ISSCC 2012 Tutorials

JITTER
basic and advanced concepts, statistics and applications

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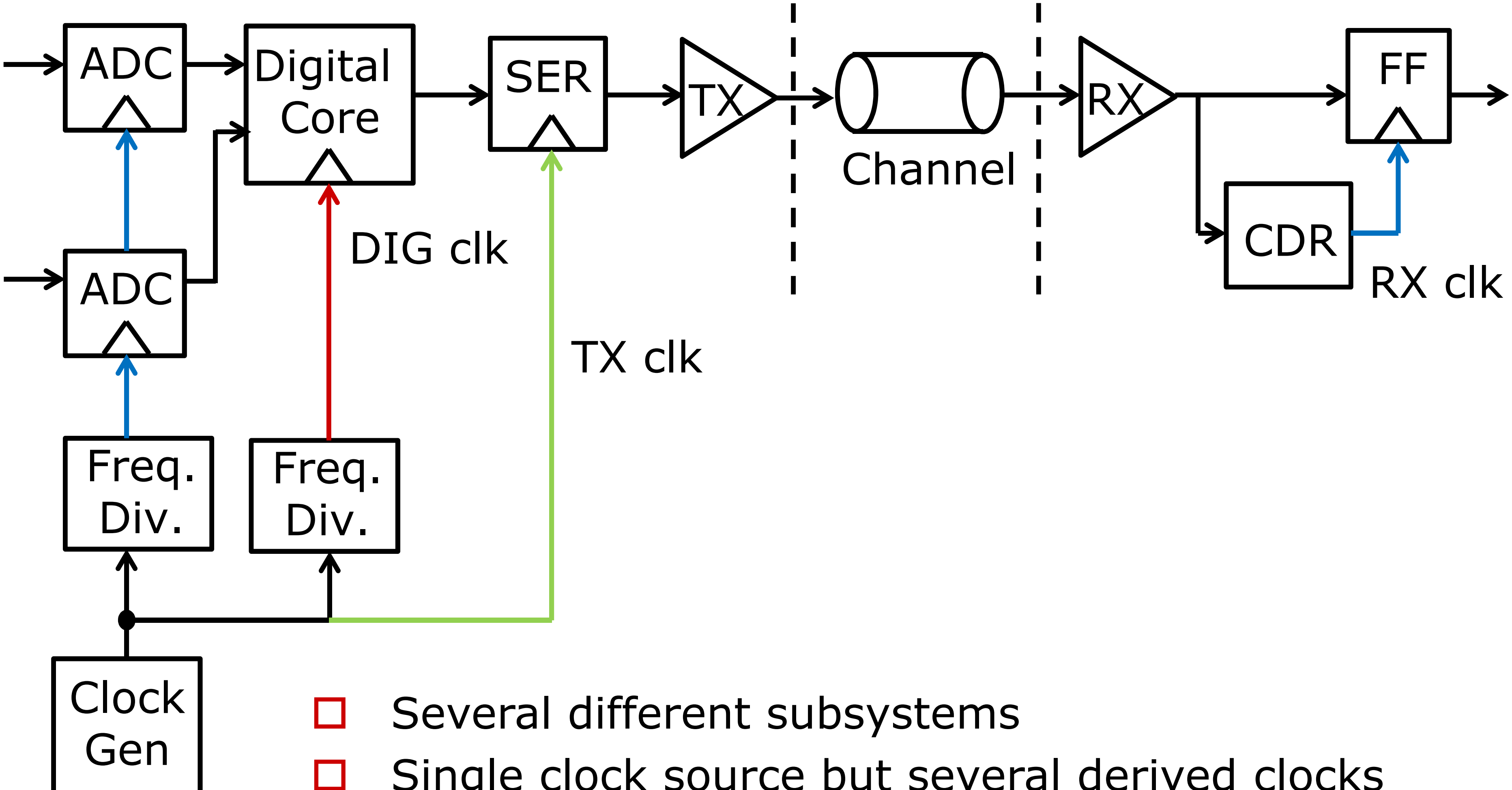
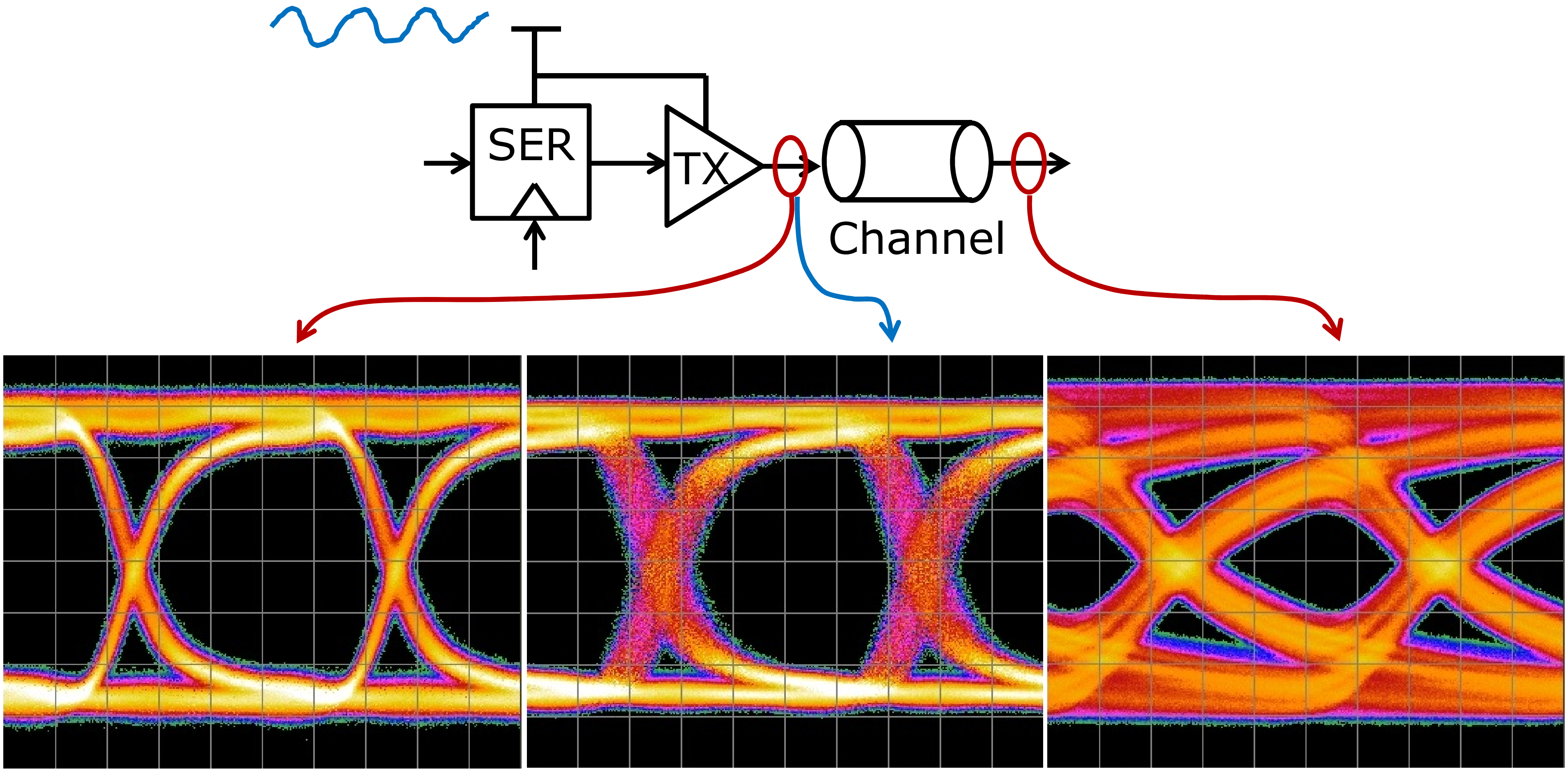
Motivation: a complex system



- Several different subsystems
- Single clock source but several derived clocks
- Each subsystem has own jitter requirements

Motivation: jitter in serial high speed TX

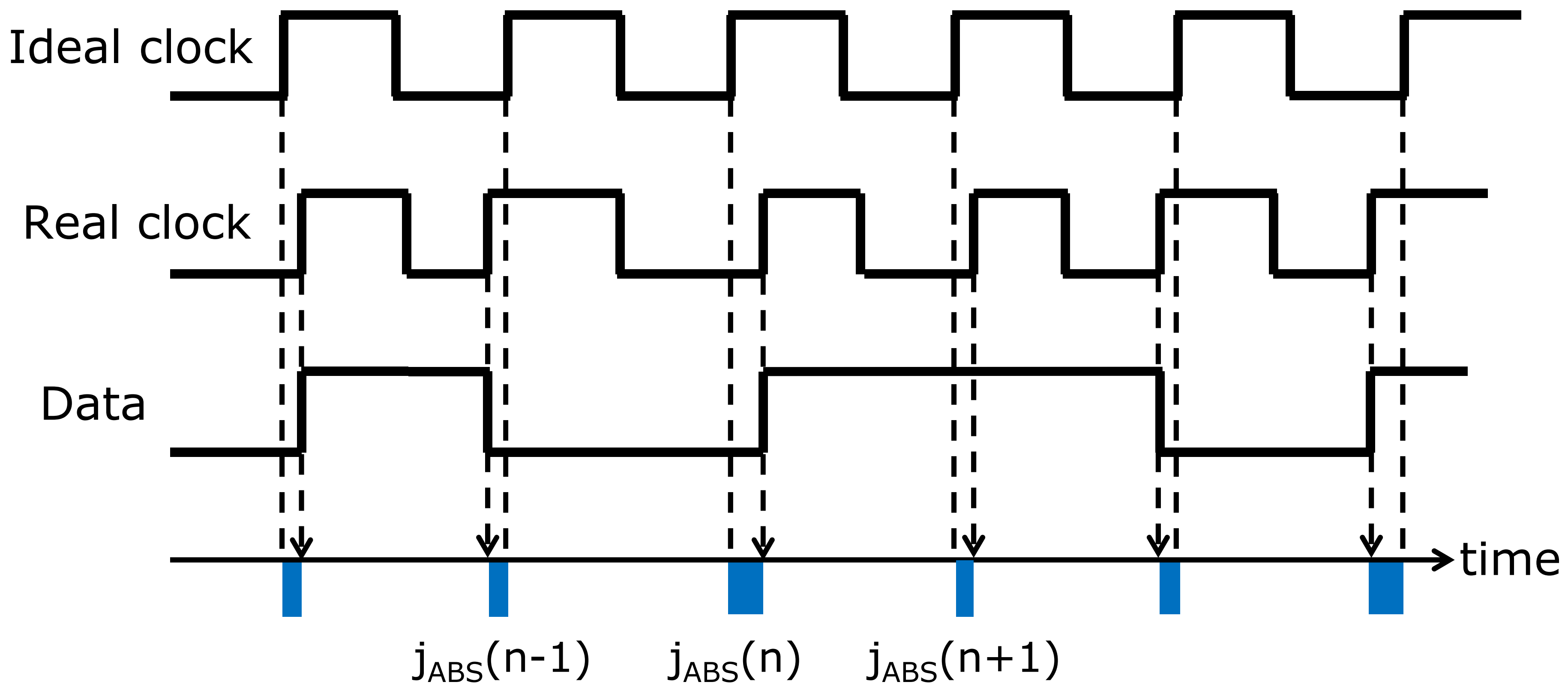


- Jitter can show different faces. How to define and quantify it?

Overview

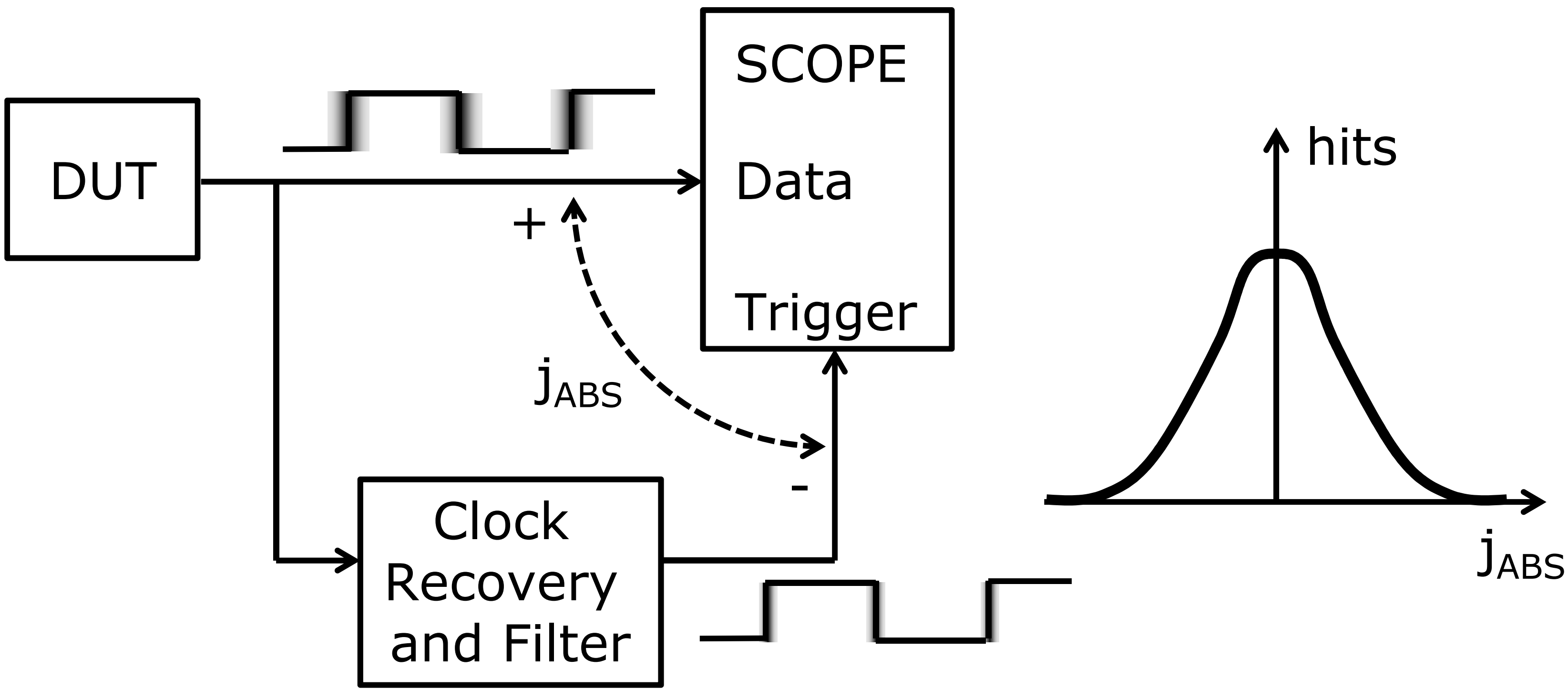
- Definition of absolute jitter
- Time and frequency domain measurements
- Phase noise and jitter
- Jitter in electronics systems and typical applications
- Self-referenced jitter and additional definitions
- Jitter statistics for gaussian and non-gaussian distributions
- Bathtub curves
- Application to high-speed serial data transmission
- Jitter and spectral spurious tones

Absolute Jitter : definition



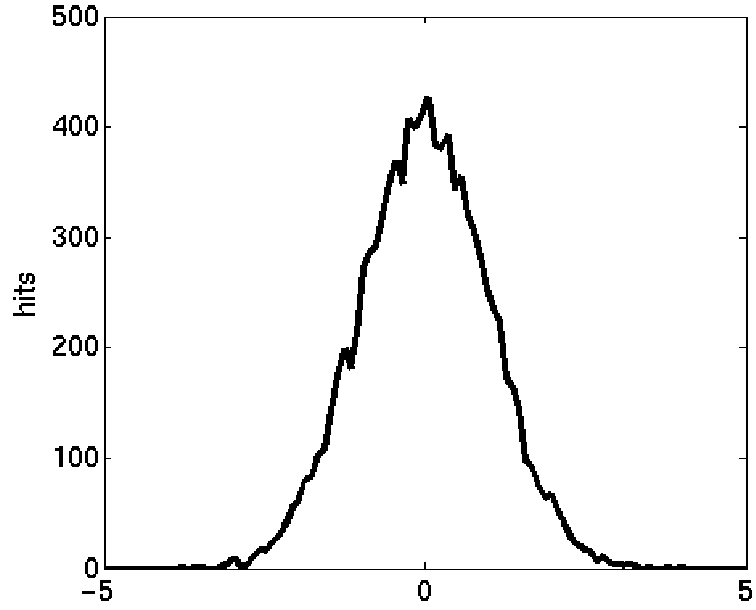
- **Absolute jitter** := Time difference between real and ideal edges

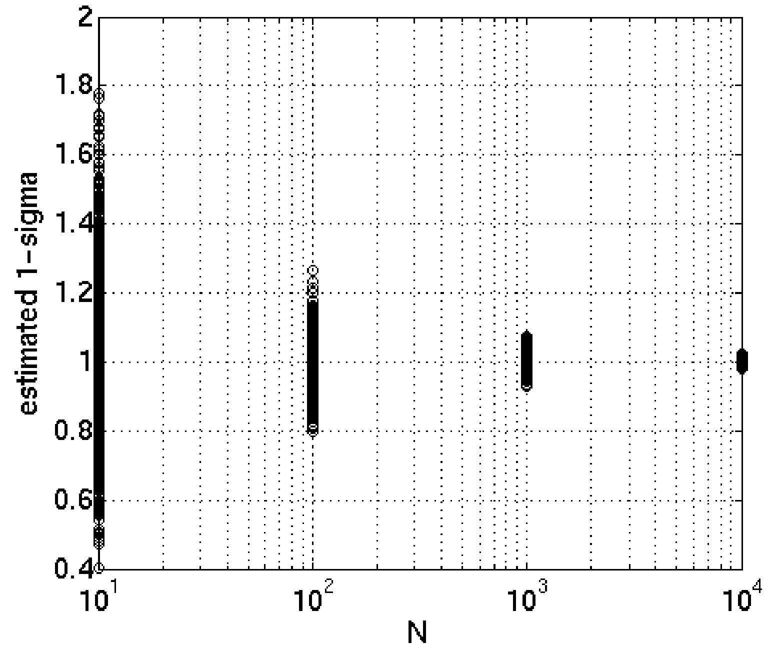
Absolute Jitter : Time Domain Meas



- Clock recovery or PLL with clean up function (included in most high-end scopes)
- Scope measures the time difference from trigger to data
- Results are typically shown in form of histograms

Estimation of RMS from Histogram (1/3)





- Estimated 1-sigma $\hat{\sigma}_{ABS} = \sqrt{\frac{1}{N-1}\sum_{1}^{N} j_{ABS}^{2}(i)}$
- N = number of hits in histogram
- The larger N, the more accurate the estimation

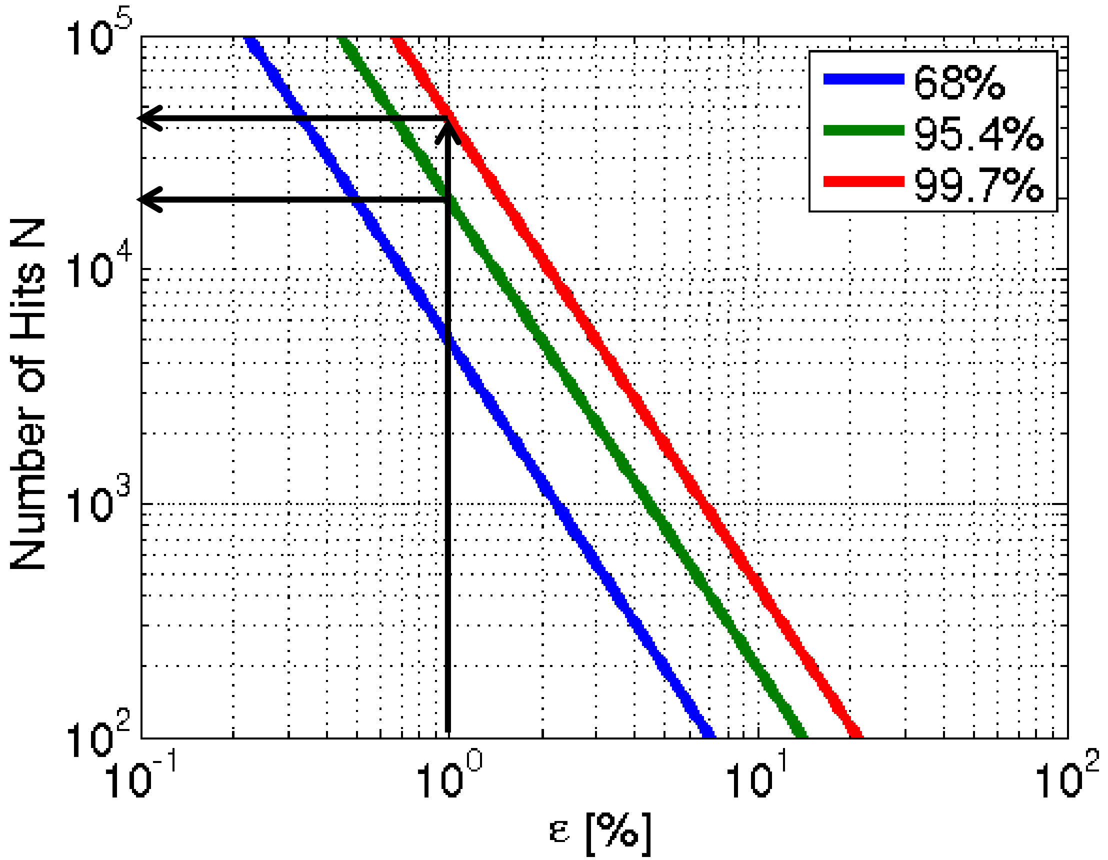
Estimation of RMS from Histogram (2/3)

- A coffee company asks you to estimate the average size of coffee beans of a farm. **You'll have to pay a fine if you are wrong.**
- Take "N" coffee beans, measure, average = **11mm**
- You want to reserve a **margin for error** = **+/- 1mm** (this is called **Confidence Interval, CI**)
- **How sure are you?** You repeat the experiment lots of times (on different beans) and find out that in **90%** of the cases the average is indeed within 11mm +/- 1mm. This "90%" is called **Confidence Level, CL**.
- With larger N => CI can be tighter or CL improves

Estimation of RMS from Histogram (3/3)

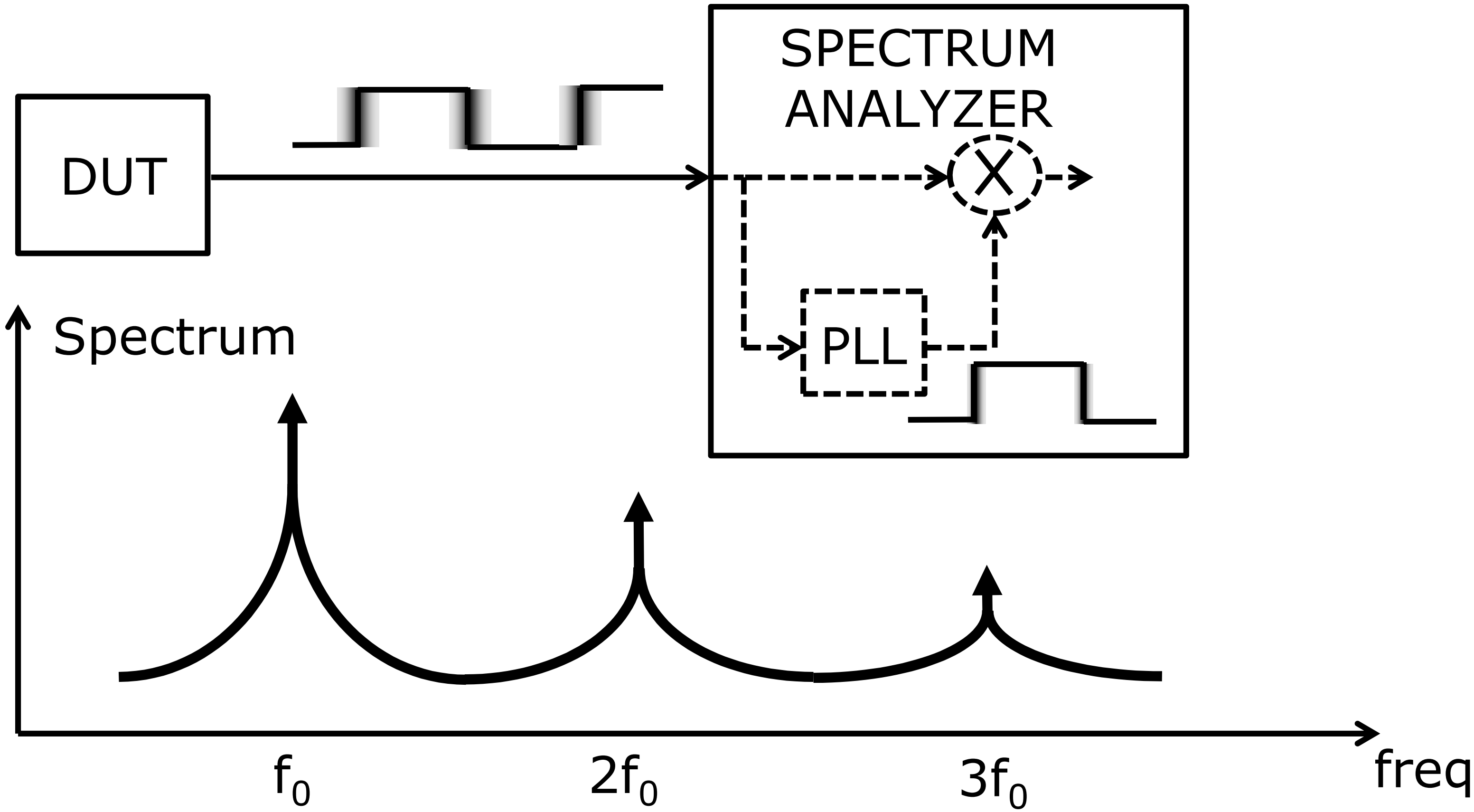
- Goal: Estimate the RMS within an error margin ε (confidence interval) and with a given confidence level
- Question: how large should N be?

$$N \geq \frac{1}{2}\left(\frac{Q}{\varepsilon}\right)^2$$



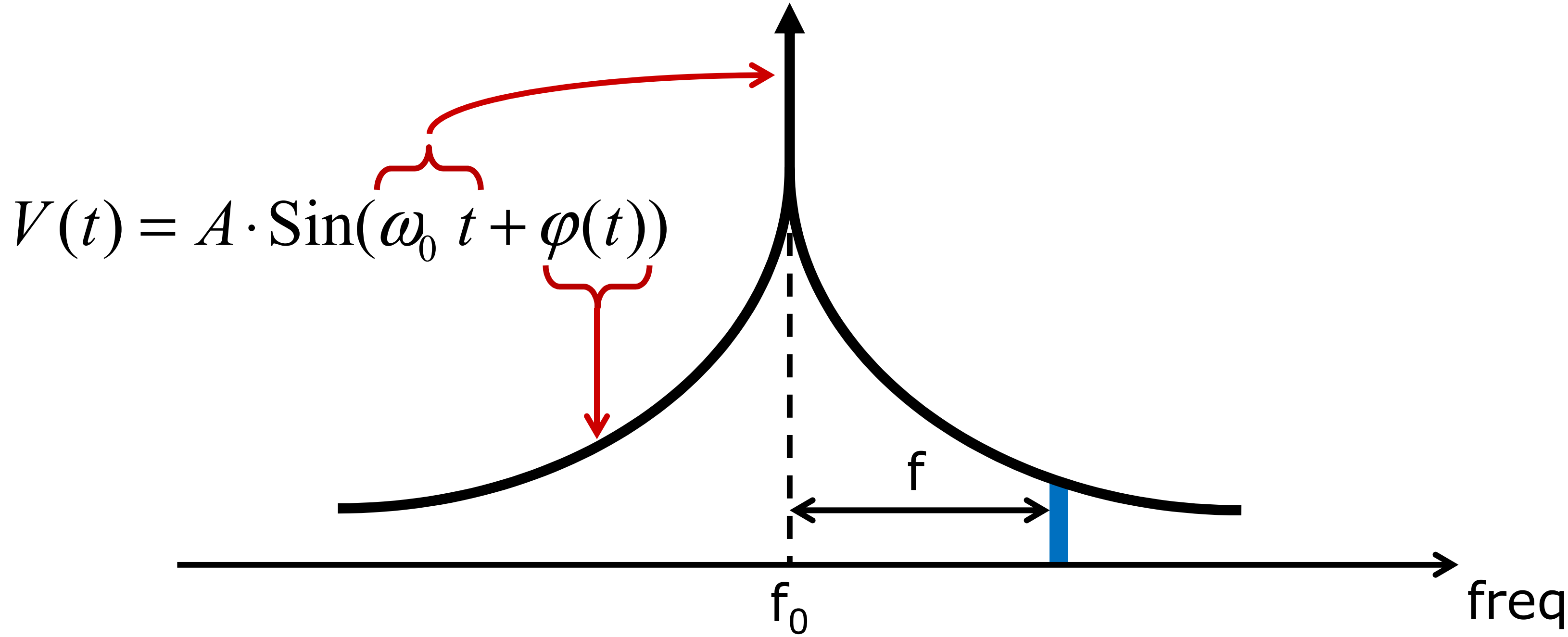
- Confidence Level:
  - 68% (Q=1)
  - 95% (Q=2)
  - 99.7% (Q=3)

