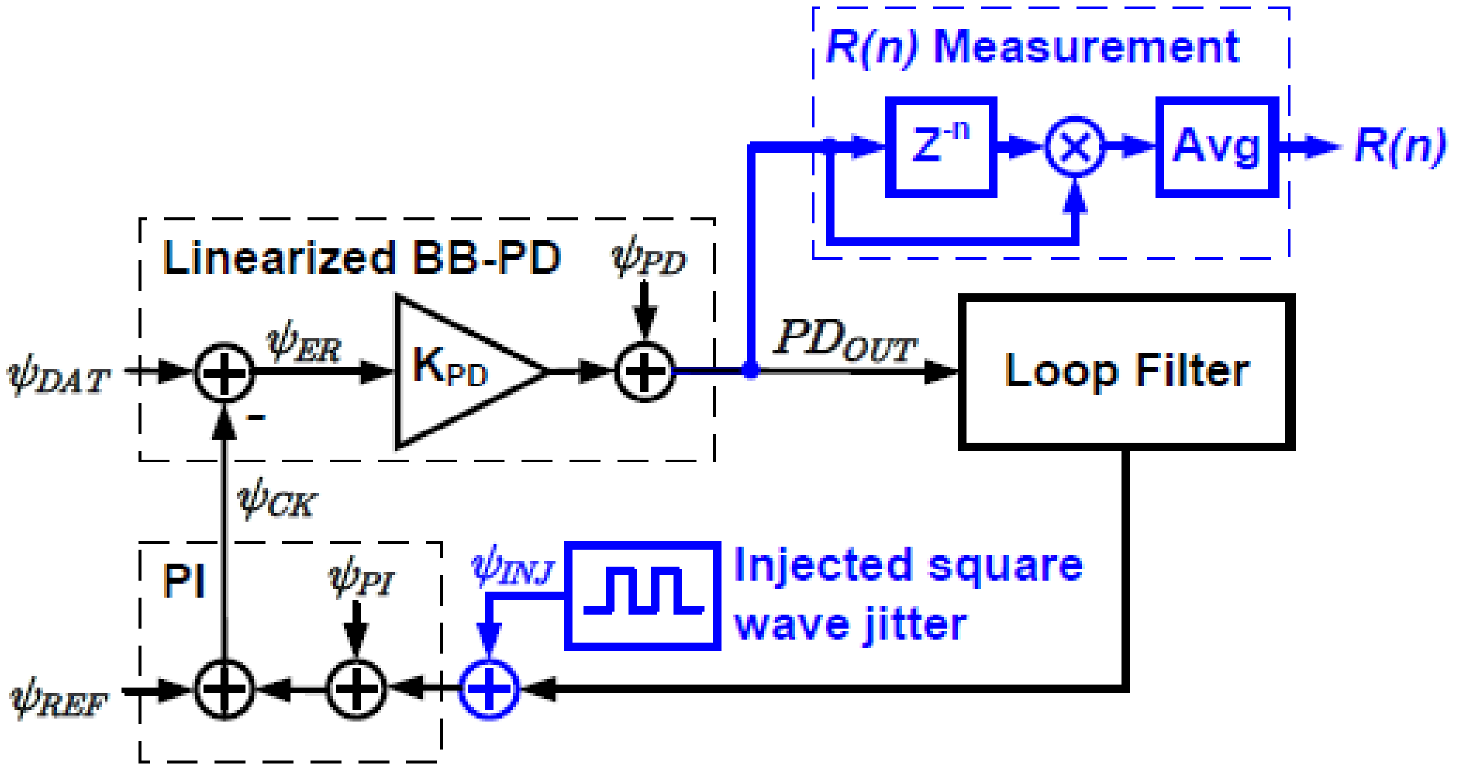
Intentional Jitter to Improve Linearity

[Takauchi JSSC '03]



Jitter Injection for Measurement

[Liang CICC'17]