Absolute Jitter : Freq Domain Meas



- Spectrum analyzer locks to ext clock and generates clean one
- Clean clock is used to mix ext clock and measure its power
- Result is shown in form of spectrum of voltage signal

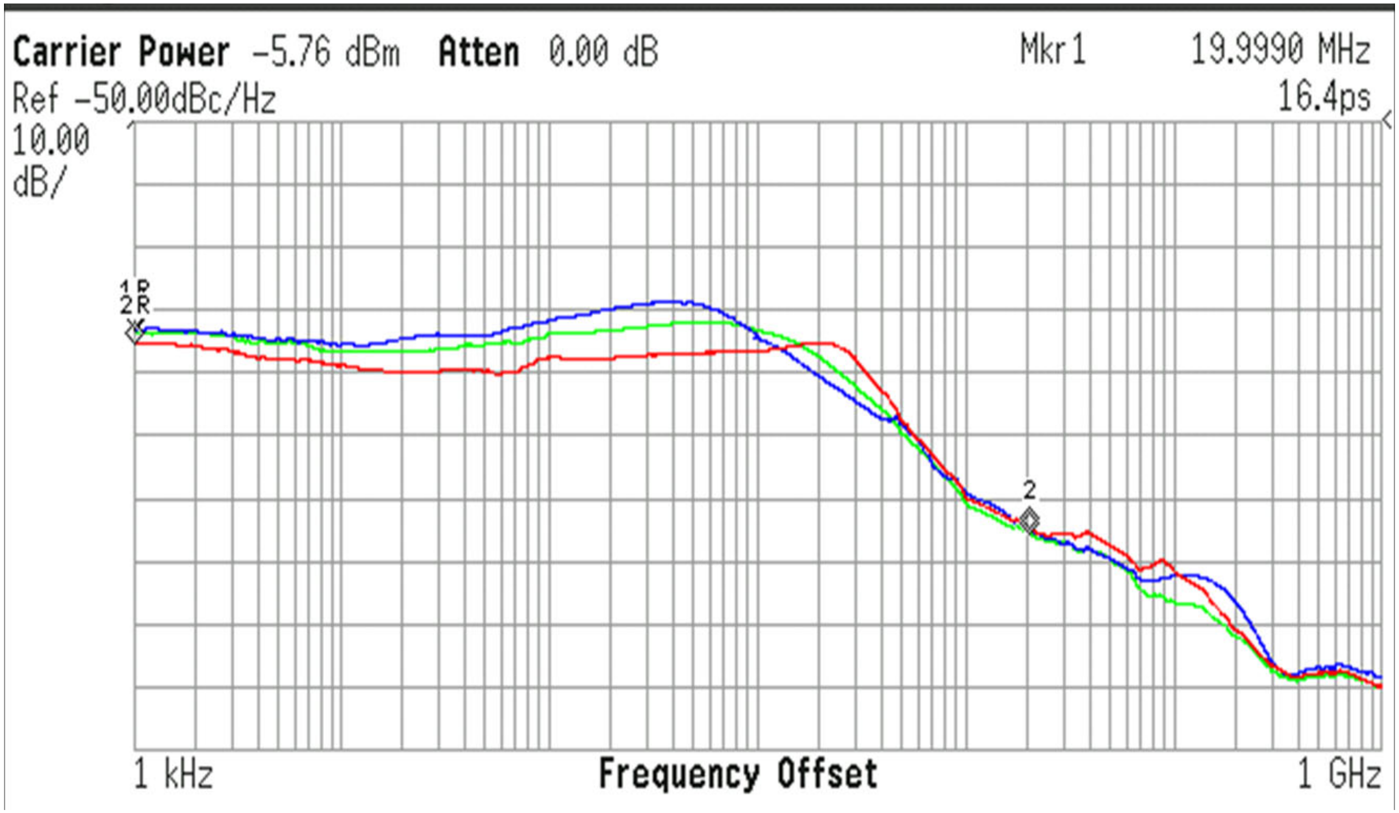
Voltage Spectrum to Phase PSD



$$\frac{\text{Power of in 1 Hz BW @ } f \text{ from Carrier}}{\text{Power of Carrier}} \cong \text{PSD of } \varphi,\ S_\varphi(f)$$

- Assumptions: No AM, Small angle modulation
- PSD is Single Side Band

Phase Noise



- PSD of φ is called **Phase Noise, *L(f)***
- Shown in log-log scale vs. frequency from carrier
- Automatically computed by most spectrum analyzers

Phase Noise to Absolute Jitter

$$V(t) = A \cdot \mathrm{Sin}(\omega_0 t + \varphi(t)) = A \cdot \mathrm{Sin}\left[\omega_0 \left(t + \frac{\varphi(t)}{\omega_0}\right)\right]$$

Time deviation wrt ideal clock, Absolute jitter

$$j_{ABS} = \frac{\varphi}{\omega_0}$$

PSD

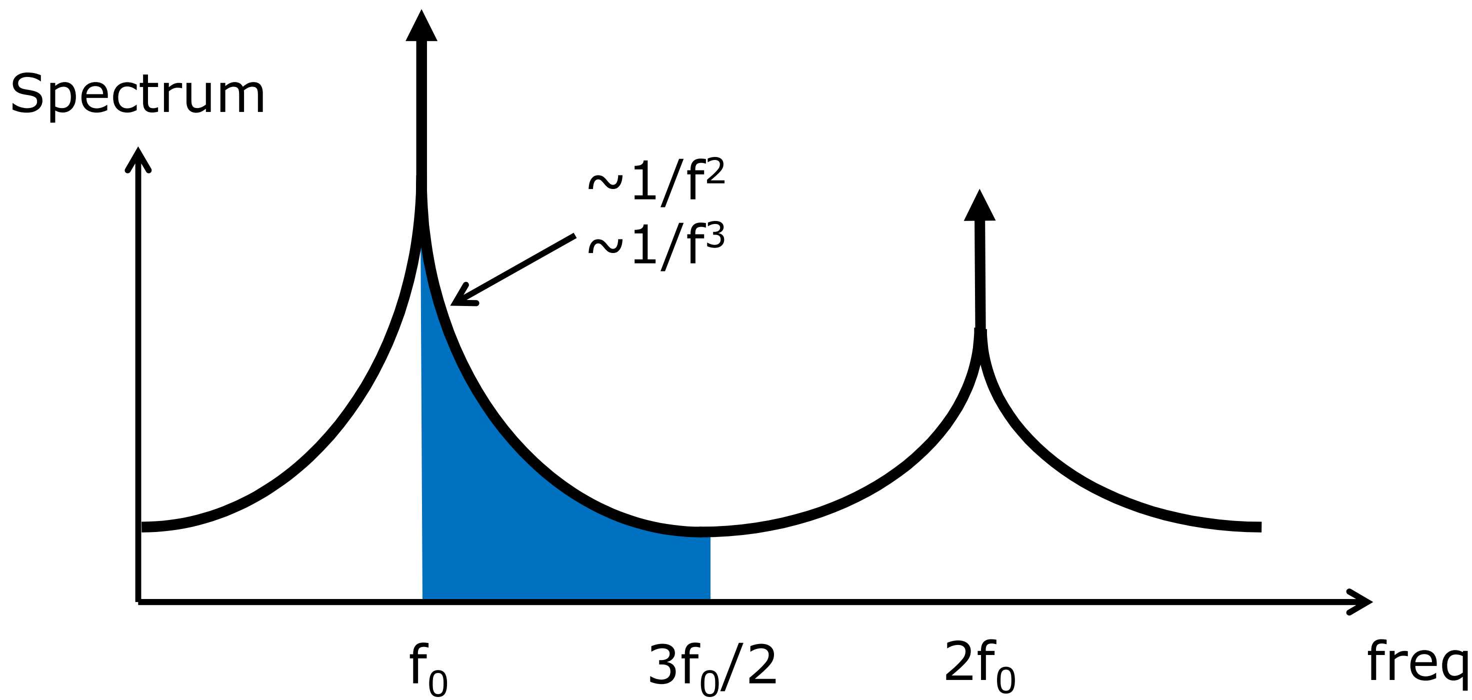
$$S_{j_{ABS}}(f) = \frac{L(f)}{\omega_0^{\ 2}}$$

Wiener-Khinchin Theorem

$$\sigma^2_{ABS} = \int_{-\infty}^{+\infty} S_{j_{ABS}}(f)\,\mathrm{d}f$$

$$\sigma^2_{ABS} = \frac{2}{\omega_0^{\ 2}} \int_0^{+\infty} L(f)\,\mathrm{d}f$$

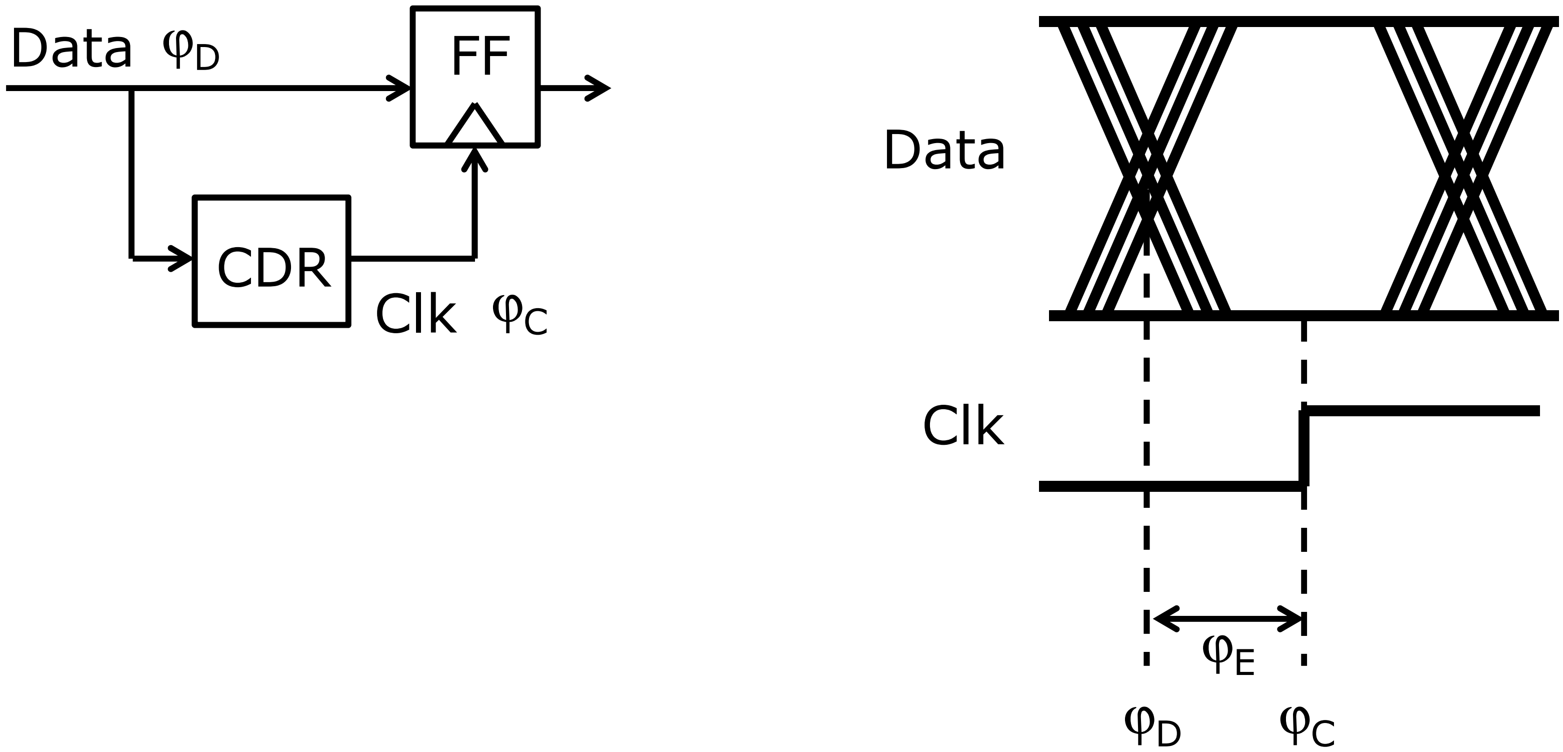
Phase Noise integration limits



$$\sigma_{ABS}^2 = \frac{2}{\omega_0^2}\int_{f_{MIN}}^{f_0/2} L(f)\,\mathrm{d}f \qquad \sigma_{ABS}^2 = \frac{2}{\omega_0^2}\int_0^{+\infty} L(f)\left|H_{SYS}(f)\right|^2 \mathrm{d}f$$

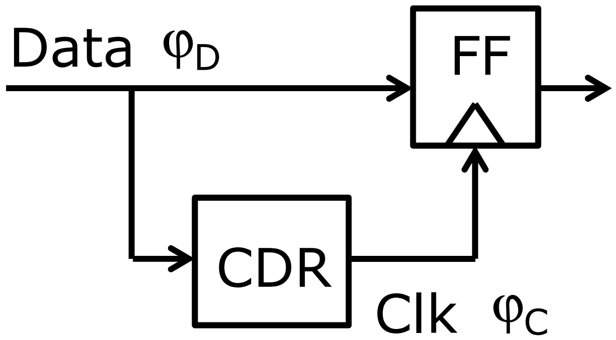
- Hard limits (f_{MIN} to $f_0/2$)
- Jitter transfer function of system under investigation

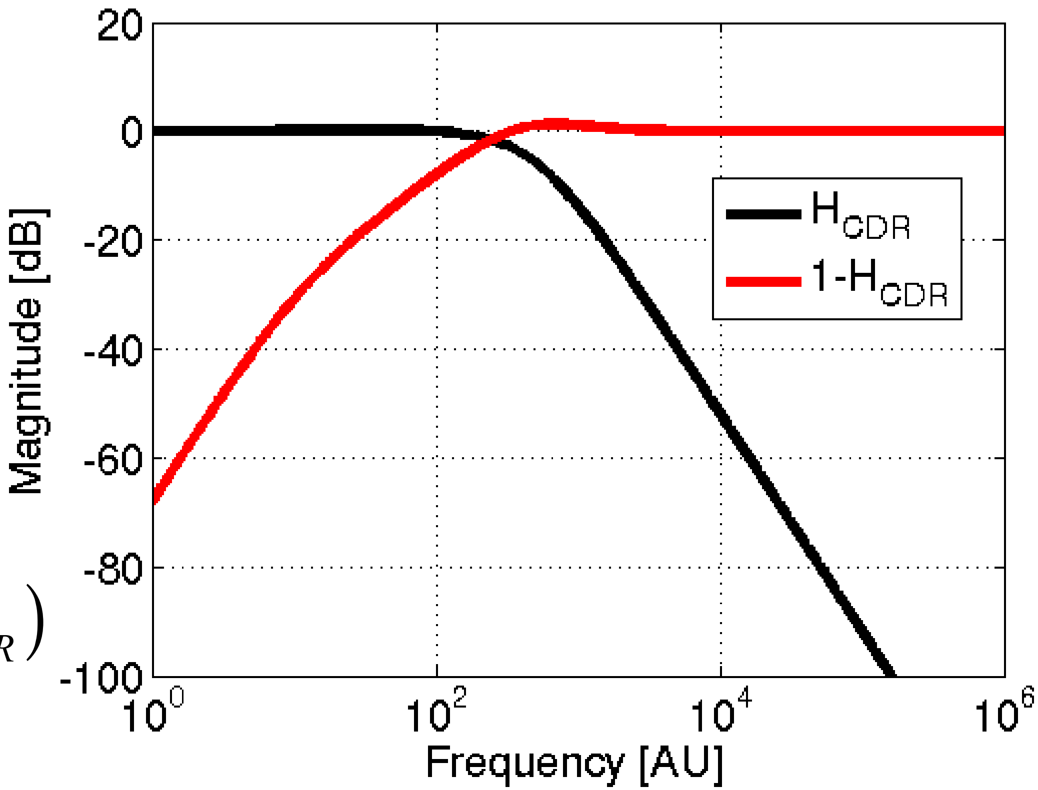
Jitter filtering in CDR systems (1/3)



- CDR system is sensitive to φ_E
- Low frequency jitter is tracked by CDR, does not hurt the BER
- High frequency jitter is not tracked by CDR, hurts the BER

Jitter filtering in CDR systems (2/3)





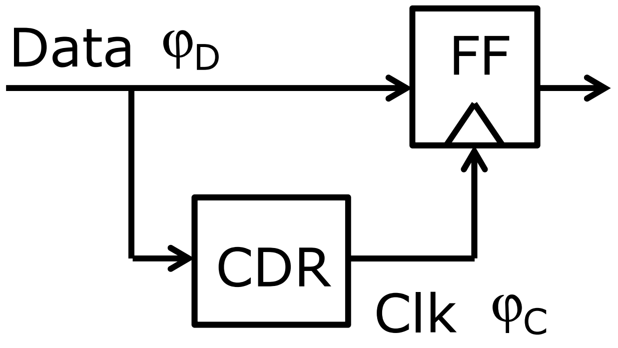
$$\varphi_C = H_{CDR} \cdot \varphi_D$$

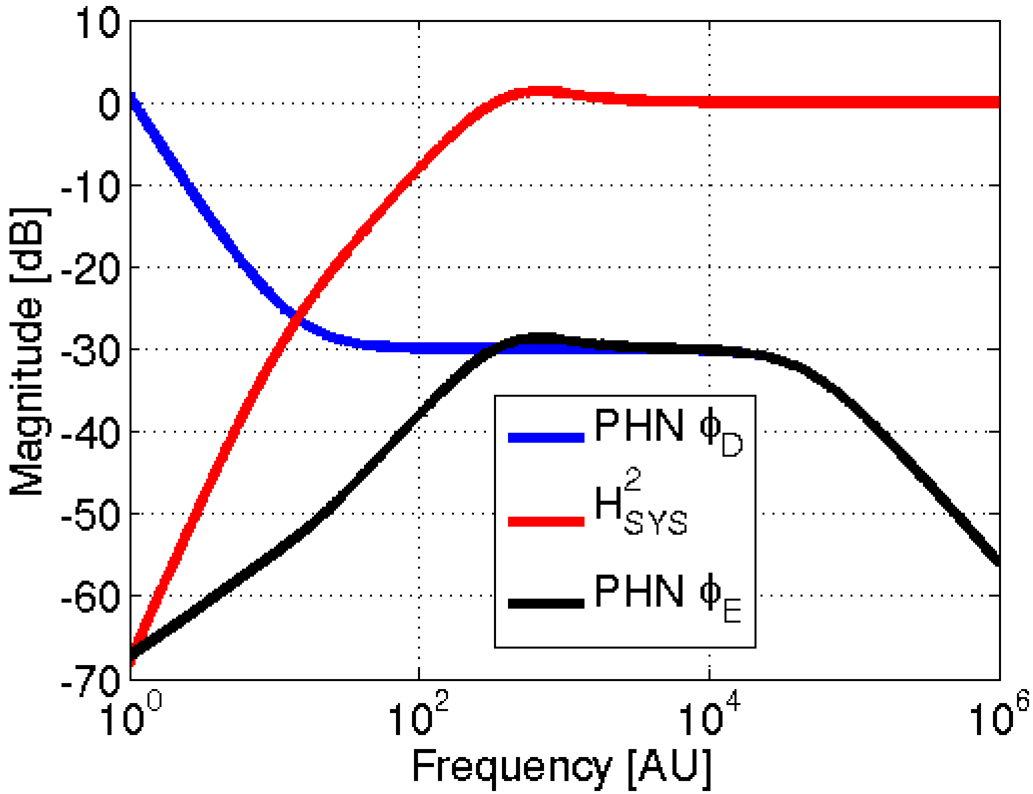
$$\varphi_E = \varphi_D - \varphi_C = \varphi_D \left(1 - H_{CDR}\right)$$

$$H_{SYS} = 1 - H_{CDR}$$

- Transfer function of CDR is a low-pass
- Transfer function of system (φ_D to φ_E) is a high-pass

Jitter filtering in CDR systems (3/3)





- Low-frequency jitter is filtered by the H_{sys} before integration
- Integral from 0 to $f_0/2$ of Phase Noise of φ_E is finite

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Summary so far

- Absolute jitter
- Measurement in time domain
- Estimation of 1-sigma value from histogram
- Measurement in frequency domain
- Phase Noise
- Relationship between Phase Noise and Absolute jitter
- Limitation of Phase Noise integration interval

What's next:

- Analyze typical applications and the type of jitter they are sensitive to
- New jitter types will be introduced

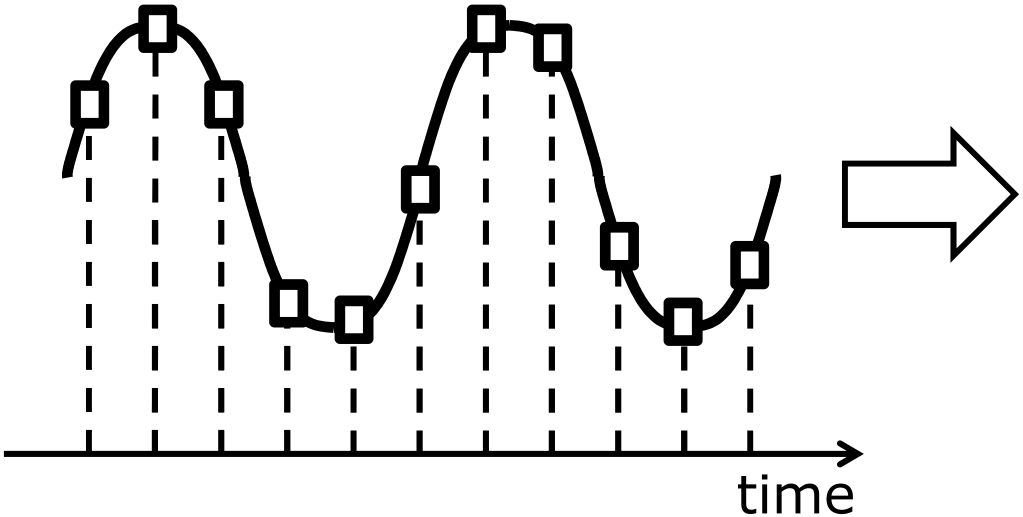
Application Scope of Absolute Jitter

- RX for High Speed interfaces (see example of CDR before)
- Sampling of analog signals (i.e. in ADC)
- Generation of analog signal from digital (i.e. in DACs)
- NOT applicable to digital clocking

Sampling of Analog Signals (1/2)

ANALOG DOMAIN

DIGITAL DOMAIN

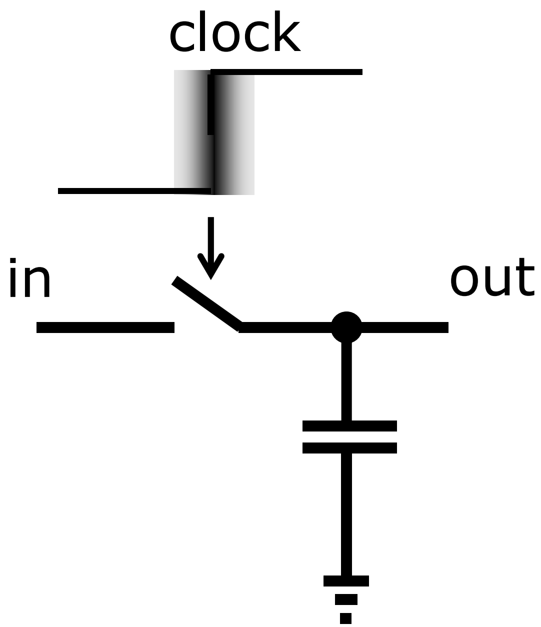


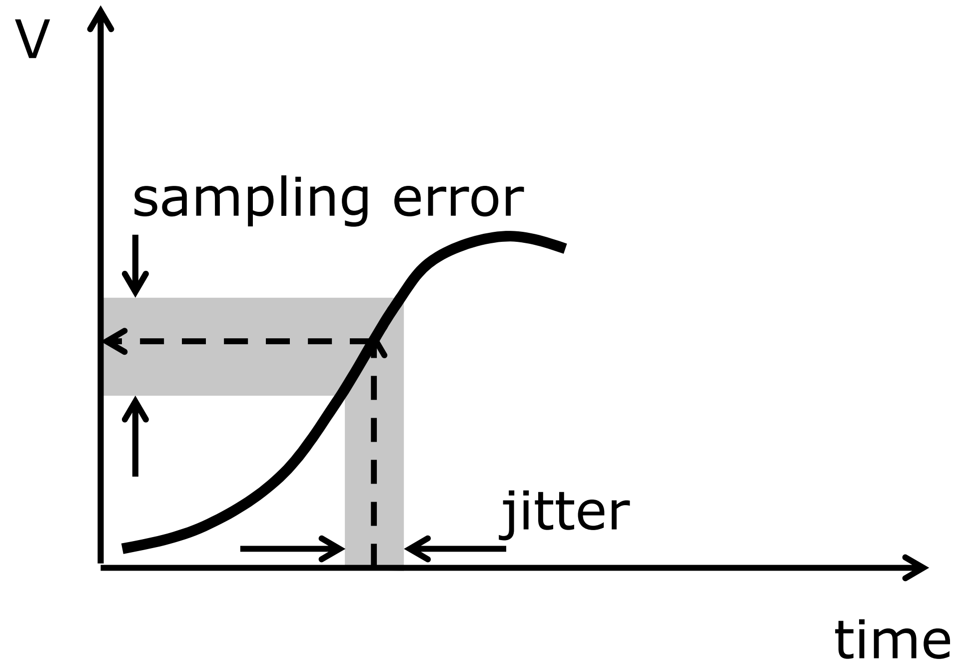
..., 23, 25, 22, 18, 17, 20, ...

Just a sequence of numbers, stored in a FIFO

- In the digital domain the time information of the sampling instant is lost
- The implicit assumption is that the samples are taken on the edges of an ideal clock
- What counts is the absolute jitter

Sampling of Analog Signals (2/2)

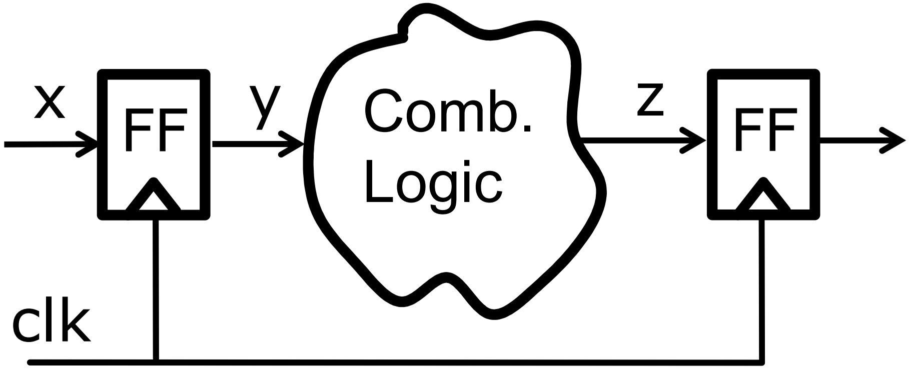


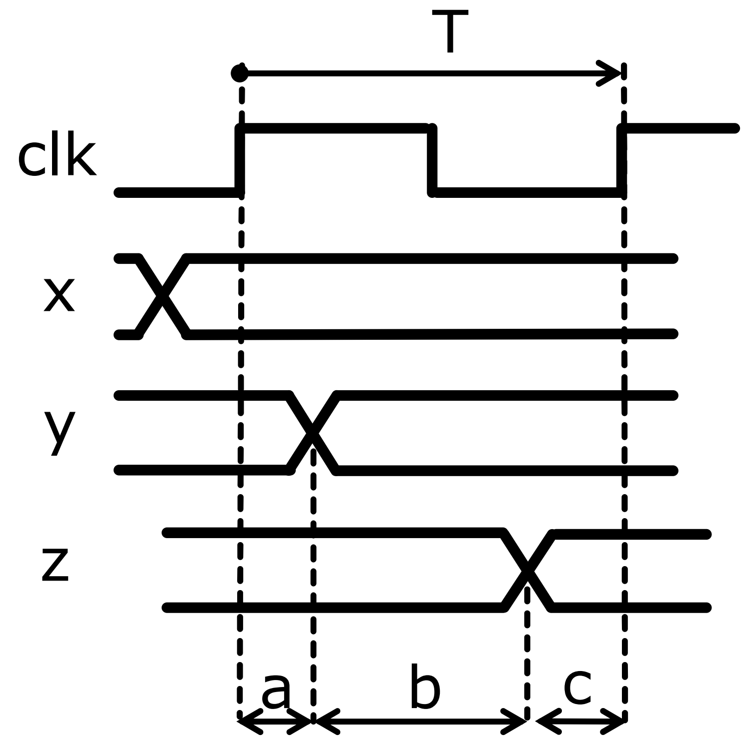


- SNR =P_{signal}/P_{error}
- P_{error} = P_{jitter} * <Slope^2>
- P_{jitter} = σ_{ABS}^2
- SNR ~ 1/ σ_{ABS}^2

$$SNR = 20\cdot\log_{10}\left(\frac{1}{2\pi f_{ANA}\sigma_{ABS}}\right) dB$$

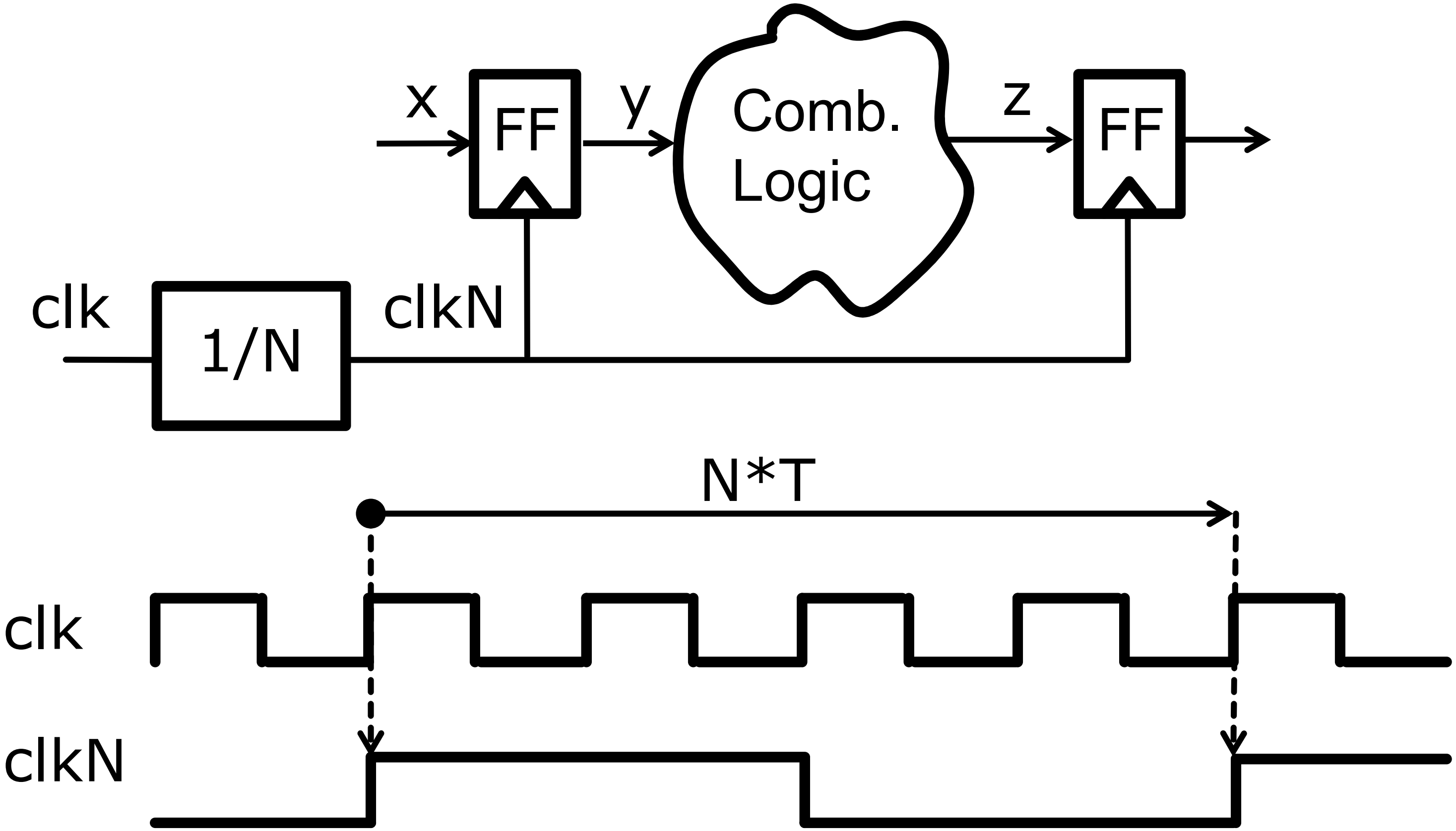
Digital Clocking (1/2)





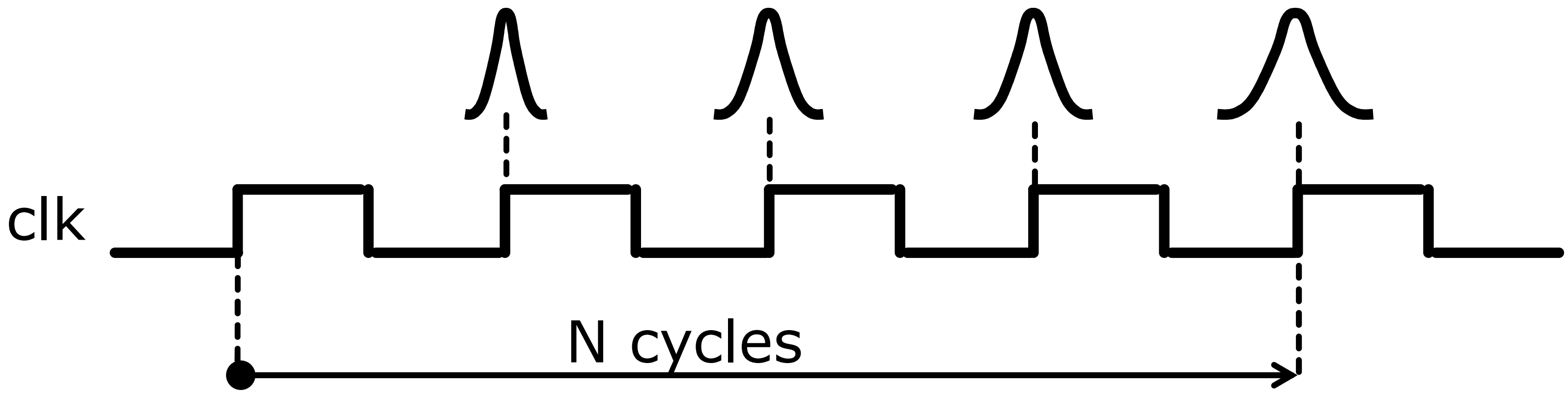
- a = clk2Q
- b = delay of logic
- For correct operation: c > FF setup time
- Constraint set on minimum duration of the clock period T (from edge to egde)

Digital Clocking (2/2)



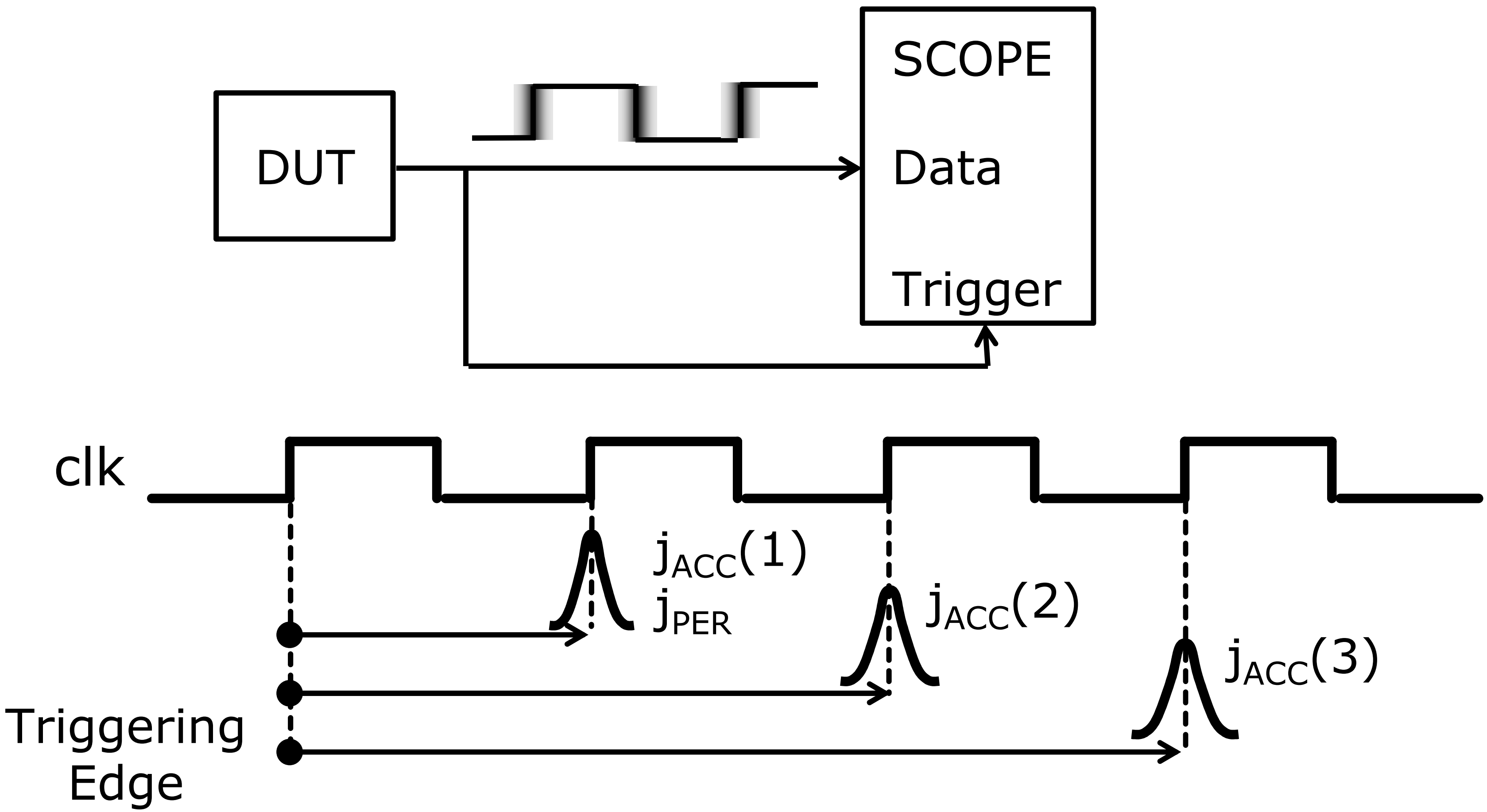
- Constraint set on minimum duration of N clock periods (from edge to the next Nth edge)

Accumulated Jitter (J_{ACC})



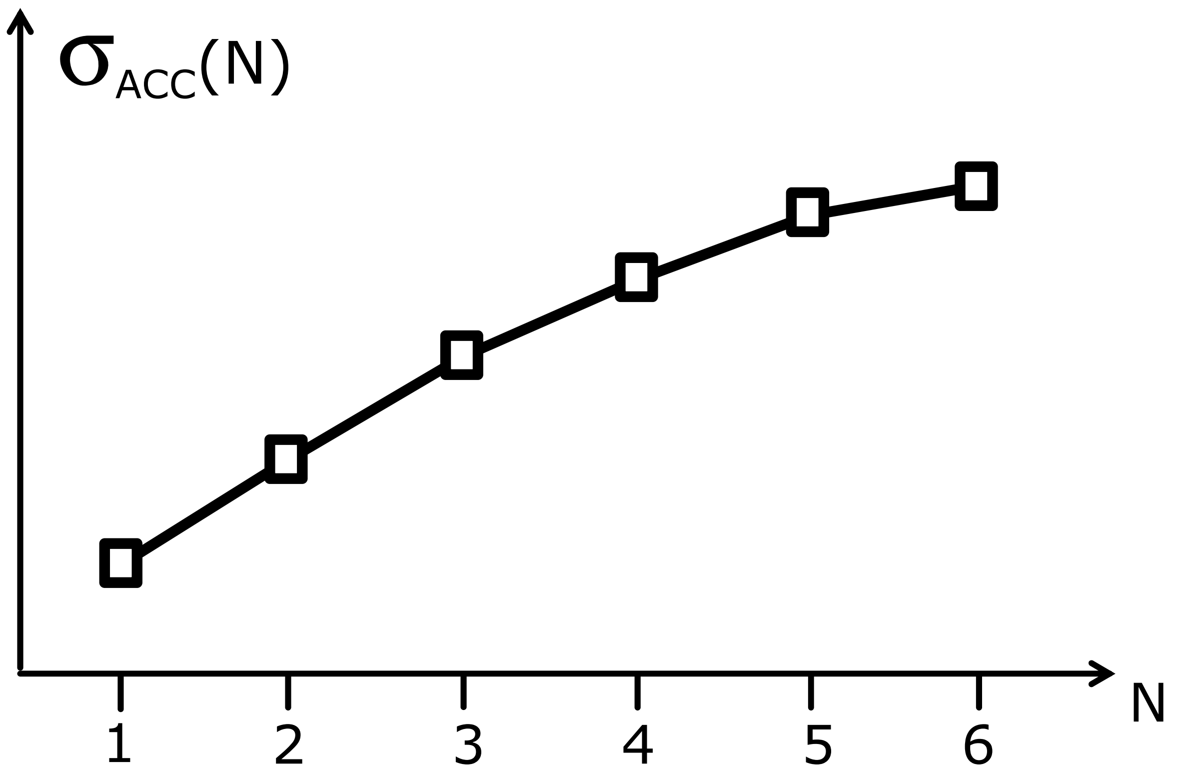
- The jitter of one edge relative to the Nth previous edge is called **Accumulated Jitter on N Cycles, $j_{ACC}(N)$**
- The Accumulated Jitter on 1 cycle is commonly called **Period Jitter, j_{PER}** (or Edge-to-Edge Jitter)

J_{ACC} : Time Domain Measurement (1/2)



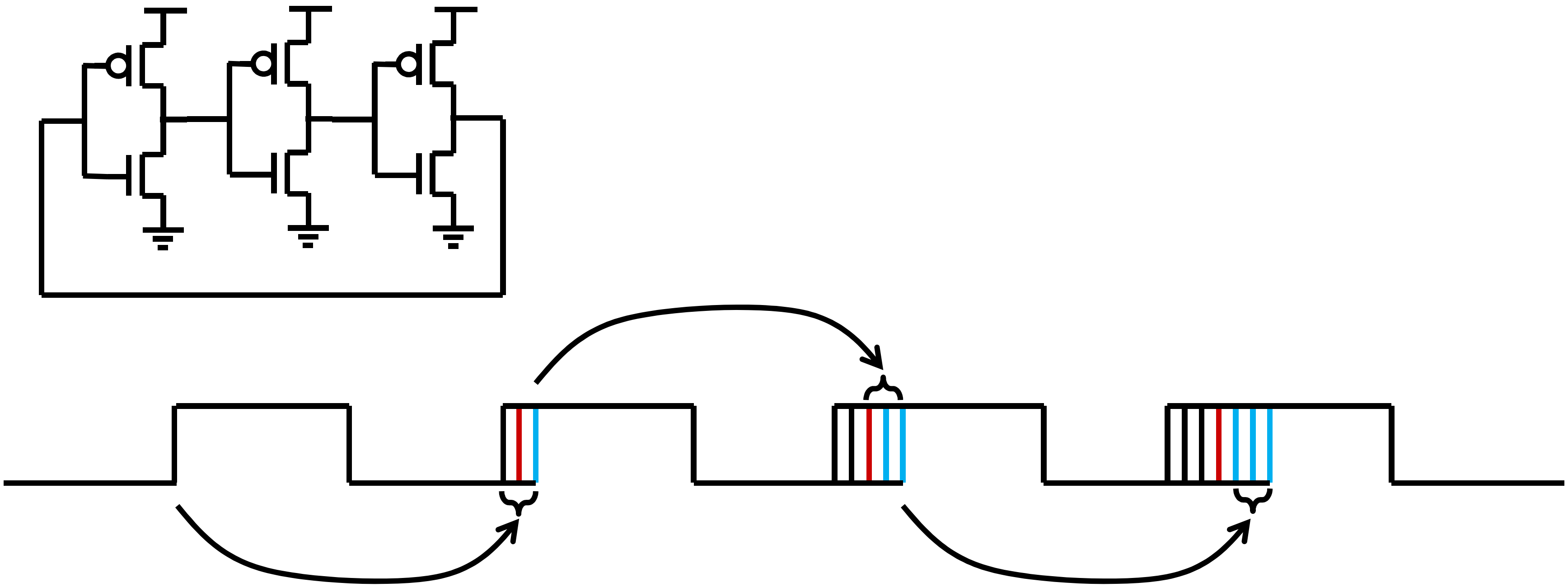
- Self-referenced measurement

J_{ACC} : Time Domain Measurement (2/2)



- Function of number of cycles N
- In real physical systems J_{acc} increases for low N

J_{ACC} in Freerunning Oscillators (1/3)



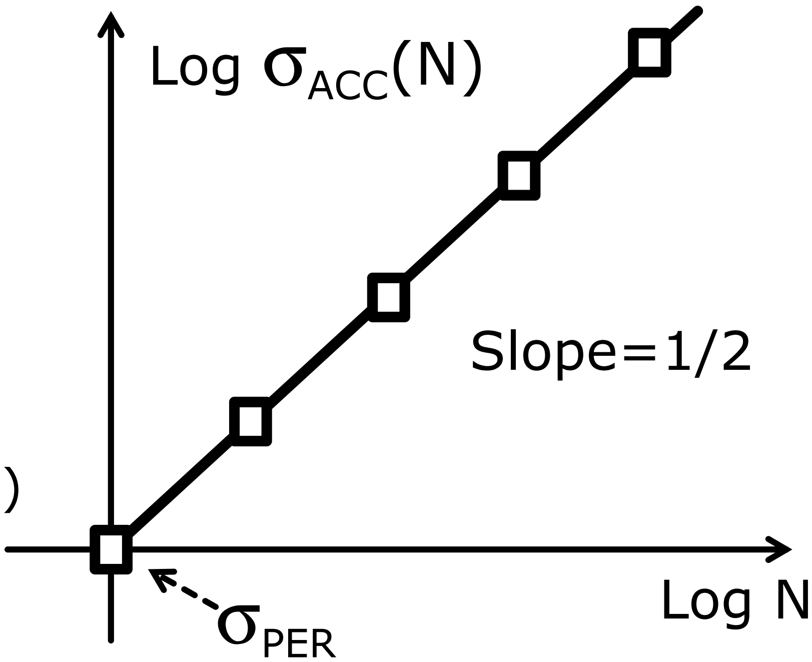
- Jitter on Edge (n) = Jitter on Edge (n-1) + Period Jitter
- Noise in each new cycle is uncorrelated
- Jitter accumulates over cycles
- No mechanism can counteract the accumulation

J_{ACC} in Freerunning Oscillators (2/3)

$$j_{ACC}(N) = j_{PER}(1) + j_{PER}(2) + \ldots + j_{PER}(N)$$

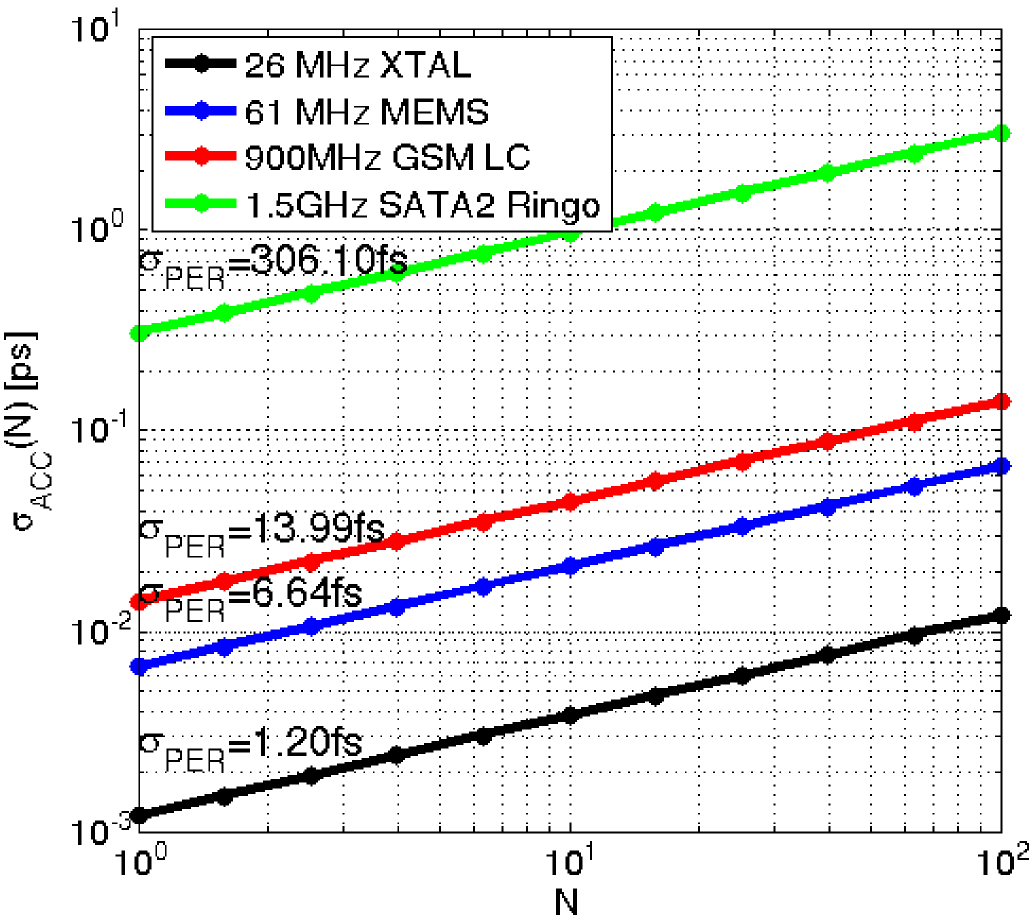
$$\sigma^2_{ACC}(N) = \sigma^2_{PER}(1) + \sigma^2_{PER}(2) + \ldots + \sigma^2_{PER}(N)$$

$$\sigma_{ACC}(N) = \sqrt{N} \cdot \sigma_{PER}$$



- Assumptions
  - Jitter in different cycles is uncorrelated (e.g. white noise)
  - Jitter is time-independent (stationary random process)

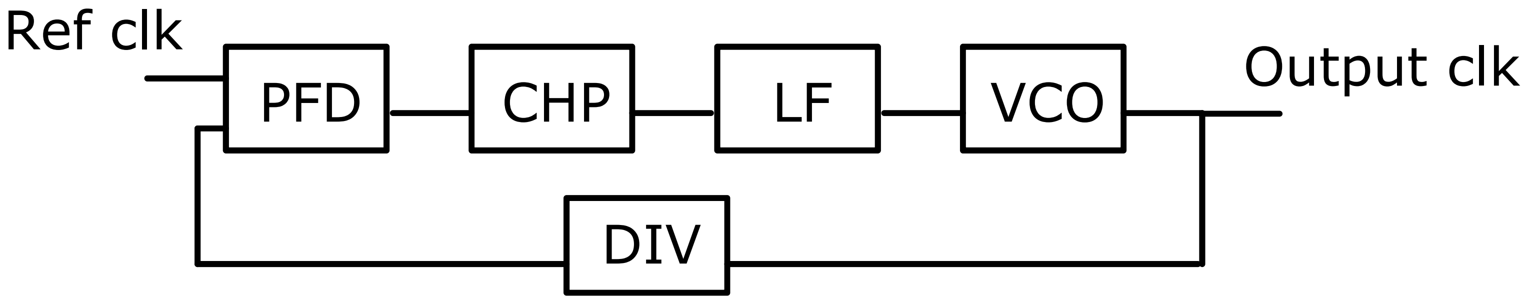
J_{ACC} in Freerunning Oscillators (3/3)

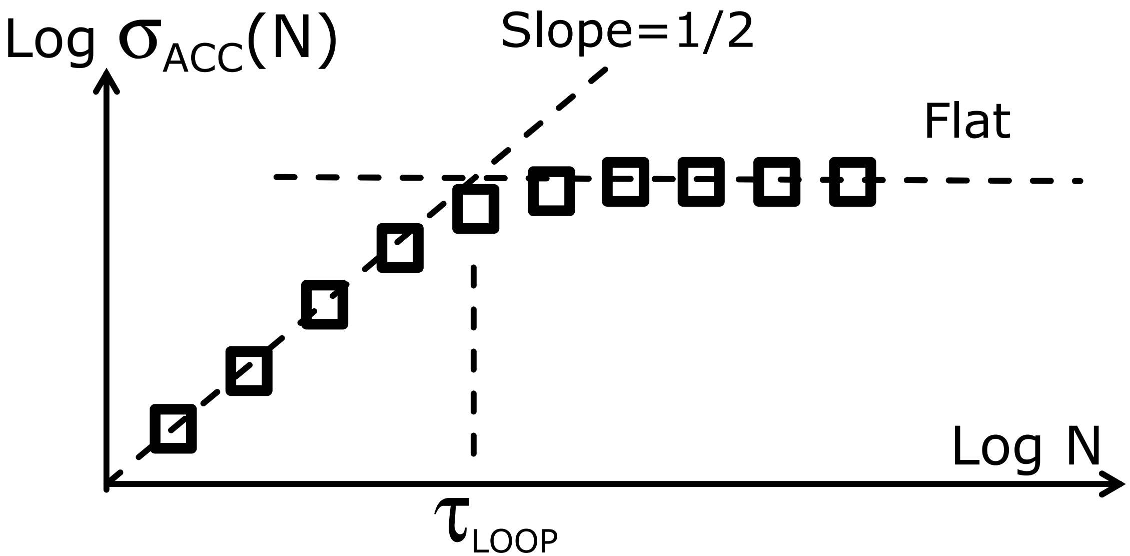


- 1.5G SATA2 RingO (5mA):
  - -115dBc/Hz @ 10e6
- 900MHz GSM LC (15mA):
  - -138dBc/Hz @ 3MHz
- 61MHz MEMS (1mA):
  - -110dBc/Hz @ 1kHz
- 26MHz XTAL (1mA):
  - -136dBc/Hz @ 1kHz