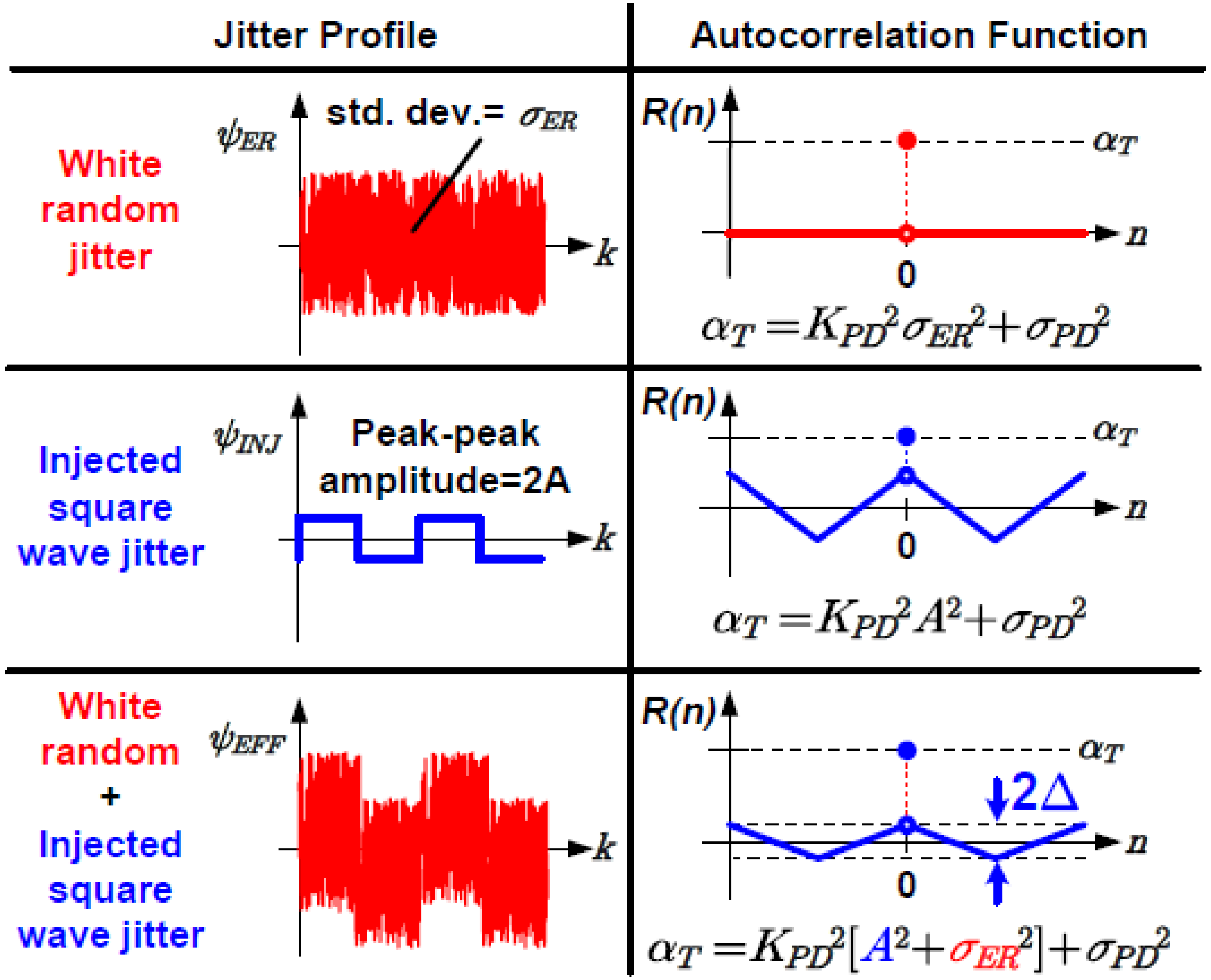


- Intentional jitter toggles LSB for PI of Edge CK
  - Helps calibrate BB-PD effective gain measurement
  - Improves accuracy of relative jitter measurement

Injected Jitter for Observability

[Liang CICC’17]

*Outstanding Student Paper Award from CICC2017!



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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
  - Autocorrelation reveals jitter behavior over time
  - PSD provides information in frequency domain

- Excess phase is a continuous random signal
  - Jitter is a sampled version of excess phase
  - Phase noise, $L(f)$, measured in dBc/Hz, is defined as the PSD of the clock divided by the carrier power at a frequency offset f from the carrier

- Jitter can be injected intentionally to improve linearity and observability

References

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