- Slope = ½ for all

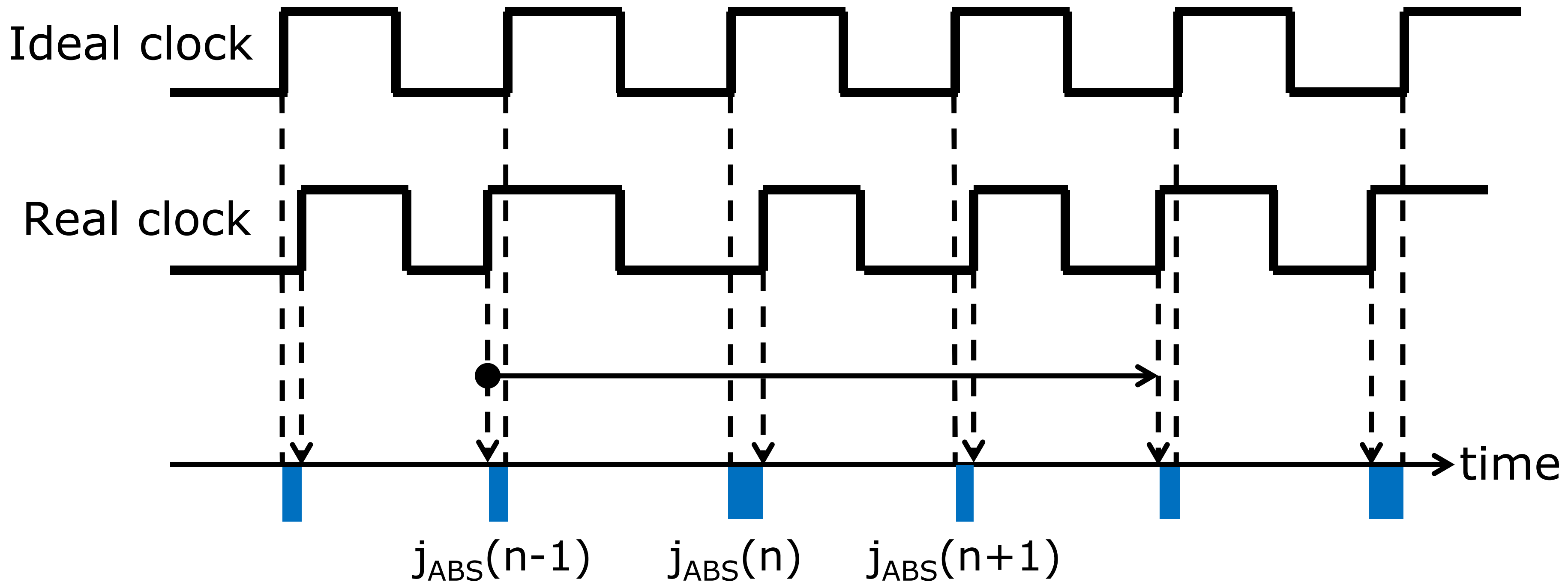
J_{ACC} in PLLs





- Comparison with a clean reference limits jitter accumulation

Accumulated vs Absolute Jitter



$$j_{ACC}(N)=j_{ABS}(n+N)-j_{ABS}(n)$$

$$j_{PER}=j_{ABS}(n+1)-j_{ABS}(n)$$

Phase Noise to J_{ACC}

$$j_{ACC}(N) = j_{ABS}(n+N) - j_{ABS}(n)$$

$$\sigma^2_{ACC}(N >> 1) = 2\sigma^2_{ABS}$$

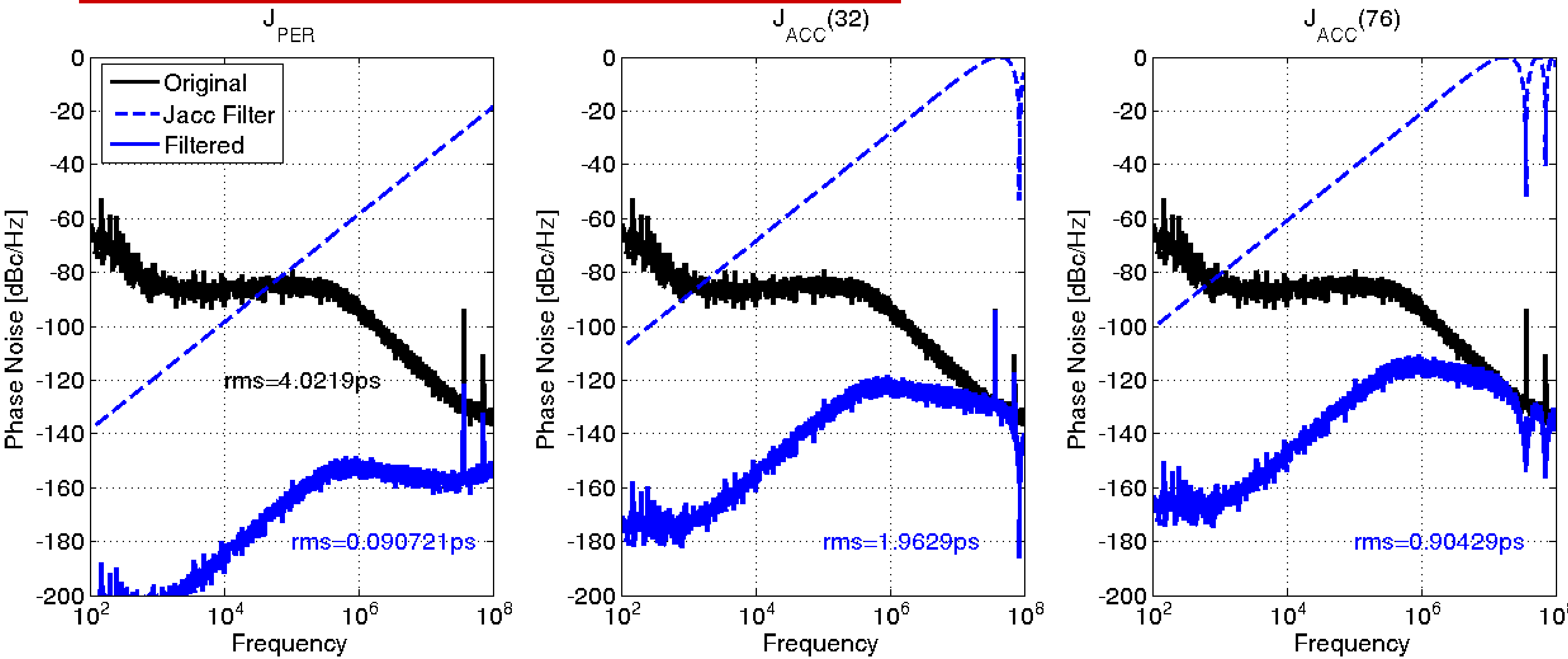
PSD

$$S_{jACC(N)}(f) = \left|1 - e^{-i2\pi f N / f_0}\right|^2 \cdot S_{jABS}(f) = \frac{4}{\omega_0^2}\sin^2\left(\frac{\pi f N}{f_0}\right) L(f)$$

Wiener-Khinchin Theorem

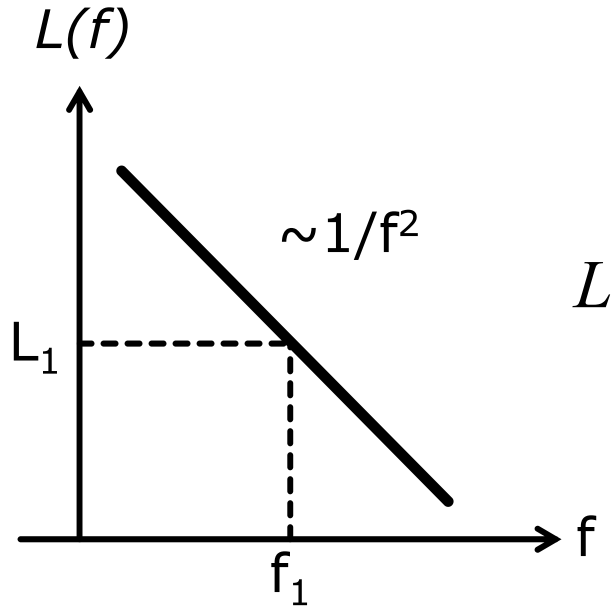
$$\sigma^2_{ACC(N)} = \frac{8}{\omega_0^{\ 2}}\int_{f_{MIN}}^{f_0/2}\sin^2\left(\frac{\pi f N}{f_0}\right) L(f)\,\mathrm{d}f$$

Phase Noise to J_{ACC}: Example



- PLL: F_{REF}=36MHz, F_{OUT}=2736MHz, DIV=76
- J_{PER} determined by high frequency components
- $J_{ACC}(N)$ determined by increasingly lower frequency components for increasing N
- $J_{ACC}(N)$ can mask spurious tones

Phase Noise to J_{ACC} :Freerunning Oscillator



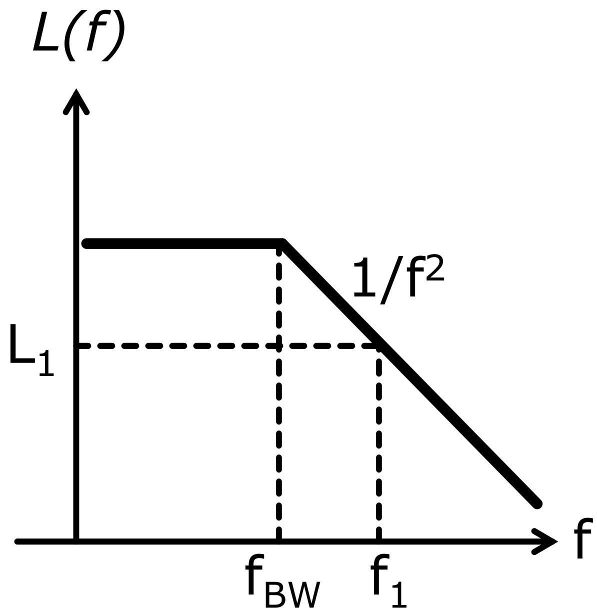
$$L(f) = L_1 \left(\frac{f_1}{f} \right)^2$$

$$\sigma^2_{ACC(N)} = \frac{L_1 f_1^2}{f_0^3} N$$

$$\sigma_{PER} = \sqrt{\frac{L_1 f_1^2}{f_0^3}}$$

- RMS Jacc increases like sqrt(N)

Phase Noise to J_{ACC} : PLL

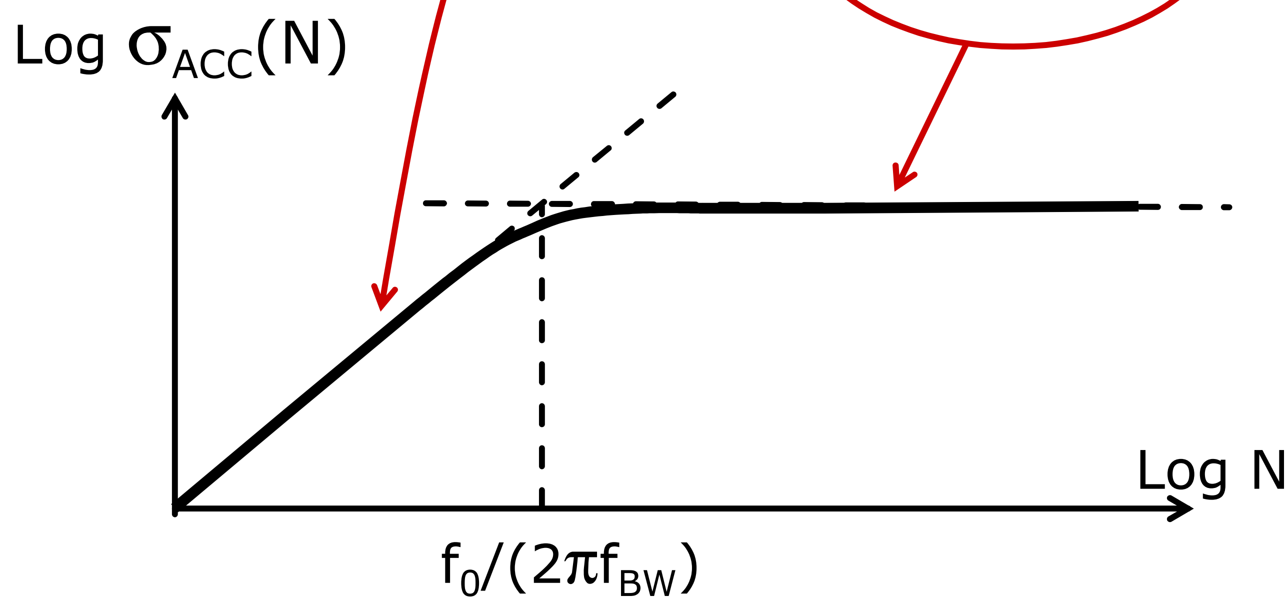


$$L(f)=\frac{L_1 f_1^2}{f_{BW}^2+f^2}$$

$$\sigma^2_{ACC(N)}=\frac{L_1 f_1^2}{f_0^3}\frac{f_0}{2\pi f_{BW}}\left(1-e^{-2\pi f_{BW}N/f_0}\right)$$

Phase Noise to J_{ACC} : PLL

- For small N: $$\sigma^2_{ACC(N)} = \frac{L_1 f_1^2}{f_0^3} N = \sigma^2_{PER} \cdot N$$
- For large N: $$\sigma^2_{ACC(N)} = \sigma^2_{PER} \frac{f_0}{2\pi f_{BW}}$$



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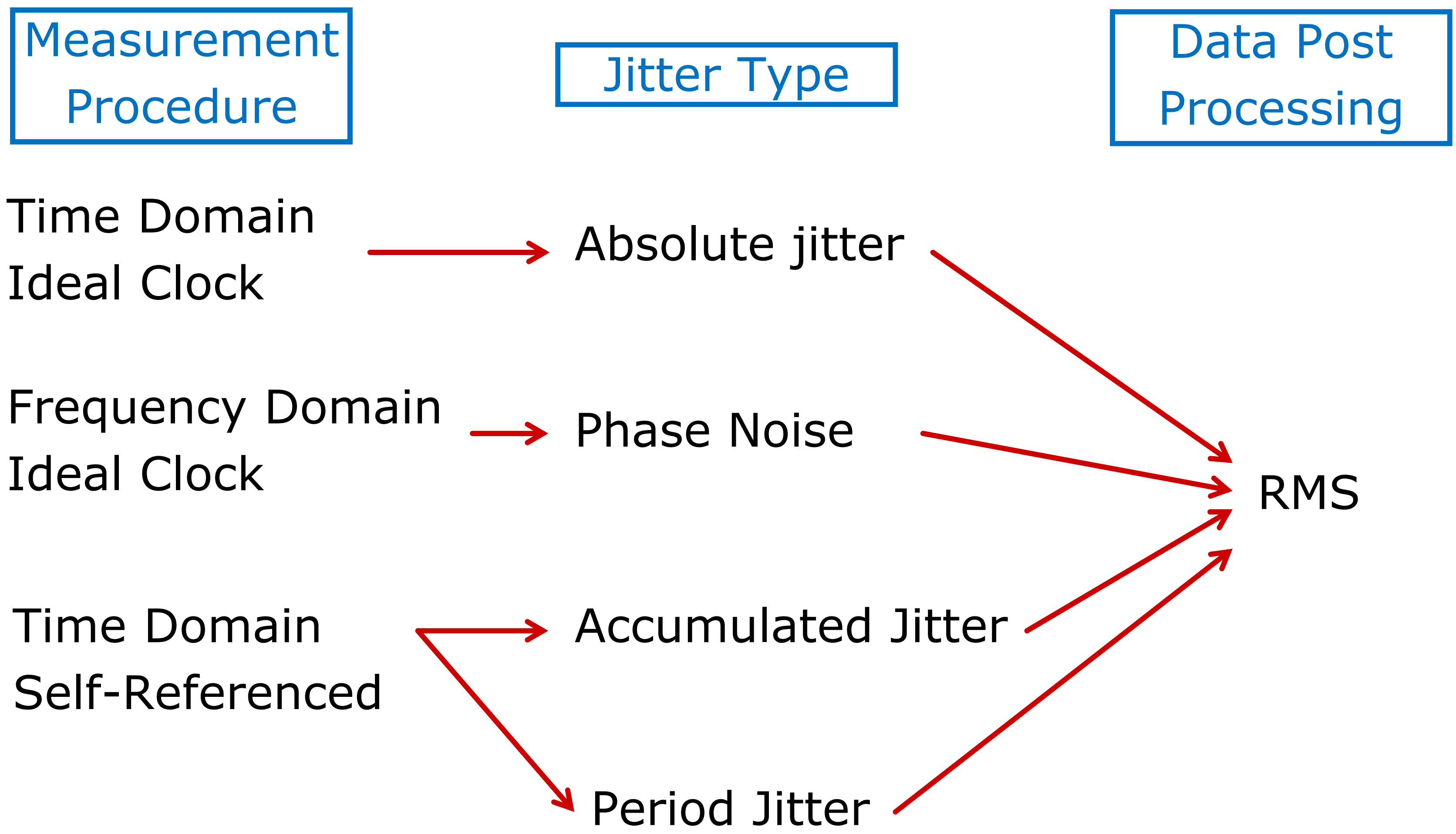
Summary so far

- Self-Referenced jitter (accumulated, period)
- Application to digital clocking
- Measurement in time domain
- Accumulated jitter for freerunning oscillators and PLLs
- Relation to absolute jitter
- How to compute J_{ACC} from Phase Noise

What's next:

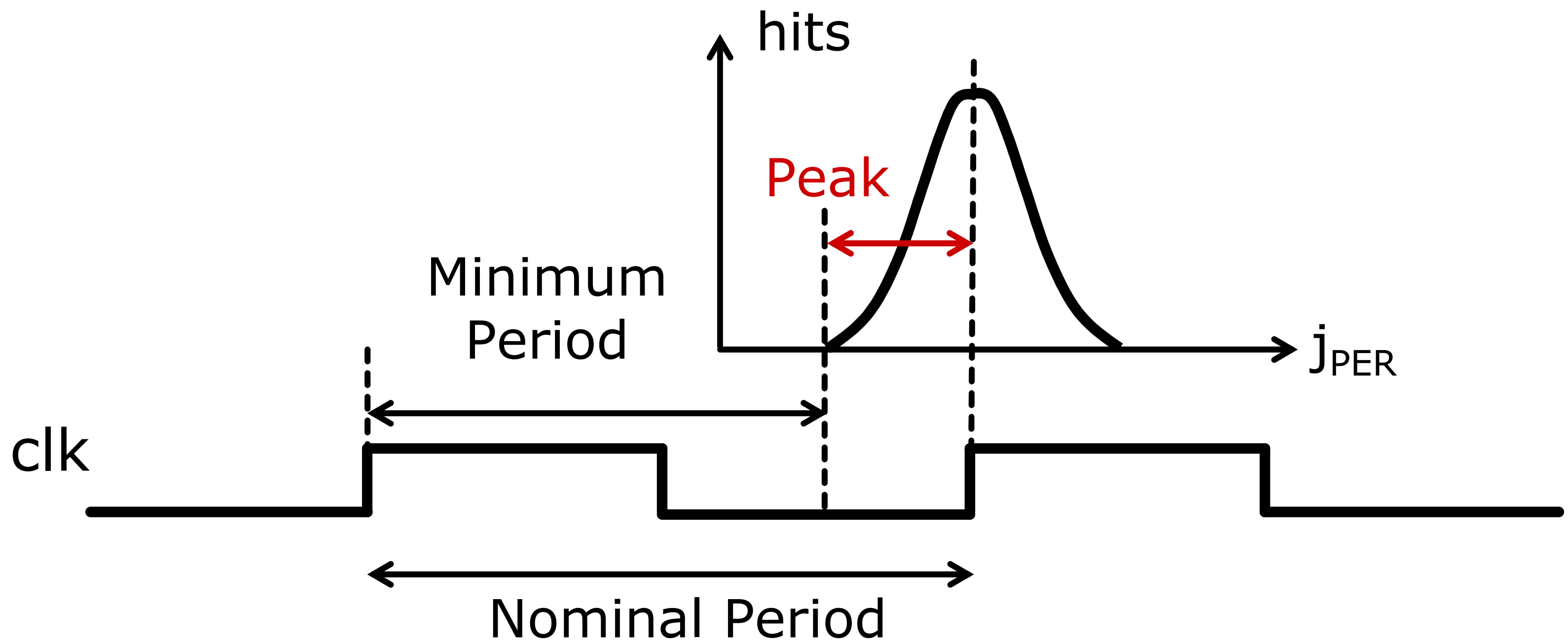
- Analyze the statistical properties of Jitter

Synoptics



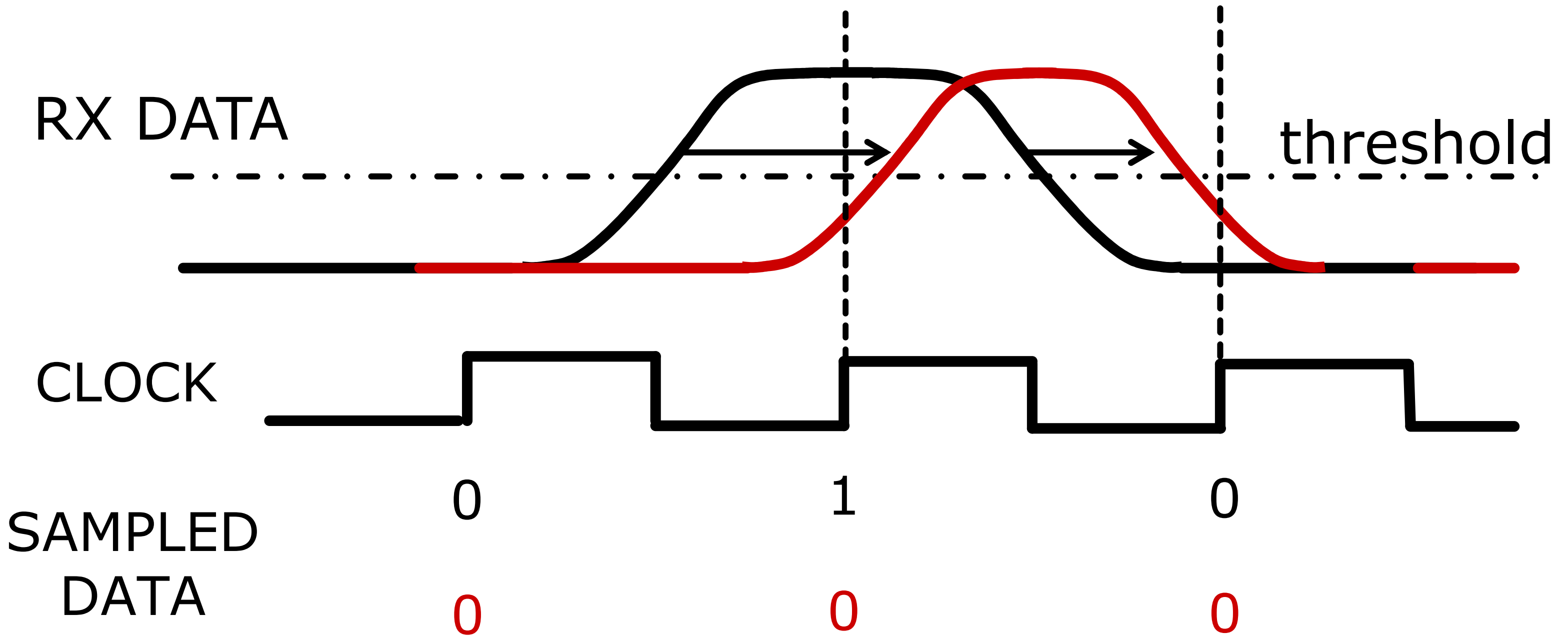
How far can we go with the RMS value?

Digital time constraining



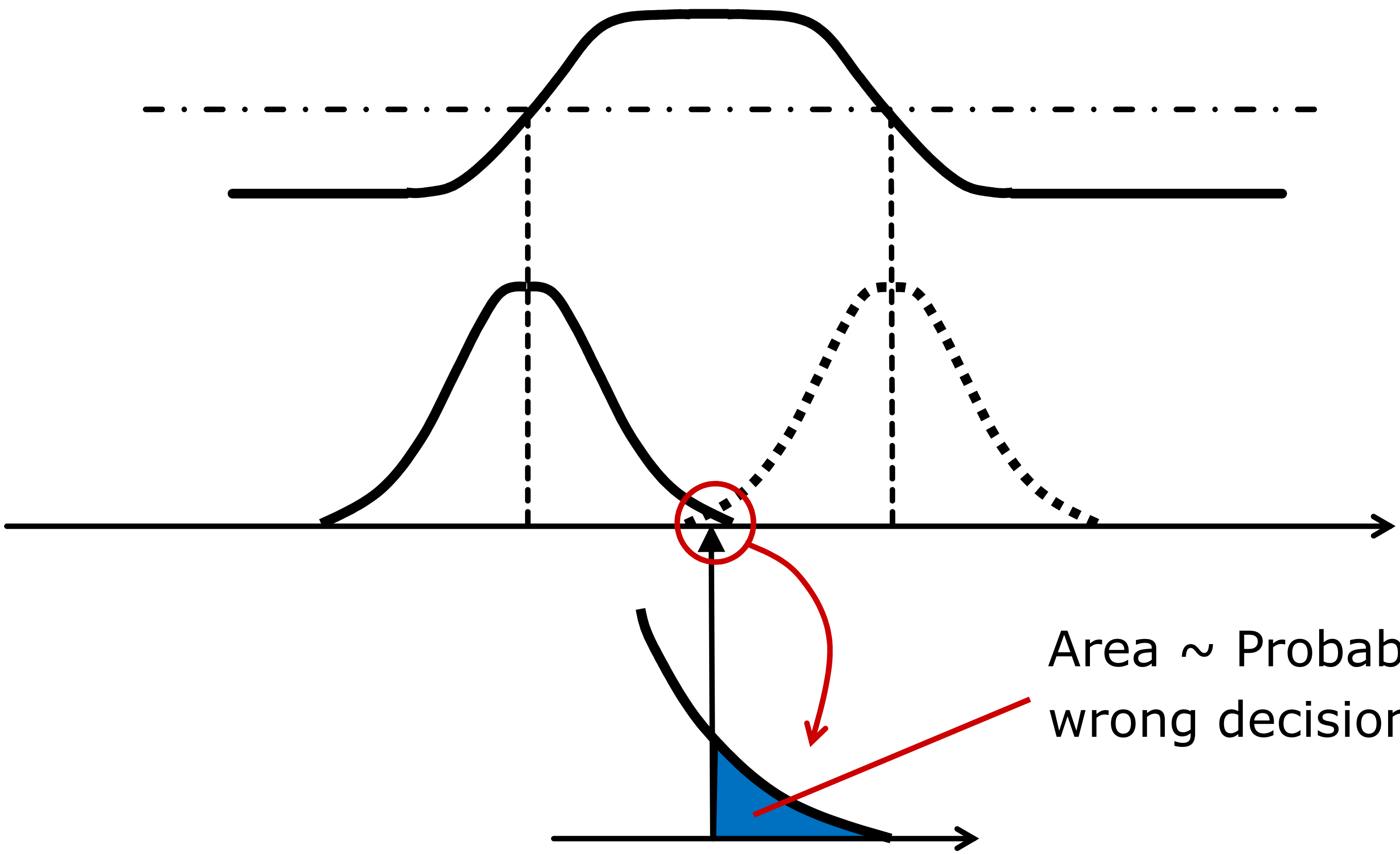
- Digital needs to satisfy setup-time for the digital block
- Looking for worst case minimum clock period
- The correct metrics is the peak, not the RMS!

High Speed Serial Data Sampling (1/2)



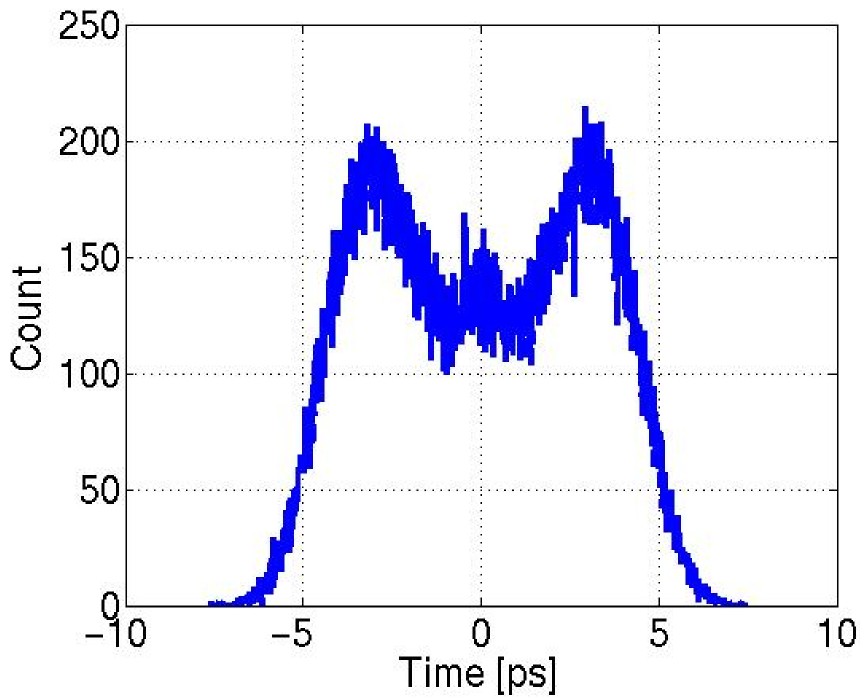
- Standards require Bit Error Rates ~ 1e-12
- Jitter on RX data moves data transitions wrt sampling point
- If jitter on data edges is larger than 0.5 UI errors will occur

High Speed Serial Data Sampling (2/2)



- BER determined by tails of the jitter distribution

Jitter Histogram and Distribution

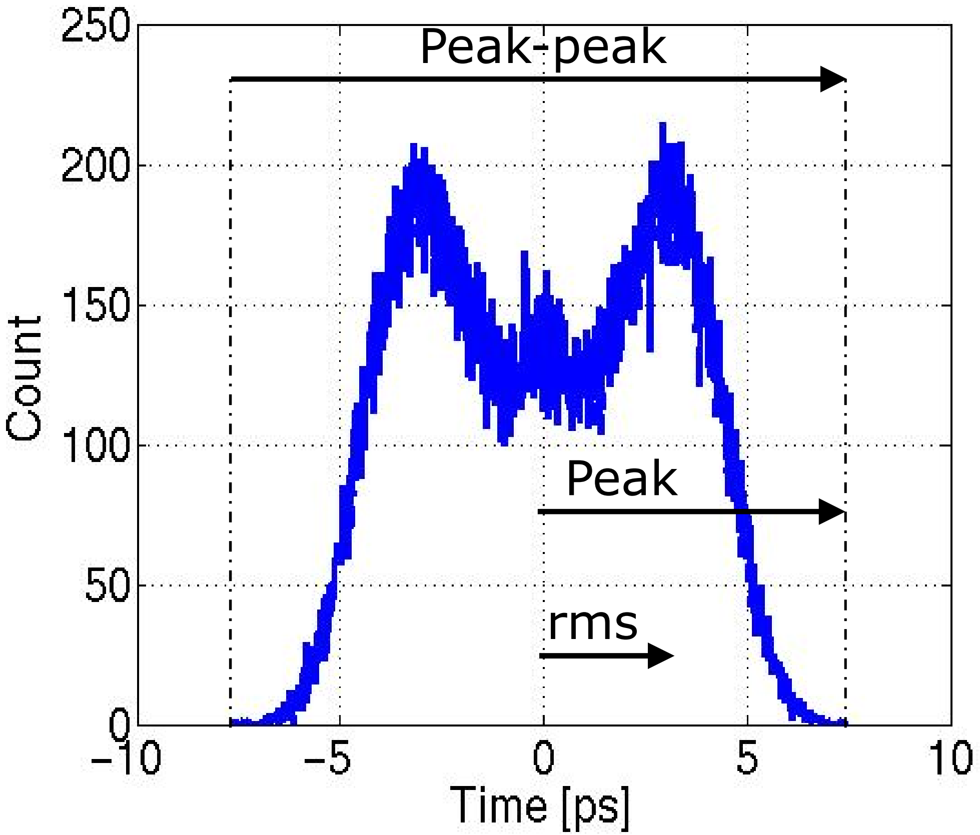


- Histogram is bounded (finite number of hits)
- Not necessarily gaussian
- Underlying jitter physical process might be unbounded

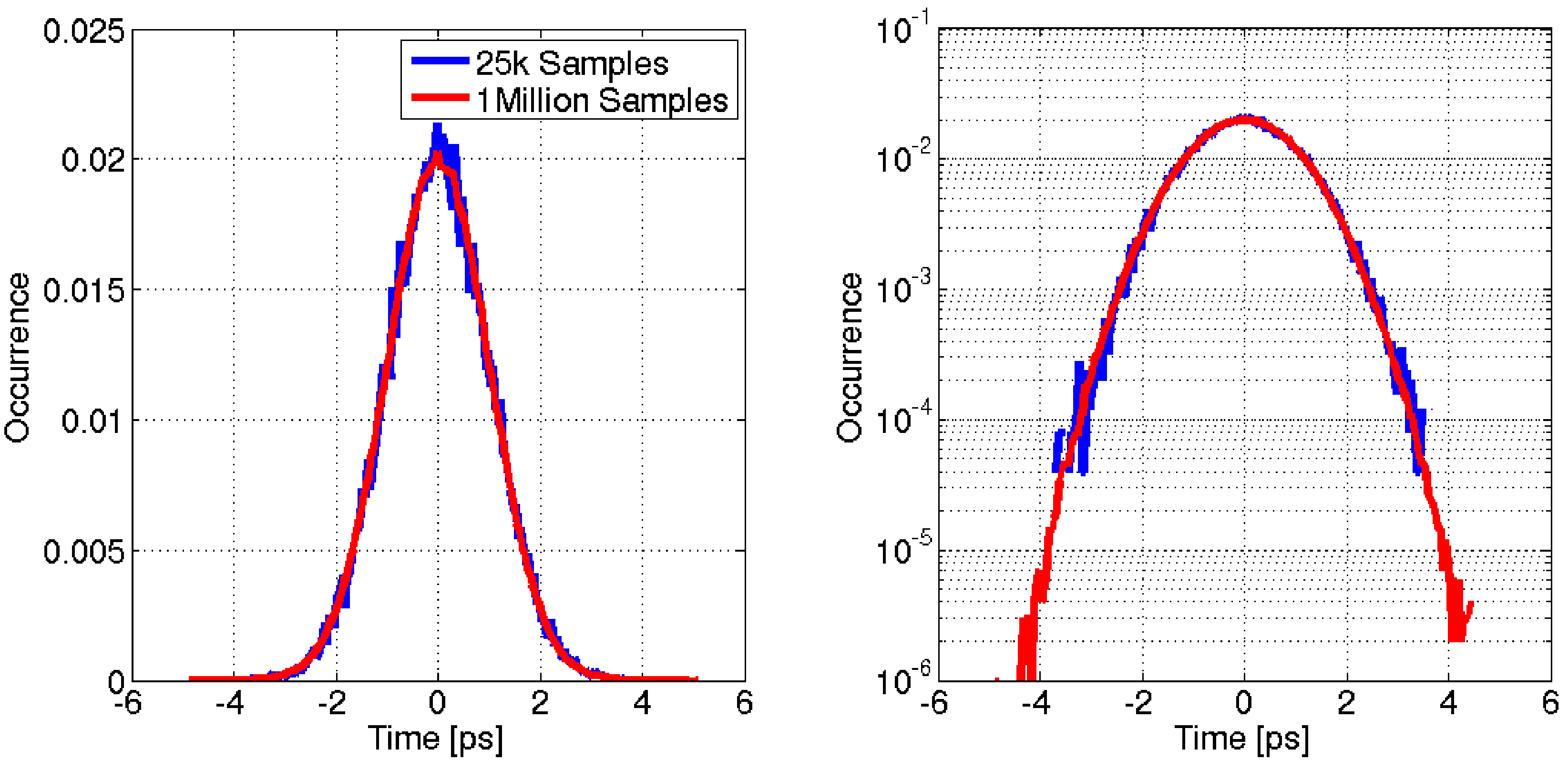
Jitter statistics

- Out of the jitter distribution several different statistical values can be calculated

- Most used
  - rms, 1-sigma
  - peak
  - peak-peak
  - 3-sigma := 3 * sigma



The peak for unbounded jitter (1/4)



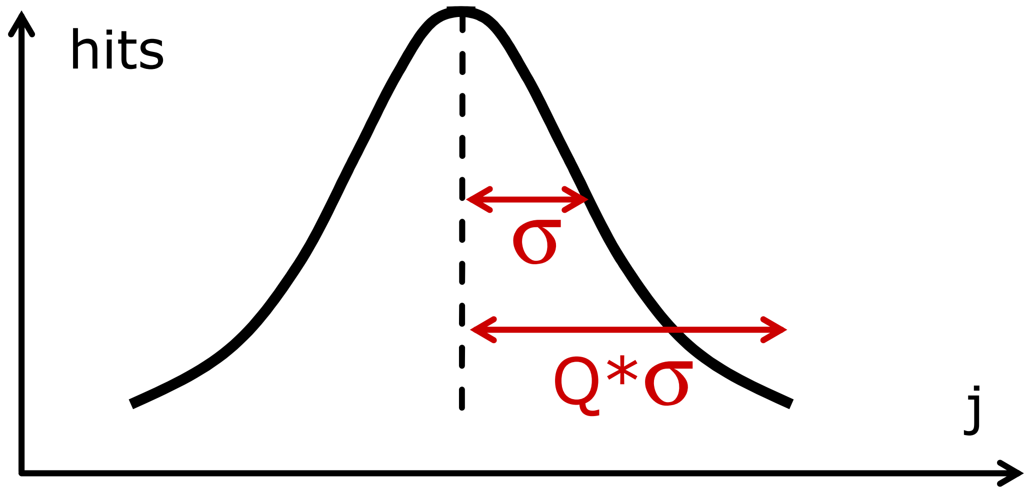
- In real circuits the thermal noise sources are gaussian
- Jitter distributions are therefore unbounded
- The peak-peak in the histogram depends on the number of hits

The peak for unbounded jitter (2/4)

- Calculate the “max−min” from the histogram
  - easy
  - result depends on number of hits
  - not very reliable, not insightful

- Calculate the rms and multiply it by a number Q
  - easy
  - result does not depend on number of hits
  - applicable only to distributions which are close to gaussian

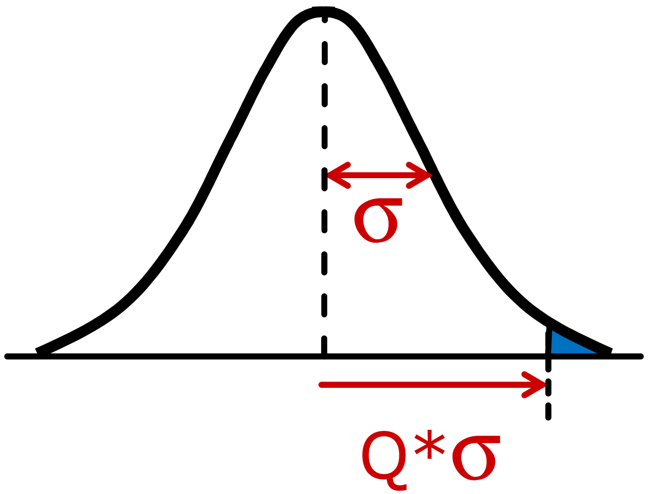
The peak for unbounded jitter (3/4)

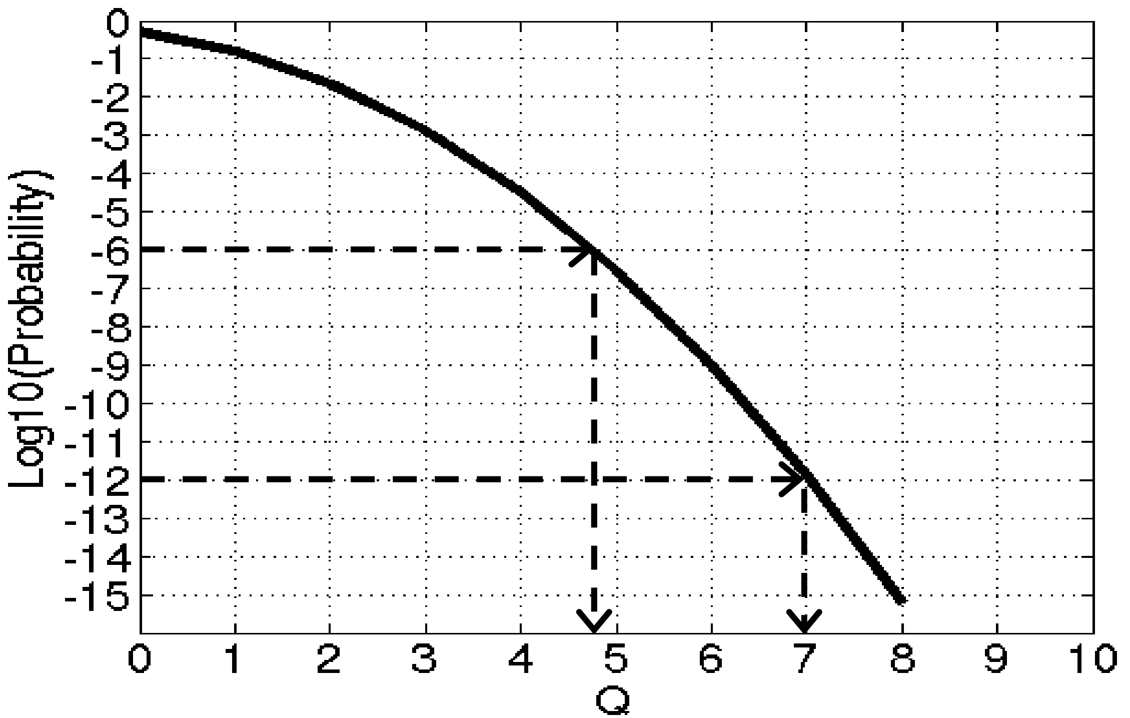


Peak := Q*σ, Peak-peak := 2*Q*σ

- The higher the Q, the lower the probability that a jitter event is beyond the peak or peak-peak (error event)
- Can be applied to any distributions, BUT
- Probability of error easy to know only for gaussian distributions

The peak for unbounded jitter (4/4)

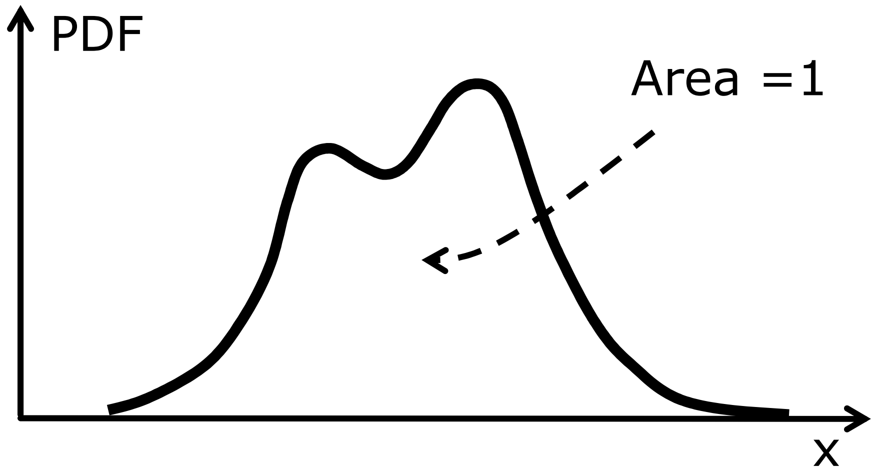


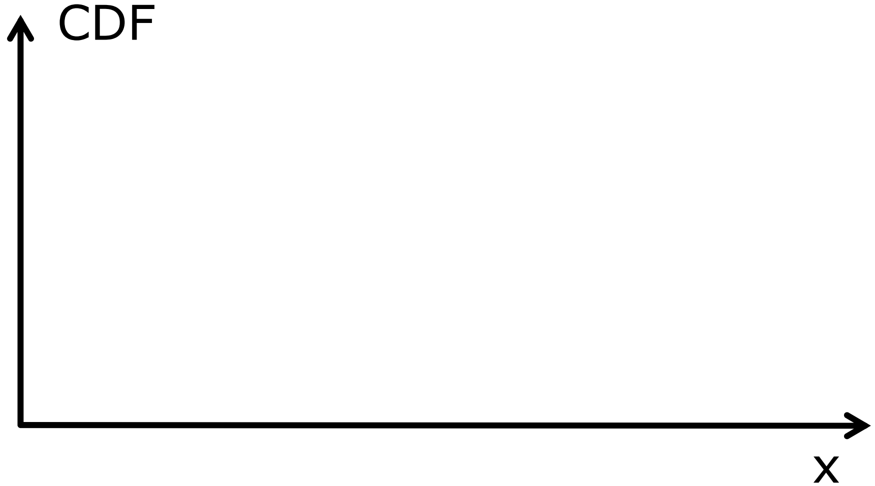


- Prob. of jitter event outside of specified peak depends on Q
- For gaussian jitter distributions easy to compute:
  - Prob < 1e-3 => Q=3.1
  - Prob < 1e-6 => Q=4.8
  - Prob < 1e-12 => Q=7.0

$$\int_{Q\cdot\sigma}^{+\infty} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{x^2}{2\sigma^2}} dx = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right)$$

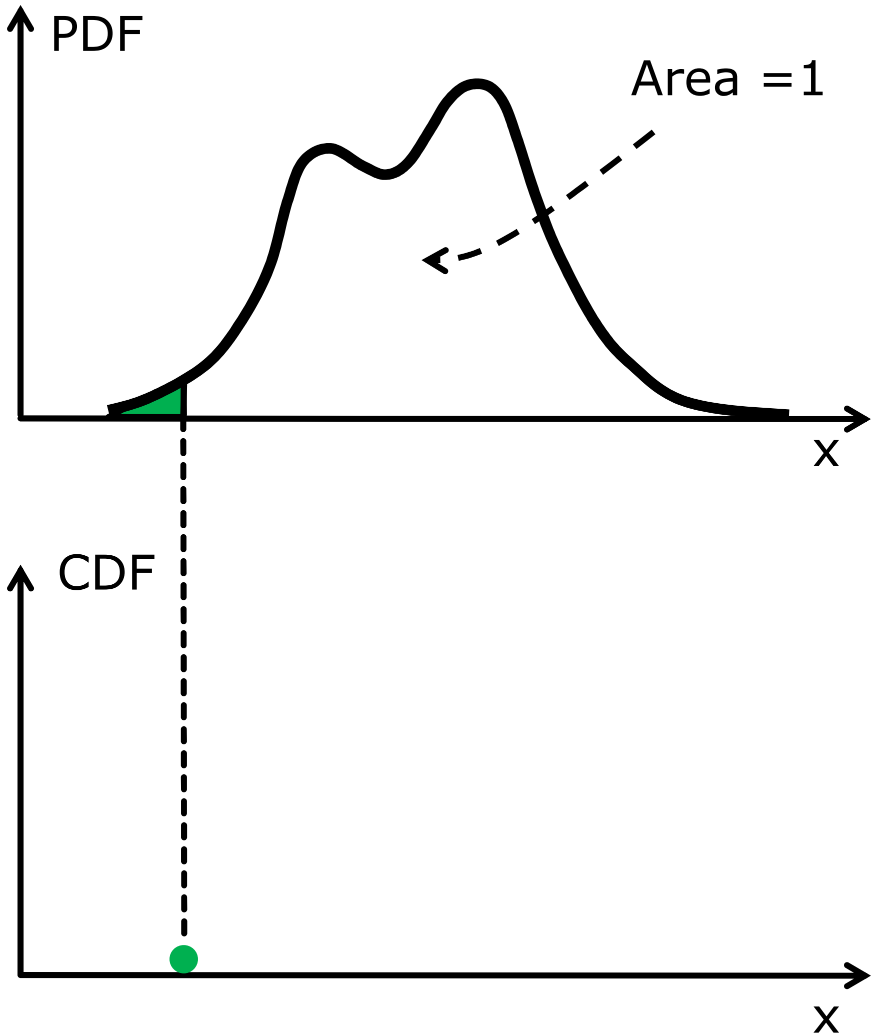
PDF and CDF





- Random Variable "RV"
- Histogram of RV normalized to Area=1 is the **Probability Density Function** (**PDF**)
- The integral from $-\infty$ to x of the PDF is the **Cumulative Distribution Function** (**CDF**)
- CDF(x)=Prob[RV<x]

PDF and CDF



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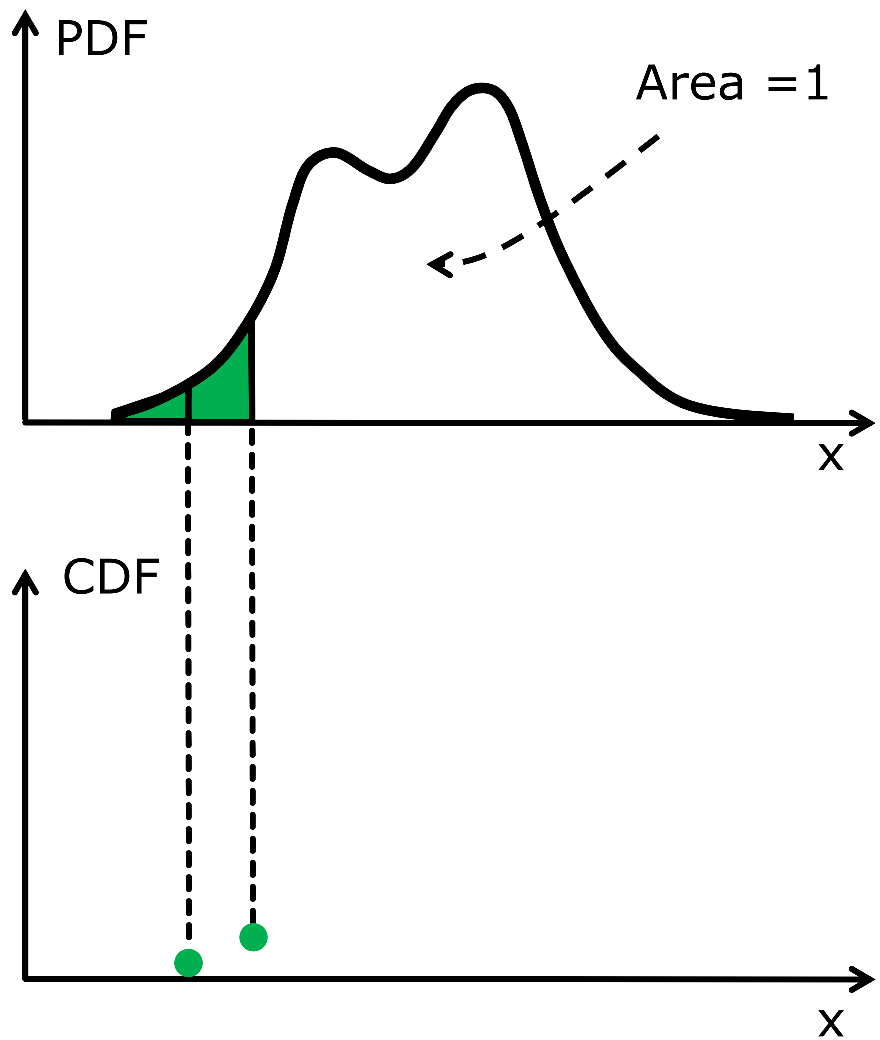
PDF and CDF



- Random Variable "RV"
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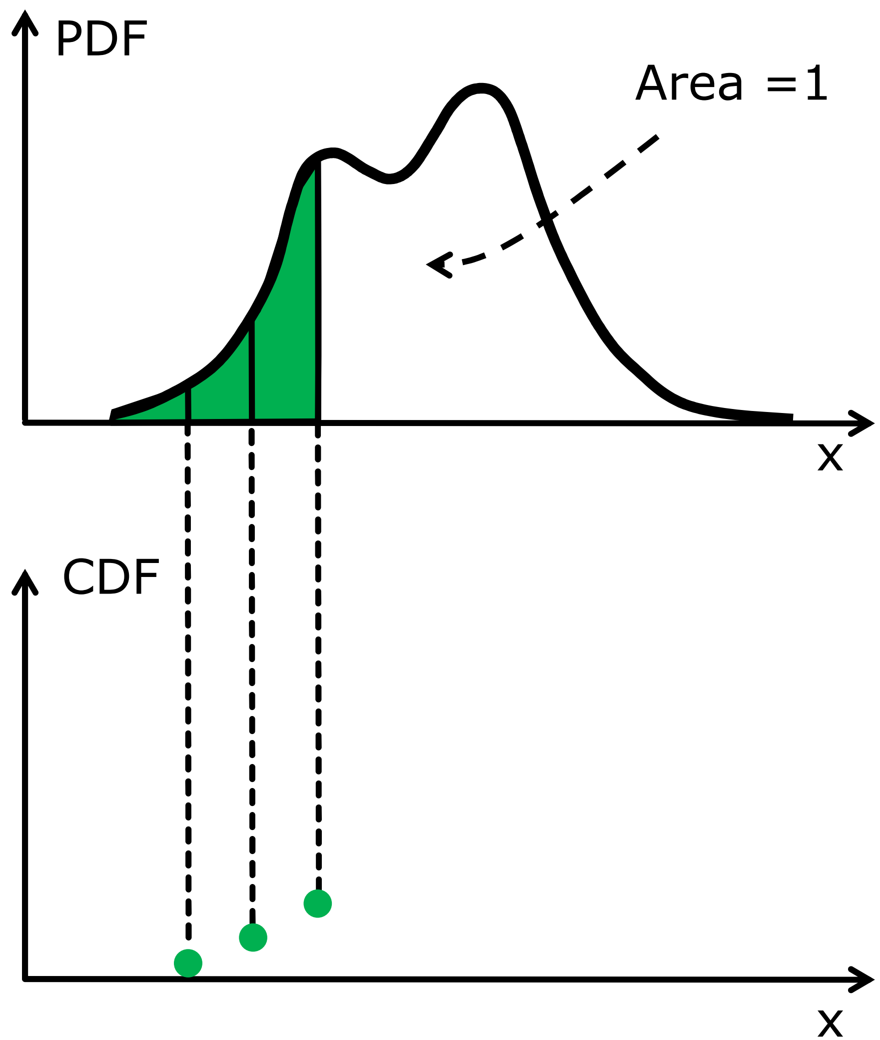
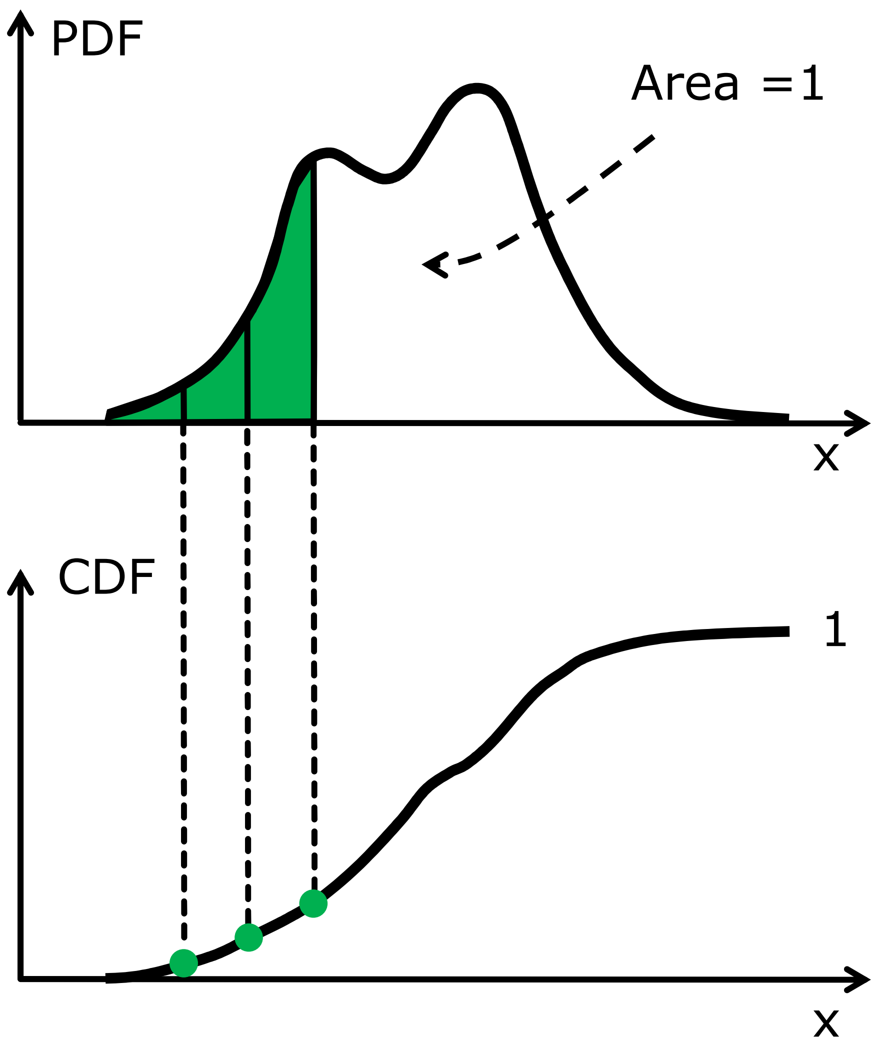
- CDF(x)=Prob[RV<x]

PDF and CDF



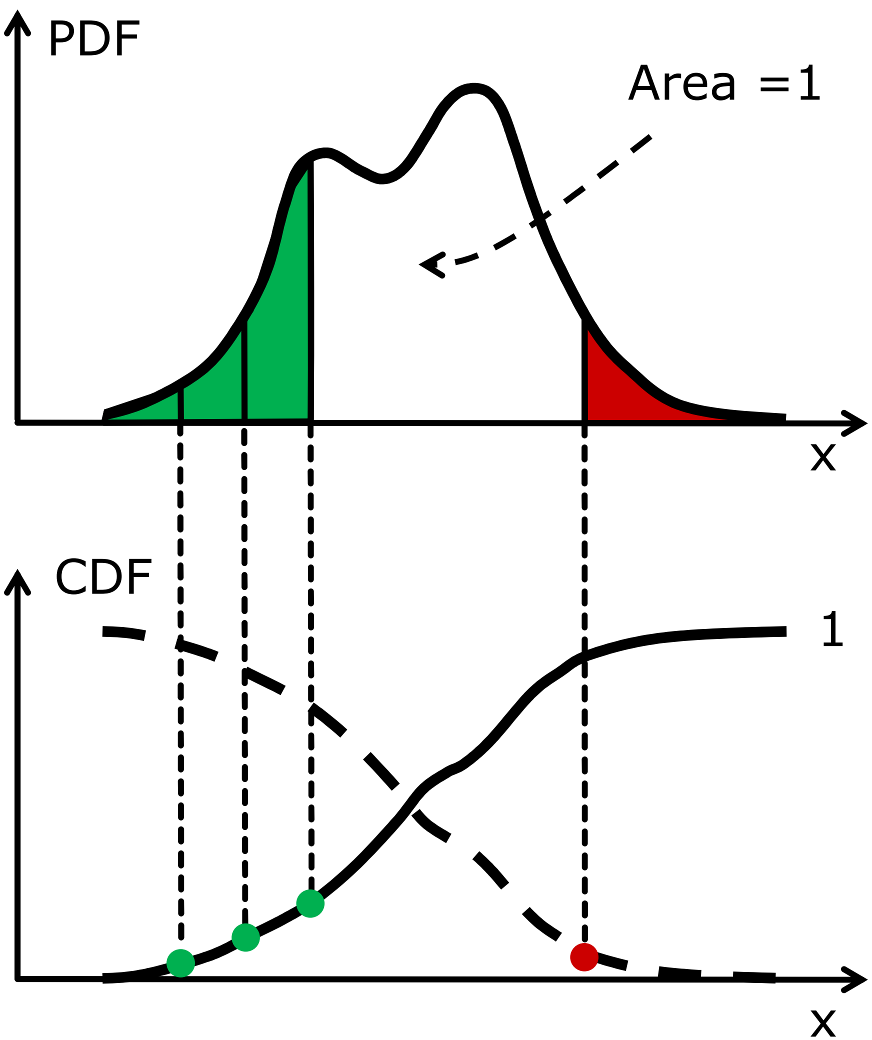
- Random Variable "RV"
- Histogram of RV normalized to Area=1 is the **Probability Density Function** (**PDF**)
- The integral from $-\infty$ to x of the PDF is the **Cumulative Distribution Function** (**CDF**)
- CDF(x)=Prob[RV<x]

PDF and CDF



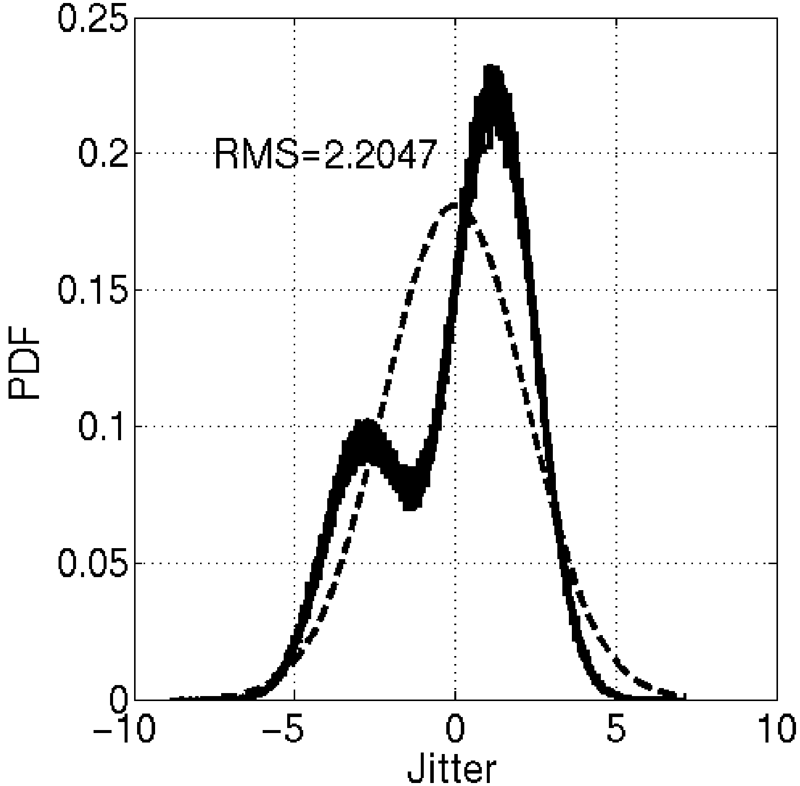
- Random Variable "RV"
- Histogram of RV normalized to Area=1 is the **Probability Density Function** (**PDF**)
- The integral from −∞ to x of the PDF is the **Cumulative Distribution Function** (**CDF**)
- CDF(x)=Prob[RV<x]

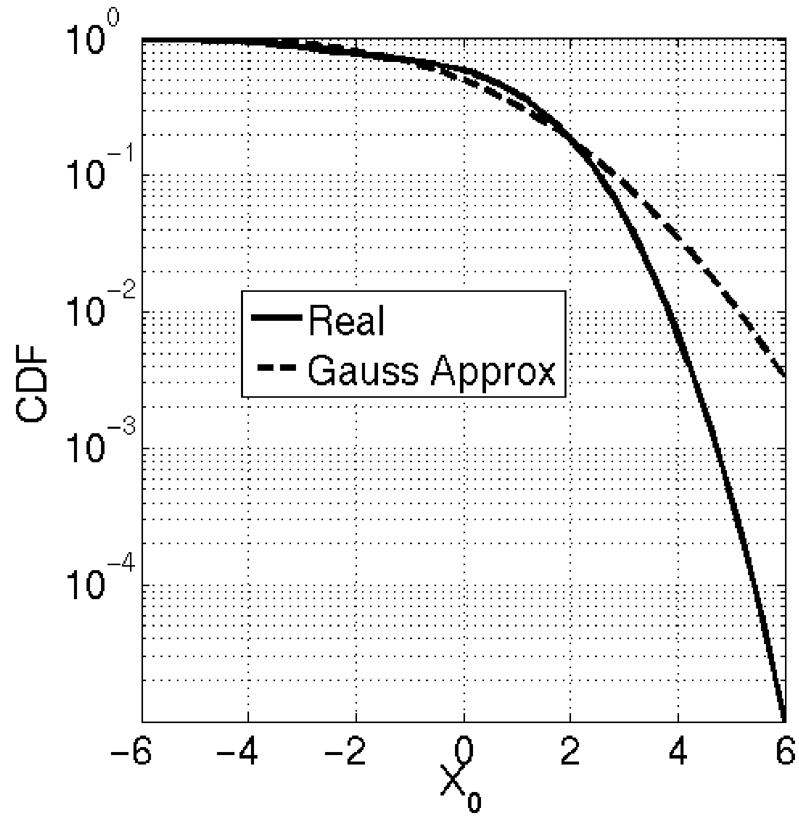
PDF and CDF



- Random Variable "RV"
- Histogram of RV normalized to Area=1 is the **Probability Density Function** (**PDF**)
- The integral from −∞ to x of the PDF is the **Cumulative Distribution Function** (**CDF**)
- CDF(x)=Prob[RV<x]
- CDF'(x)=Prob[RV>x]

What if jitter is not gaussian?





- Q*σ approach for non-gaussian distributions leads to wrong estimation of error probability

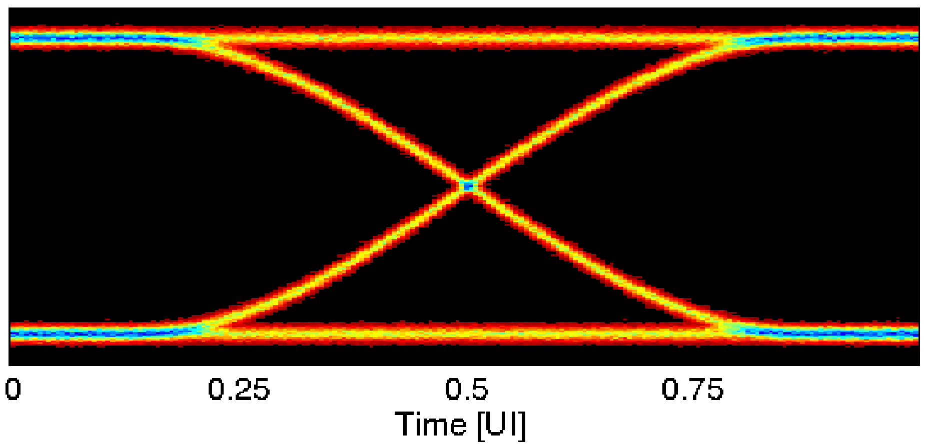
Summary so far

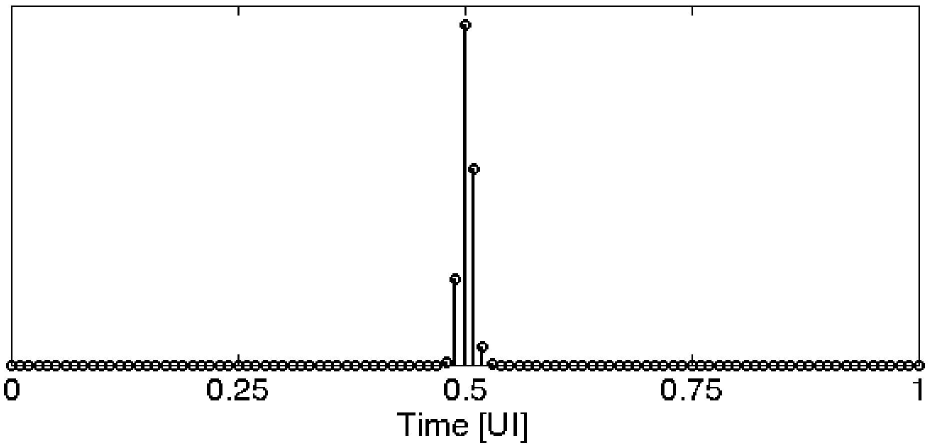
- Lots of important applications are not affected by the RMS value of Jitter
- "Tail" behavior of jitter might be more important
- Statistical properties of gaussian jitter distributions
- Multiplying the rms jitter by factor Q leads to wrong results if jitter is not gaussian

What's next:

- Develop a method to characterize jitter distributions which are not gaussian

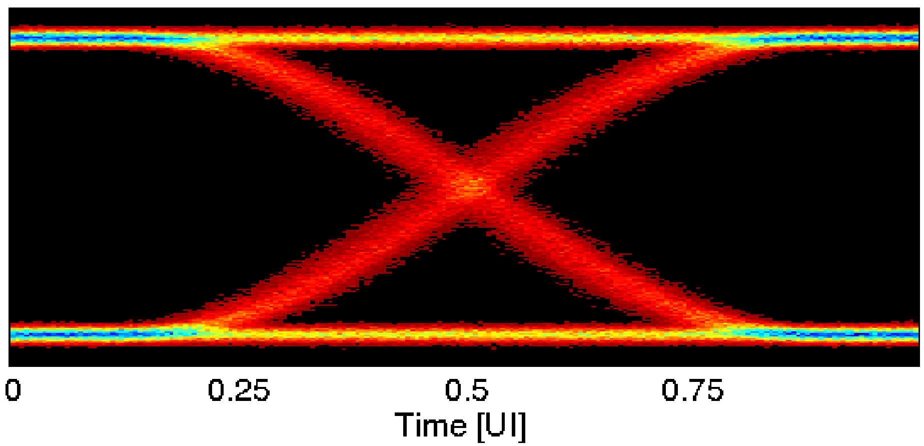
Ideal Eye Diagram

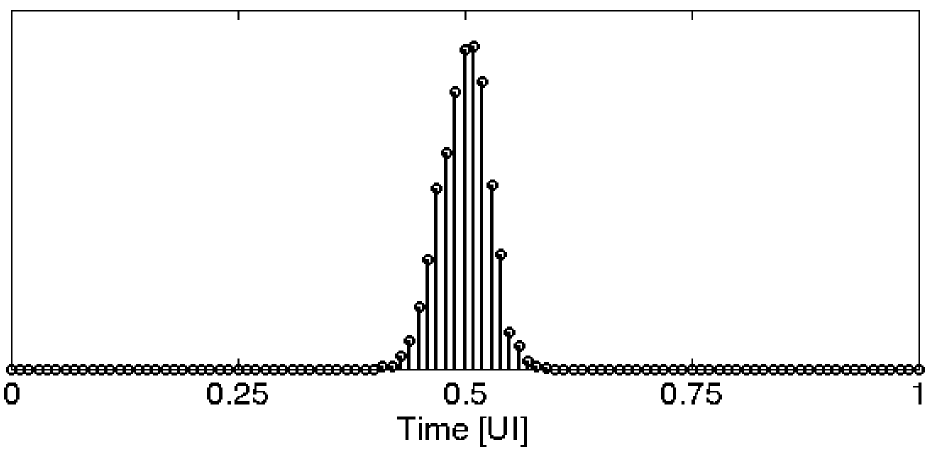




- Sharp Transition
- Histogram shows one peak

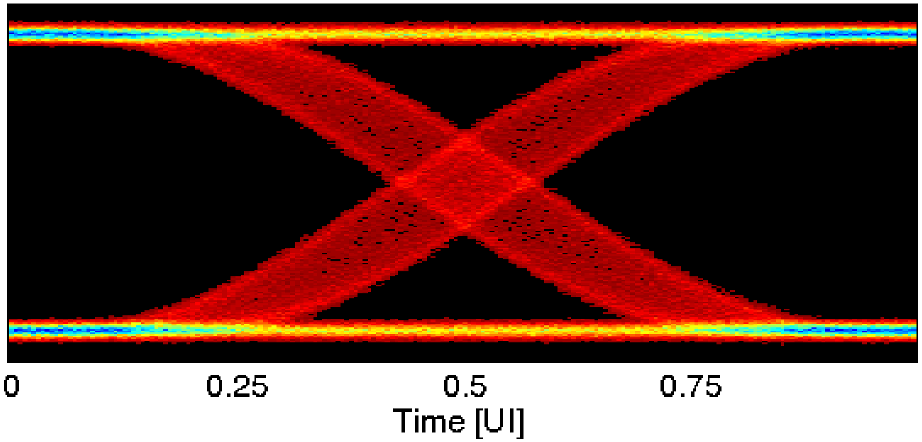
Eye Diagram: Random Jitter (RJ)

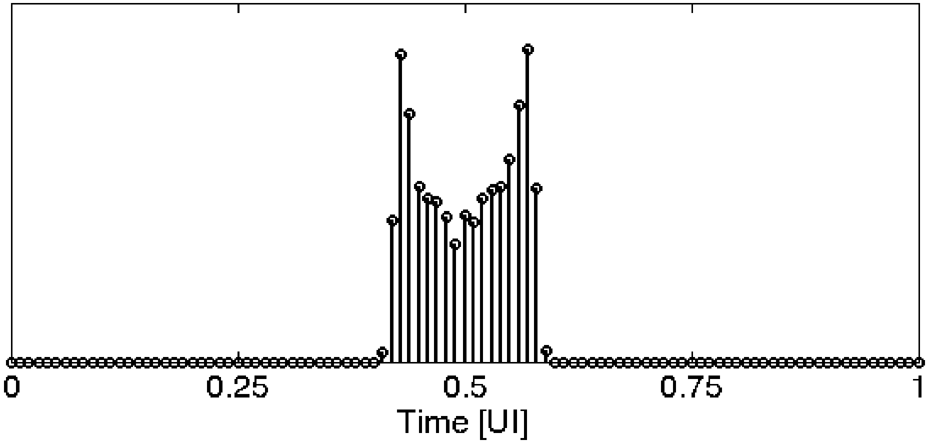




- Transitions are blurred
- Histogram shows "gaussian" distribution
- Due to:
  - Device thermal noise
  - Device flicker noise
  - Composite effect of many uncorrelated noise sources

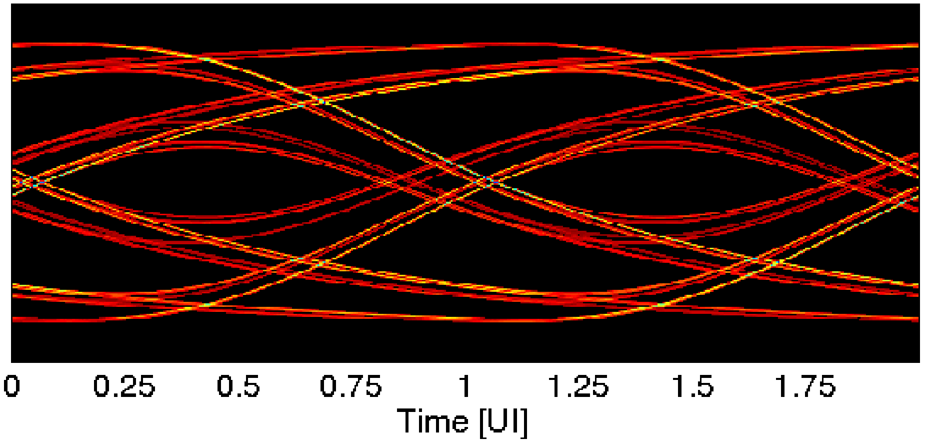
Eye Diagram: Periodic Jitter (PJ,SJ)

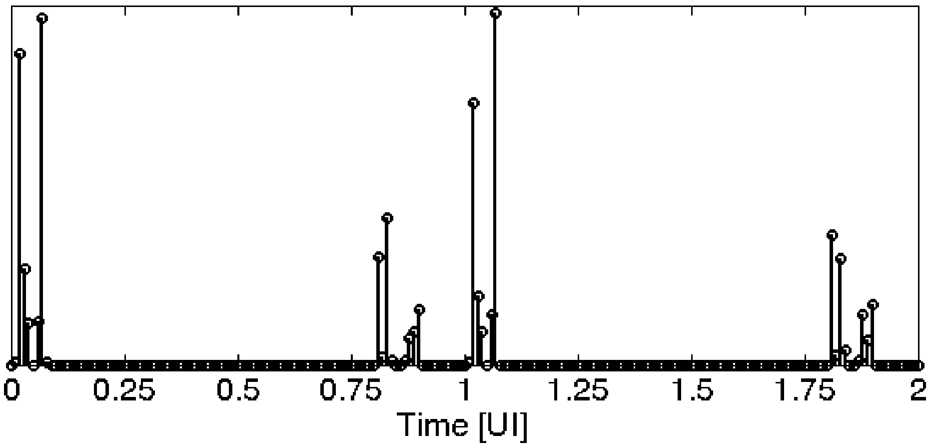




- Transitions are spread
- Histogram shows bounded distribution
- Figure shows example for case of sinusoidal jitter
- Due to:
  - Power supply noise
  - Strong local RF carrier
  - Spurious tones in PLL

Eye Diagram: Data-Dep. Jitter (DDJ, ISI)





- Transitions are "concentrated" is some "hot Spots"
- Histogram shows discrete peaks
- Due to:
  - Channel or TX bandwidth limitation (waveform does not reach full scale level unless there are several bits in a row with same polarity)

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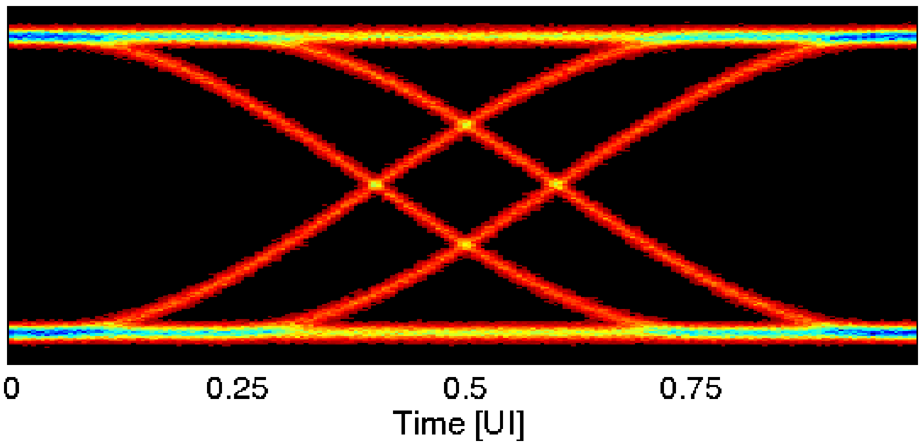
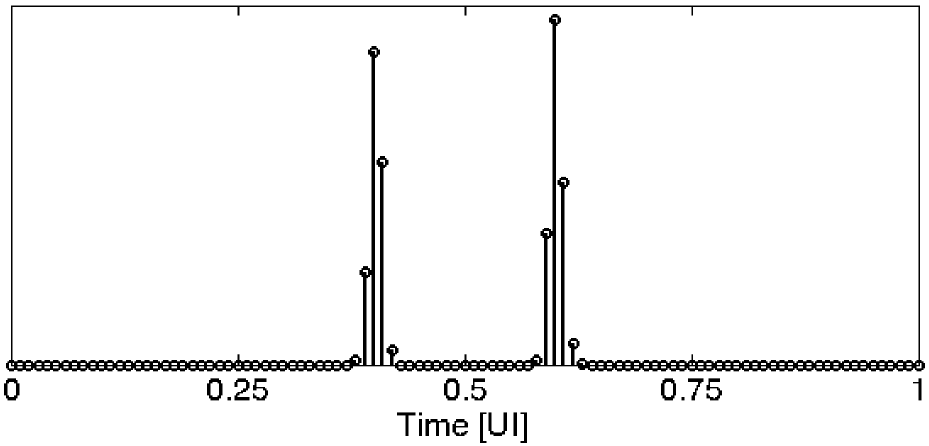
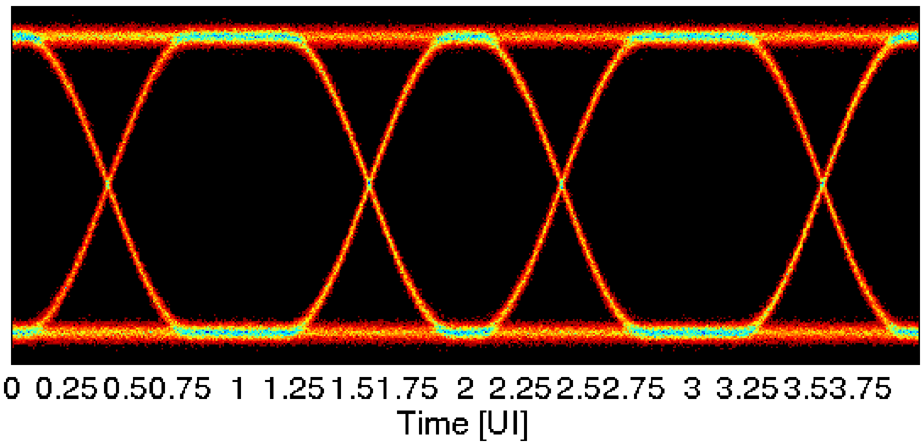
Eye Diagram: Duty Cycle Distortion (DCD)

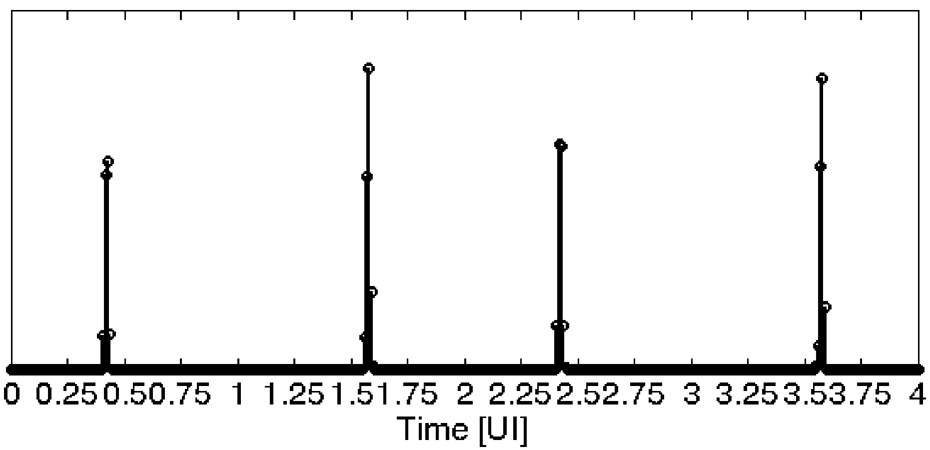




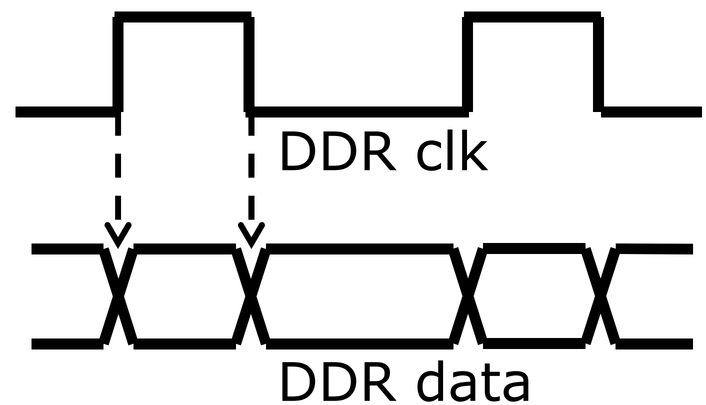
- Transitions are concentrated in two hot spots
- Histogram shows two equally large peaks
- Due to:
  - Duty Cycle Distortion (e.g. in DDR systems)

Eye Diagram: Duty Cycle Distortion (DCD)

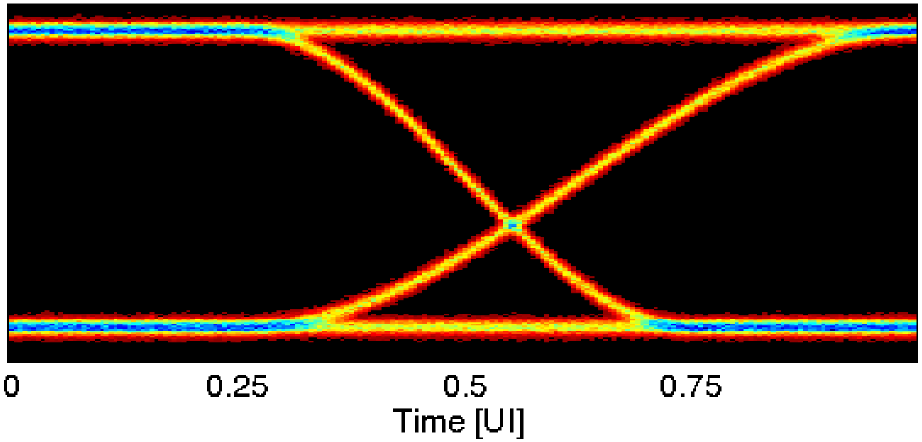


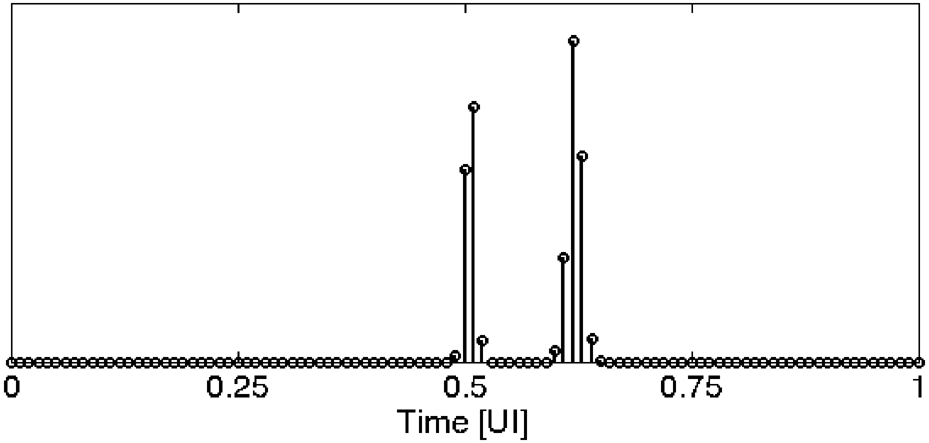


- DCD is evident when the eye is unfolded over more UIs
- Typical in DDR systems



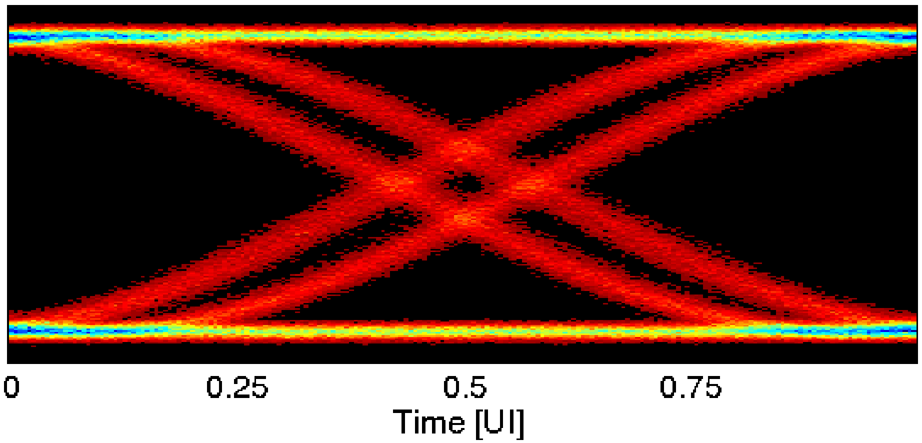
Eye Diagram: Rise/Fall Time Asymm.

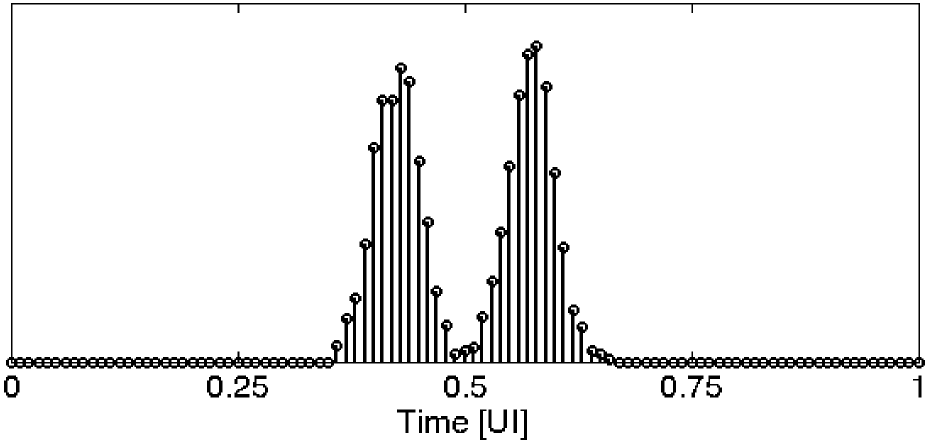




- Similar Histogram as for DCD
- Due to:
  - Rise and Fall Time Asymmetry
  - RX threshold not centered

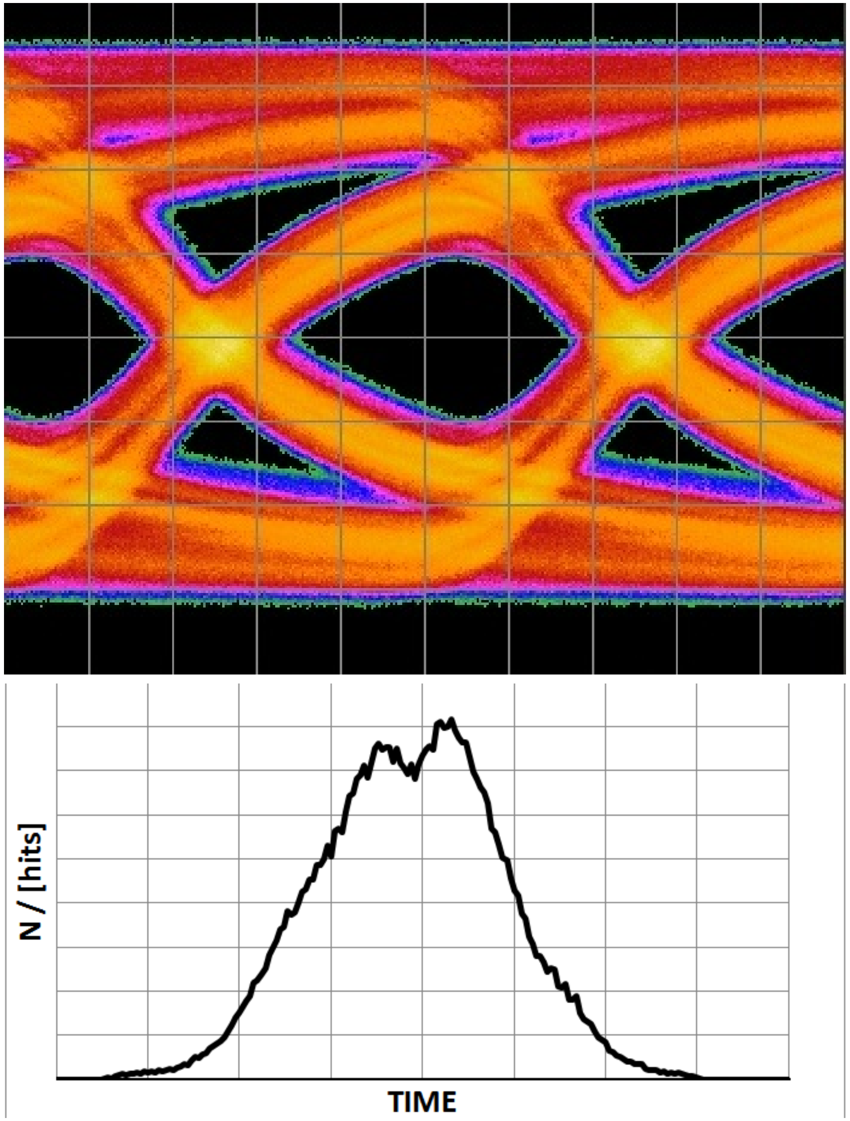
Eye Diagram: Multiple Jitter Sources





- In real systems lots of jitter sources are present at the same time
- In figure: example of DCD + RJ
- **The resulting distribution is the convolution of the single distributions**

Eye Diagram: Multiple Jitter Sources



- Measurement taken after 50 inches of FR4
- Data transitions show deterministic patterns plus blurred behavior
- Histogram shows an unbounded, clearly not gaussian distribution

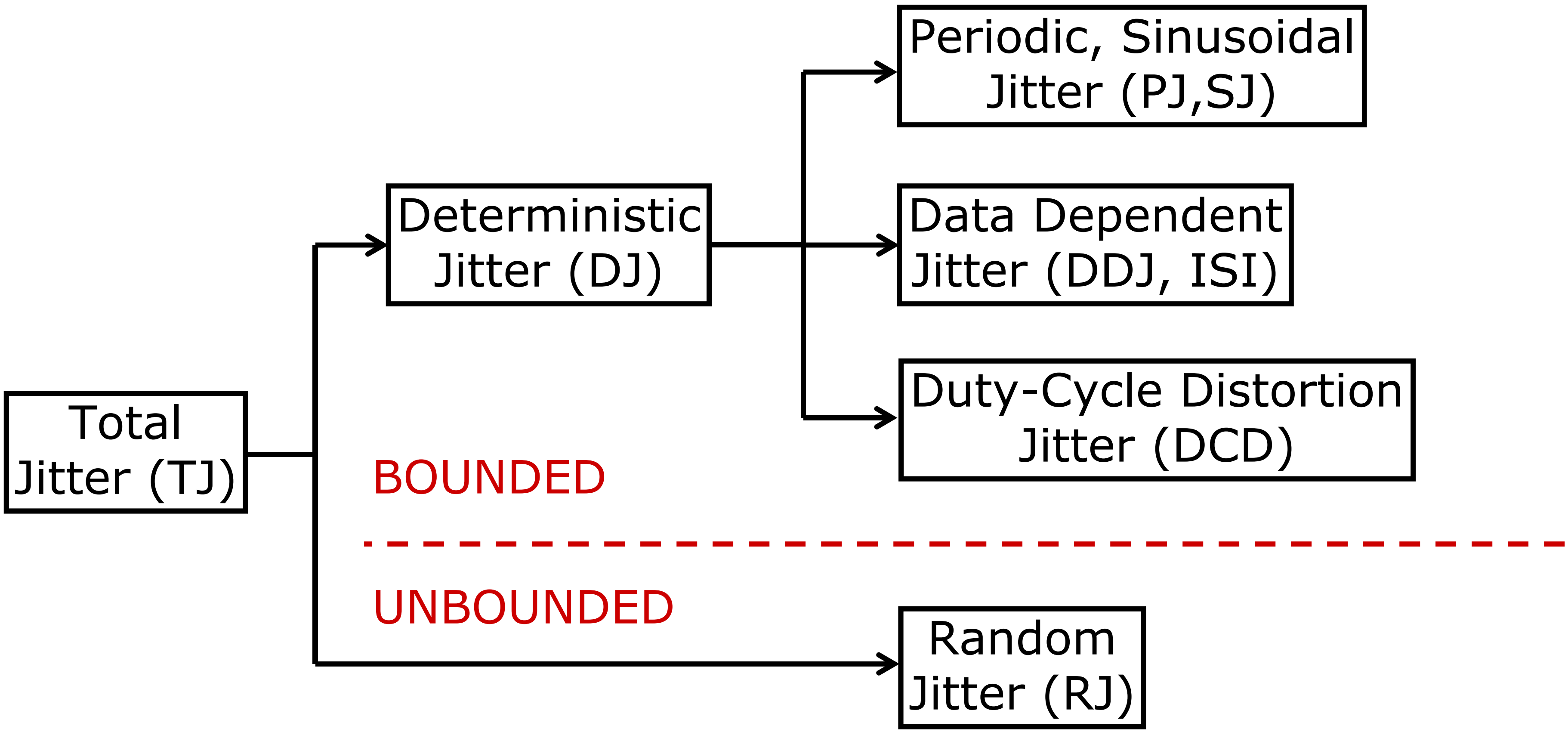
Jitter Decomposition (1/4)

- Jitter is the result of:
  - Device Noise (flicker + thermal)
  - System non-idealities (nonlinearities, limited channel BW, spurious tones in PLL spectrum, duty-cycle, …)
  - External disturbances (supply noise, switching noise, crosstalk, …)
- Device noise contributors are gaussian, **unbounded**
- Other contributors generate **bounded** distributions

Jitter Decomposition (2/4)

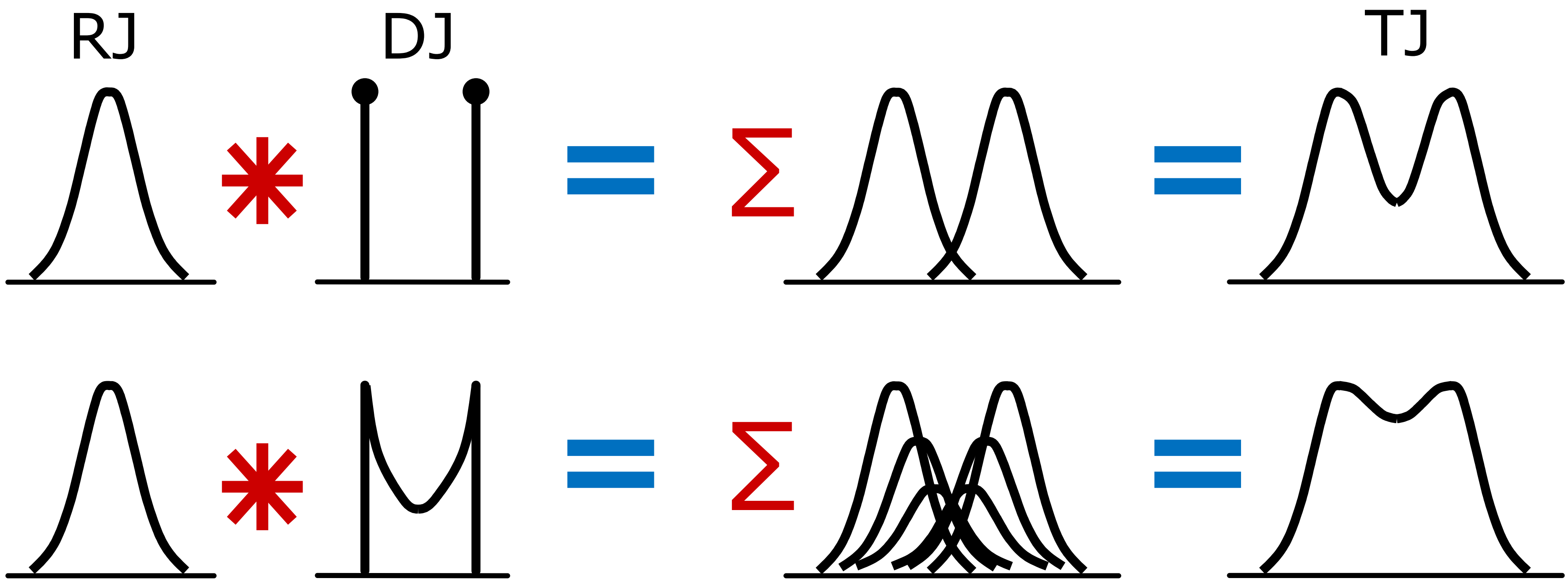
- Idea: consider the total jitter distribution as the combination of:
  - deterministic components
  - random component
- **Deterministic Jitter (DJ)** := any jitter with **bounded** distribution
- **Random Jitter (RJ)** := any jitter with **unbounded** distribution (gaussian)
- The result of DJ and RJ is called **Total Jitter (TJ)**

Jitter Decomposition (3/4)

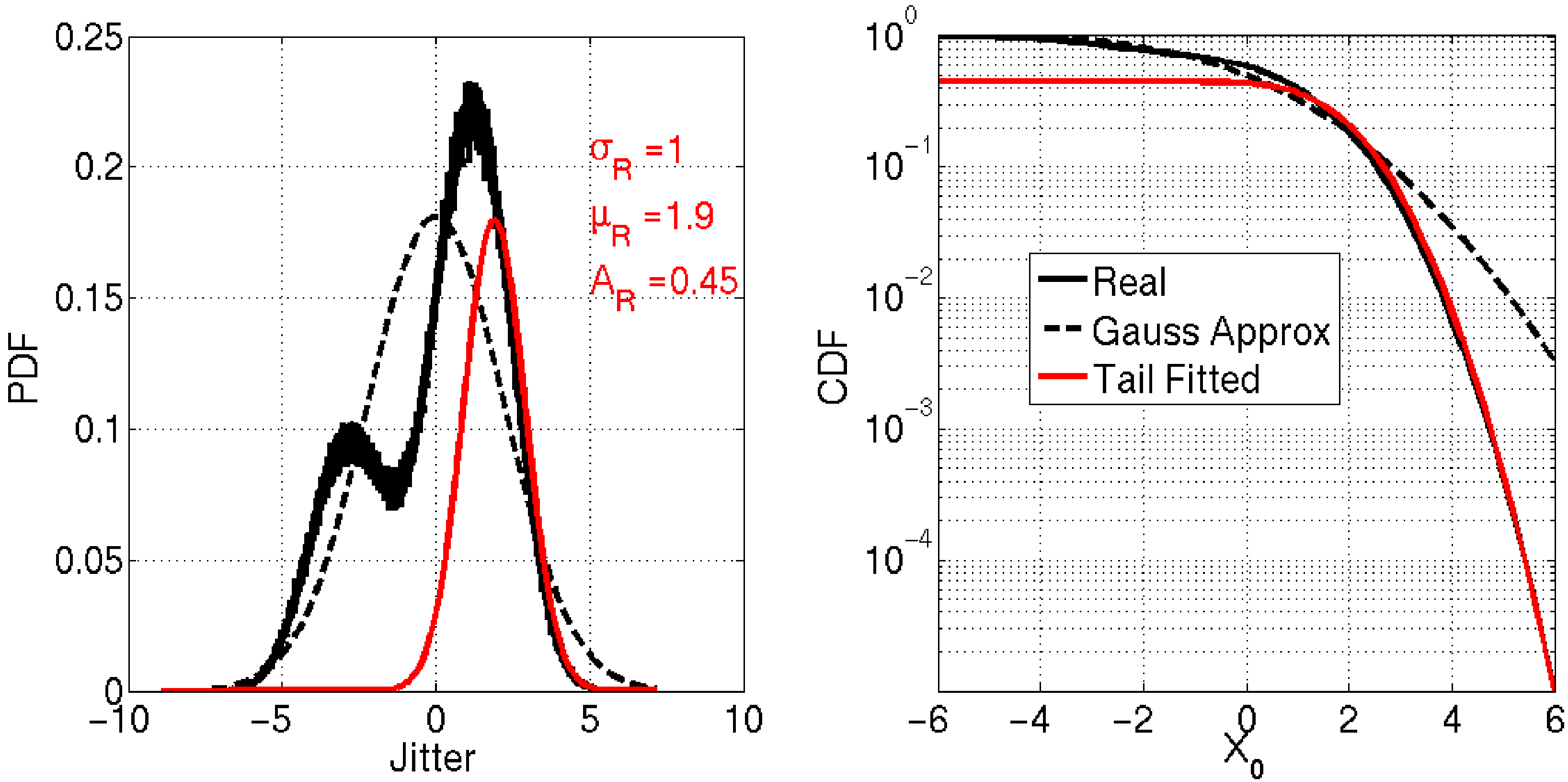


Jitter Decomposition (4/4)

- From Probability Theory: the distribution of the sum of independent random variables is the **convolution** of the single distributions
- Hence: the distribution of TJ is the **convolution** of the distributions of RJ and DJ

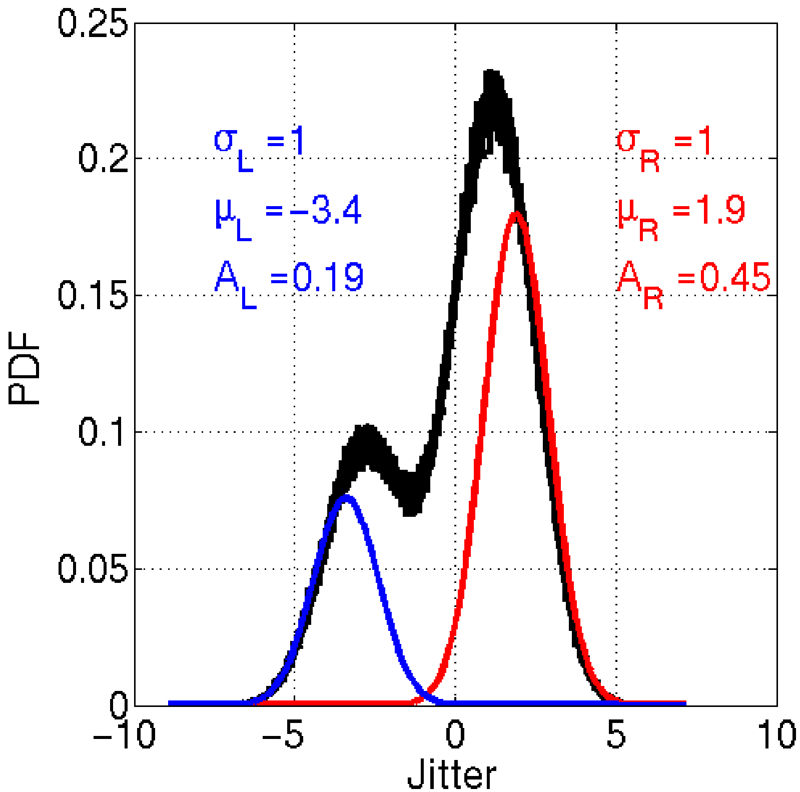


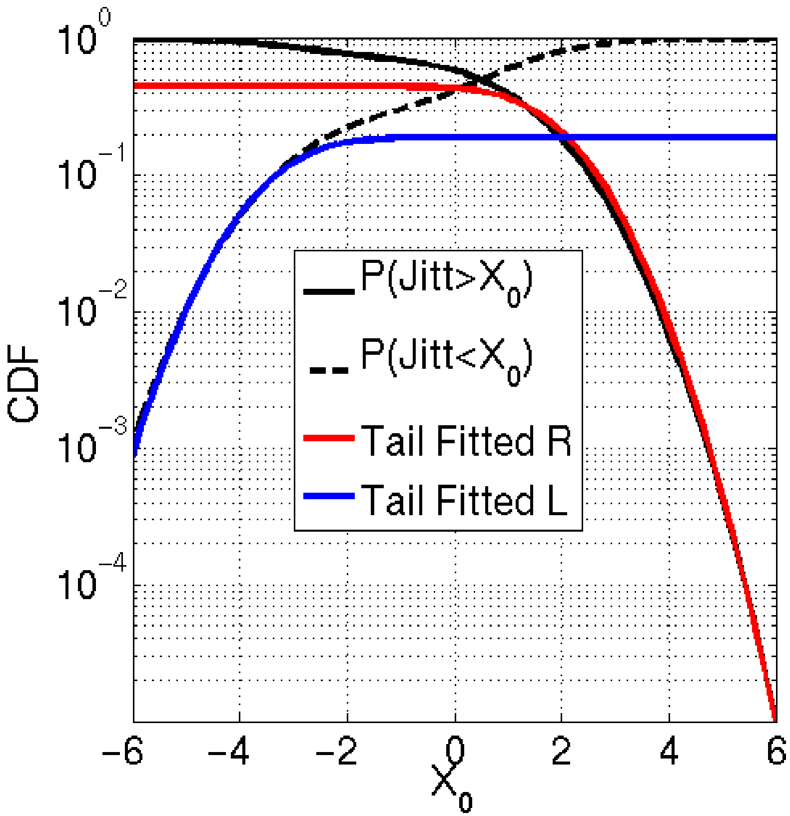
Tail Fitting (1/3)



- Idea: fit a gaussian curve to the tail of the distribution
- Probability of error obtained used the fitted curve is matching the real one
- 3 Parameters: σ, μ, A

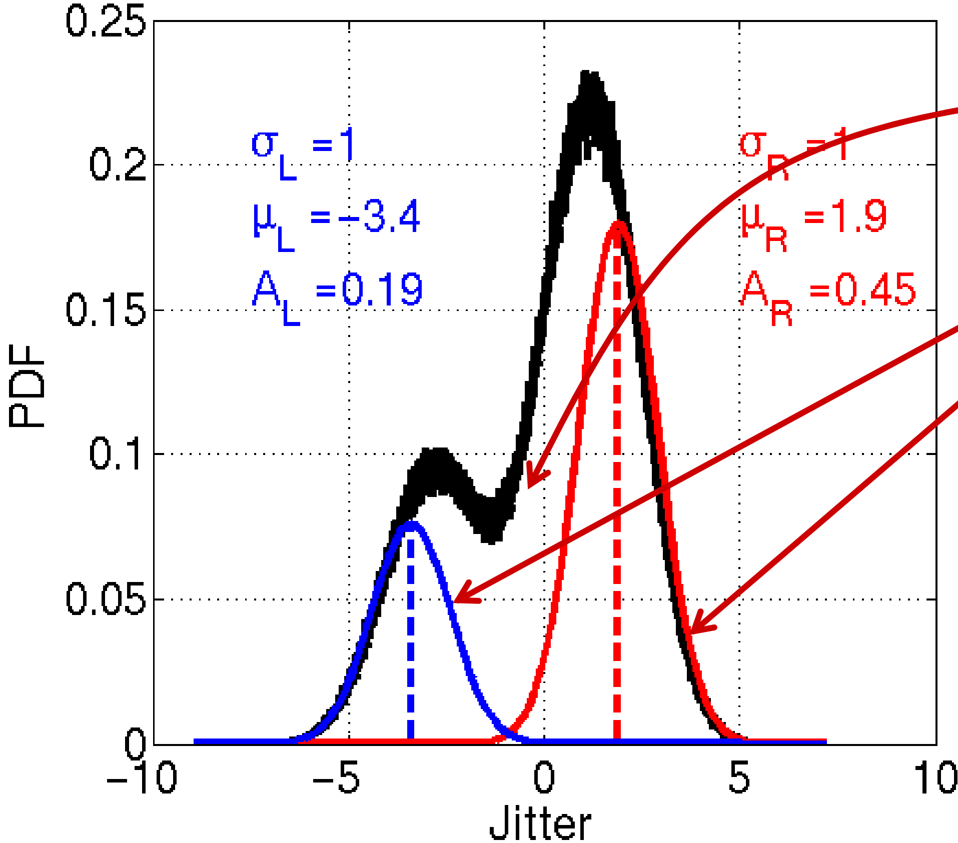
Tail Fitting (2/3)





- Do the same for the left tail
- 6 Parameters: σ_R, μ_R, A_R, σ_L, μ_L, A_L
- Probability of error left and right can be accurately described

Tail Fitting (3/3)



DJ Component

RJ Components

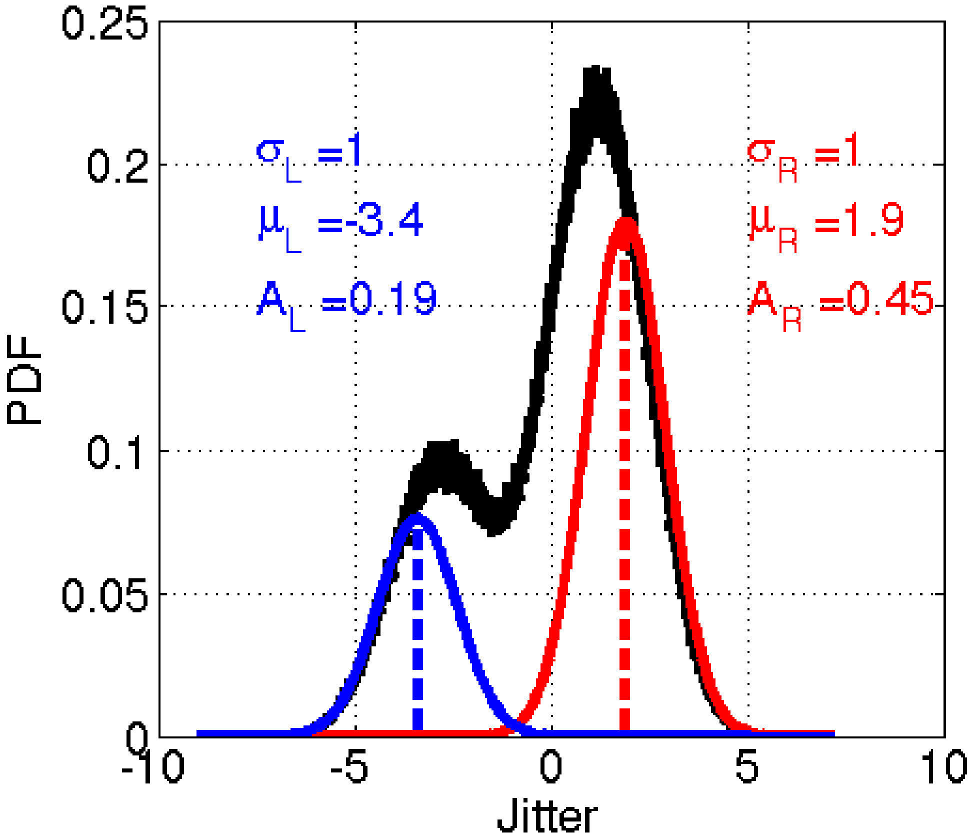
- $Peak_R = \mu_R + Q * \sigma_R$
- $Peak_L = \mu_L - Q * \sigma_L$
- $PkPk = \mu_R - \mu_L + Q * (\sigma_R + \sigma_L)$

$\mu_R - \mu_L$: DJ

$(\sigma_R + \sigma_L)$: RJ

DJ + RJ: TJ

TJ and Probability



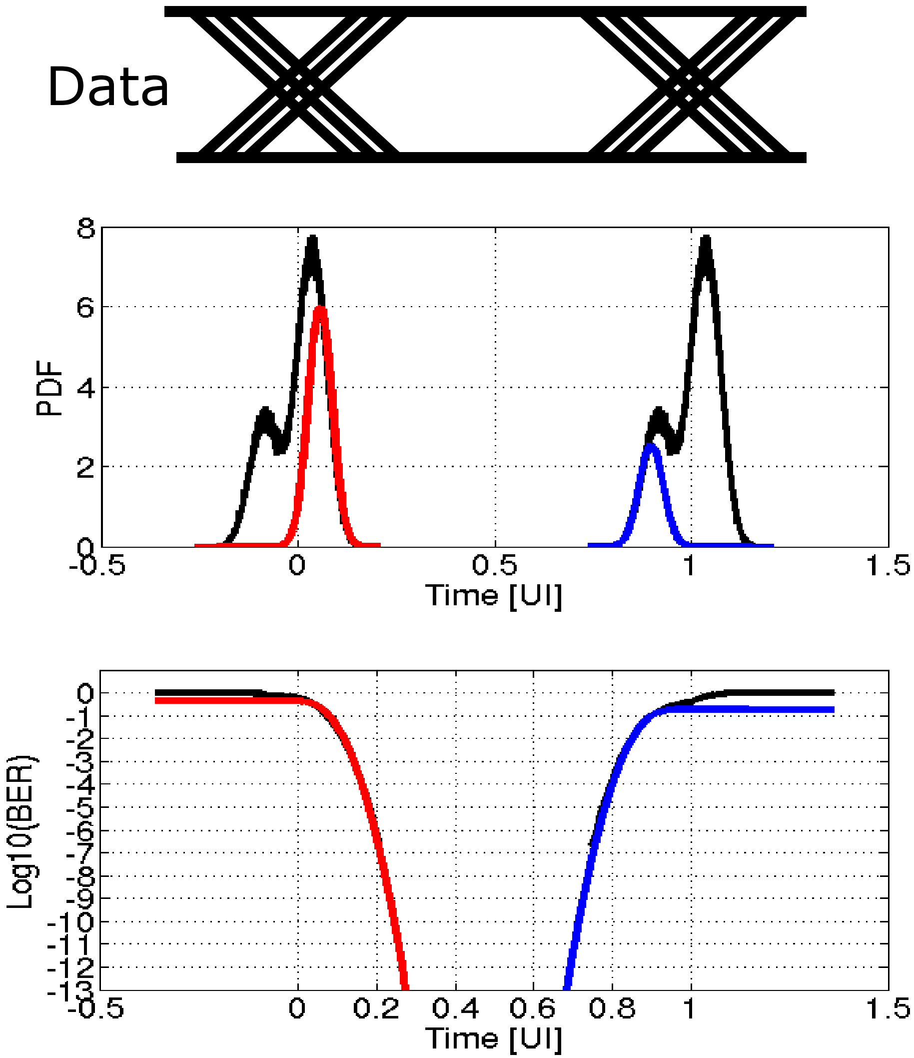
- TJ = $\mu_R - \mu_L + Q * (\sigma_R + \sigma_L)$
- Usually $\sigma_R = \sigma_L = \sigma$

↓

- TJ = DJ + 2 *Q * σ

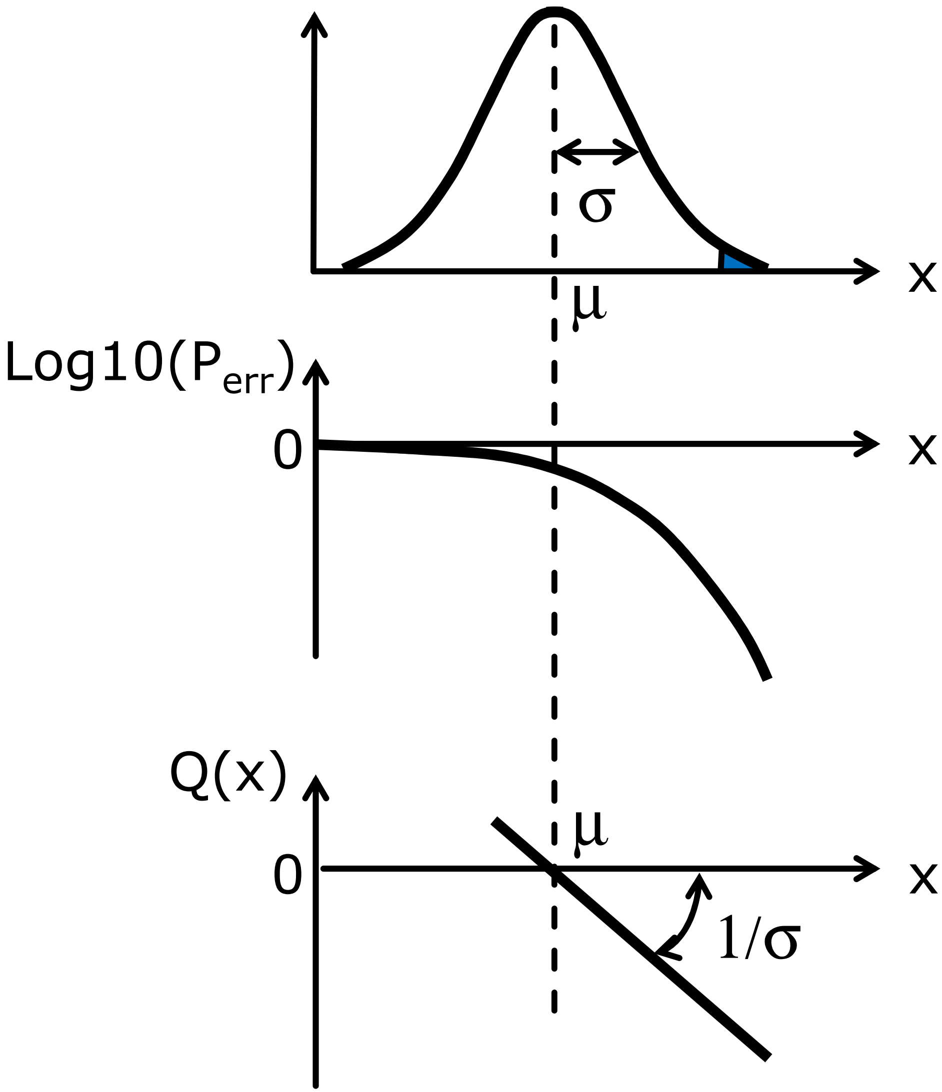
- Prob(Jitter outside TJ range)= $\frac{A_R + A_L}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \cong \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right)$

Bathtub plot (1/3)



- The bathtub plot is obtained by building the CDFs of the jitter on the left and right data edges
- It shows the probability of error versus the sampling point
- Used to estimate the eye opening for very low BER levels

Bathtub plot (2/3): Q-scale



- Q-scale used to linearize the bathtub plot for gaussian distributions

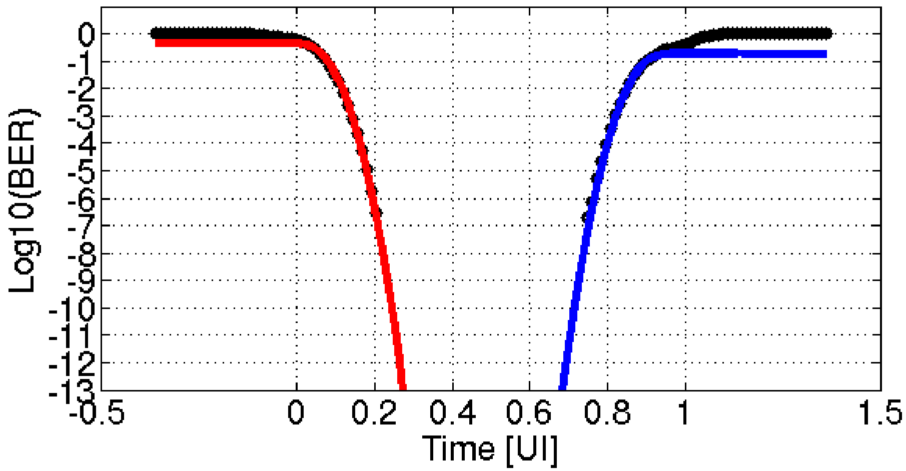
$$P_{err}(x) = \frac{1}{2} erfc\left(\frac{x-\mu}{\sqrt{2}\sigma}\right)$$

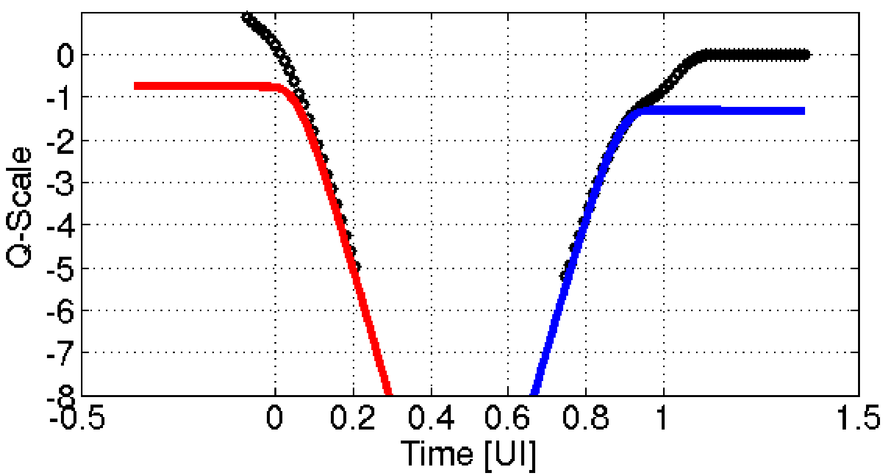
$$Q(x) := -\sqrt{2} \cdot erfc^{-1}\left(2 \cdot P_{err}(x)\right)$$

$$Q(x) = \frac{\mu - x}{\sigma}$$

- $P_{err}=10^{-15}$ -> Q=-7.95
- $P_{err}=10^{-12}$ -> Q=-7.03
- $P_{err}=10^{-9}$ -> Q=-5.99
- $P_{err}=10^{-6}$ -> Q=-4.75

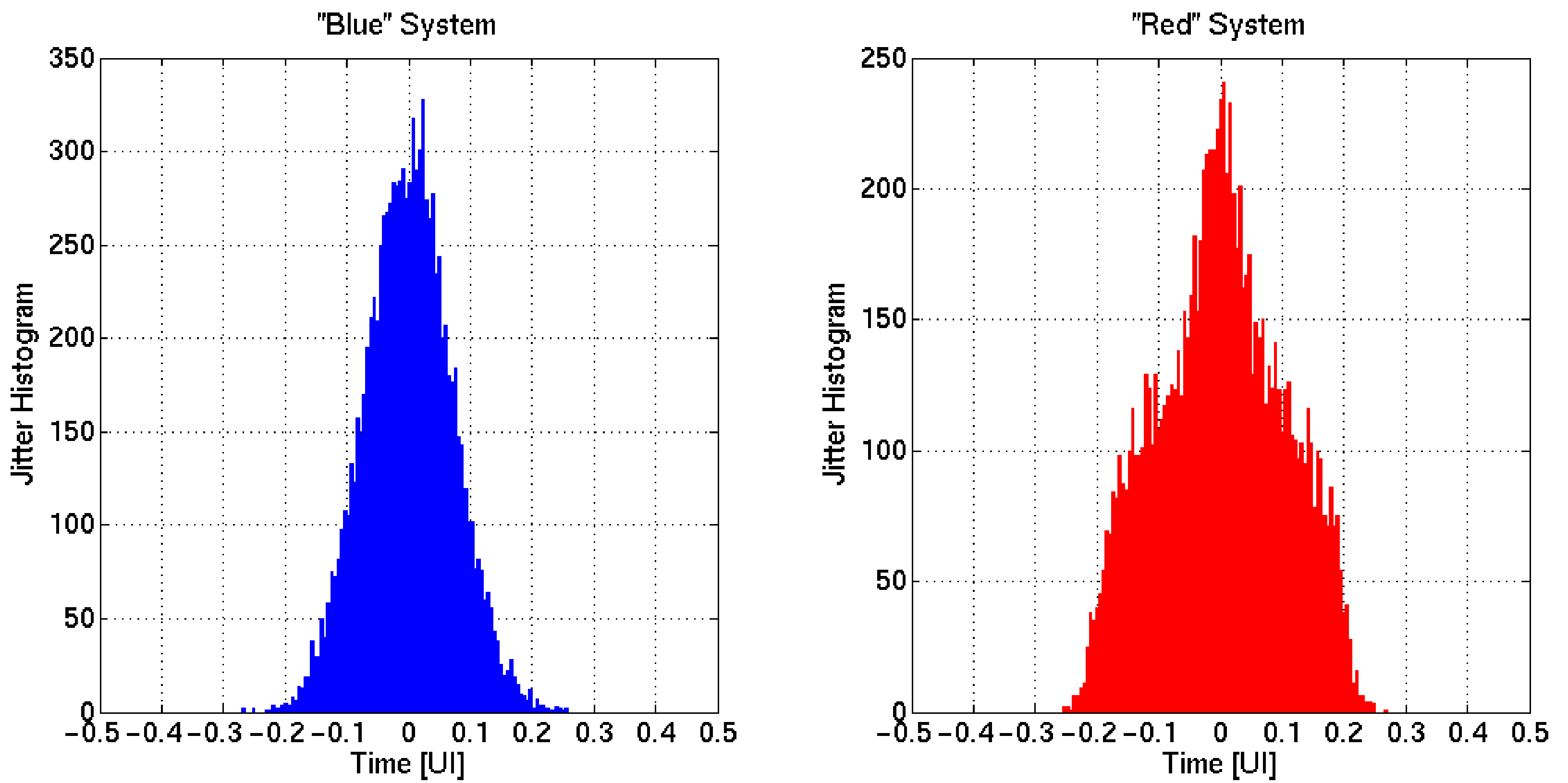
Bathtub plot (3/3)





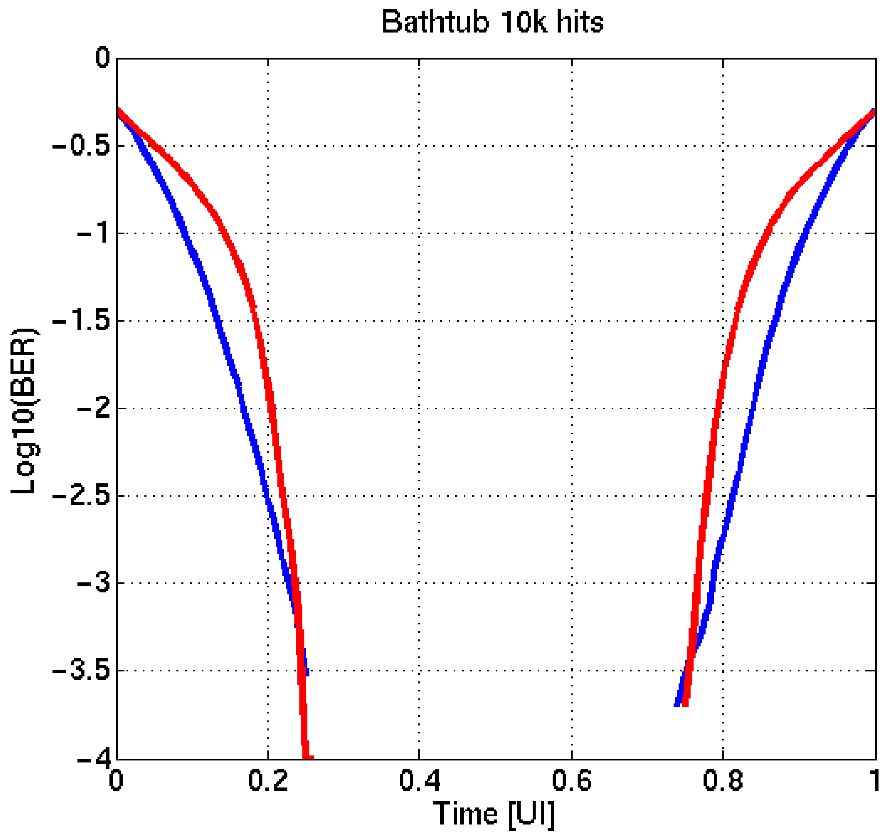
- Gaussian components in Q-scale are linear
- Linear interpolation to lower Q (BER)
- Used to understand when RJ contribution starts to dominate

Bathtub Example (1/4)



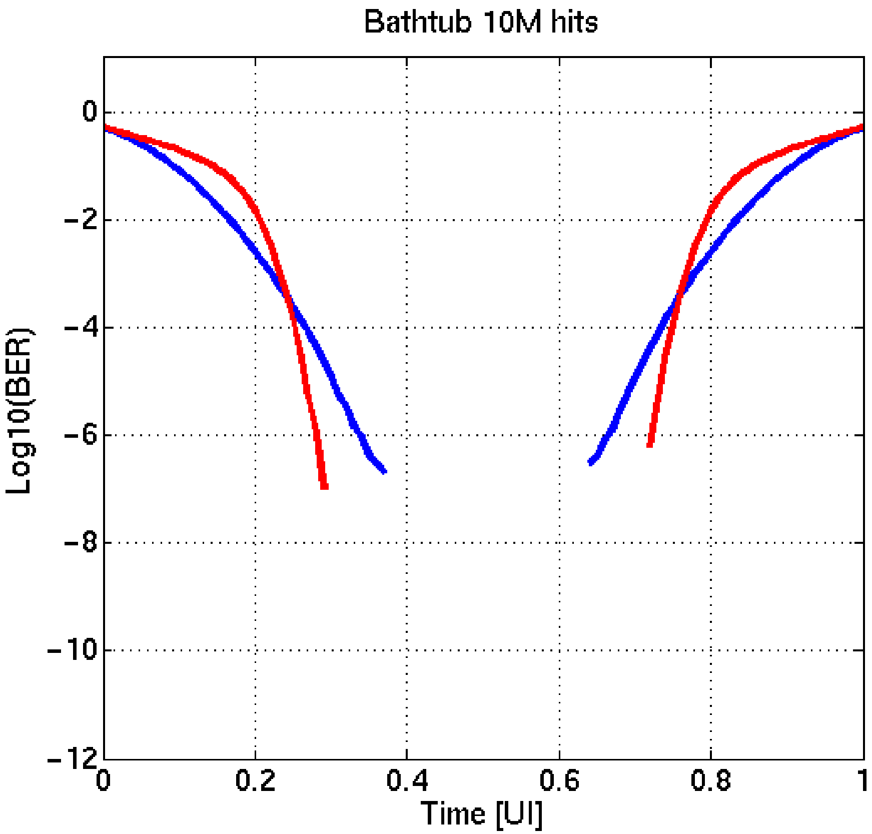
- Two systems with different jitter histograms over 10k hits
- Although the histograms are different the peak to peak jitter seems to be the same

Bathtub Example (2/4)



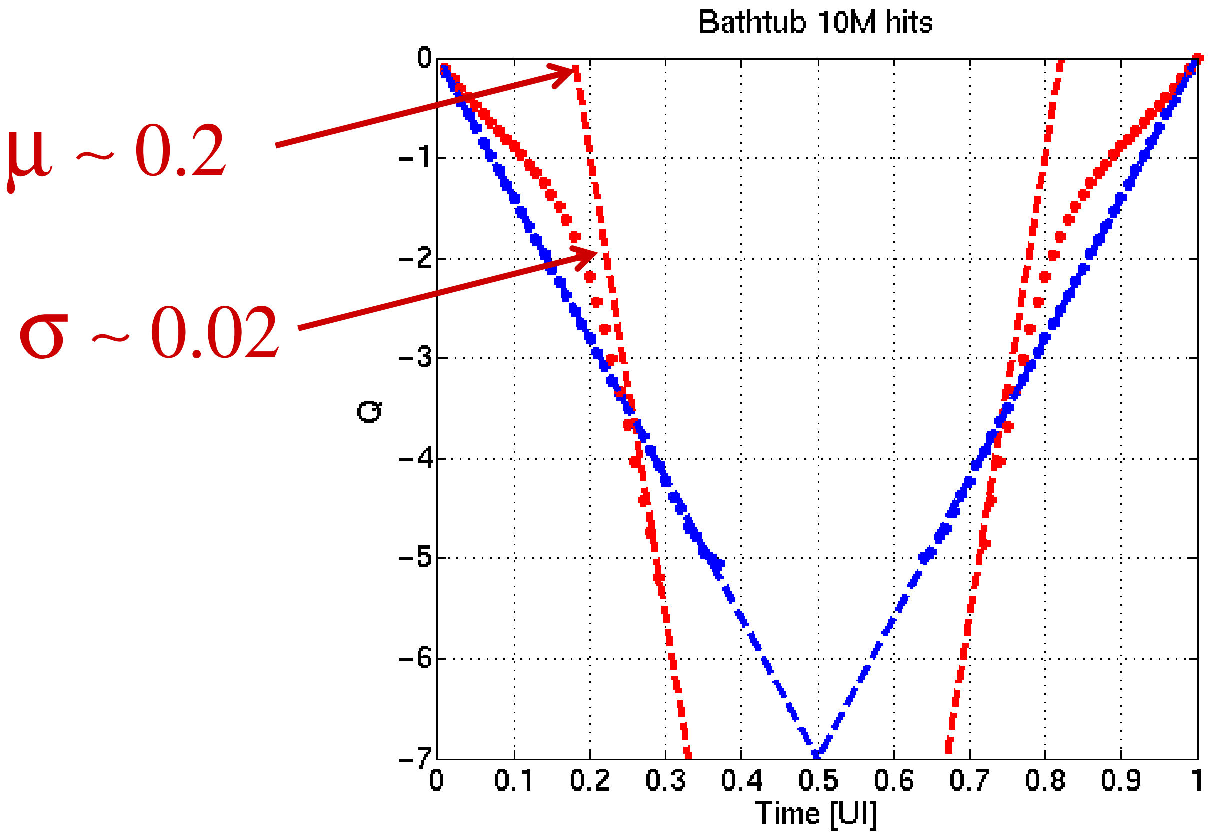
- Bathtub over 10k hits
- "Red" system has steeper slopes as "Blue" one
- For low BER, "Red" system seems to be better

Bathtub Example (3/4)



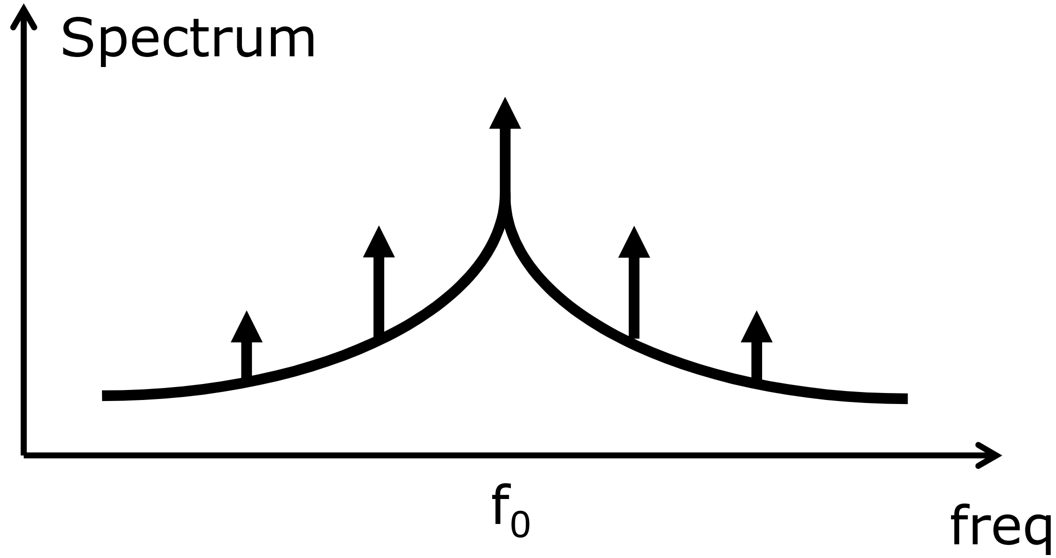
- Bathtub over 10 Million hits
- "Red" system definitely has larger eye opening for low BER
- From this graph Eye Opening @ 1e-12 not easy to predict

Bathtub Example (4/4)



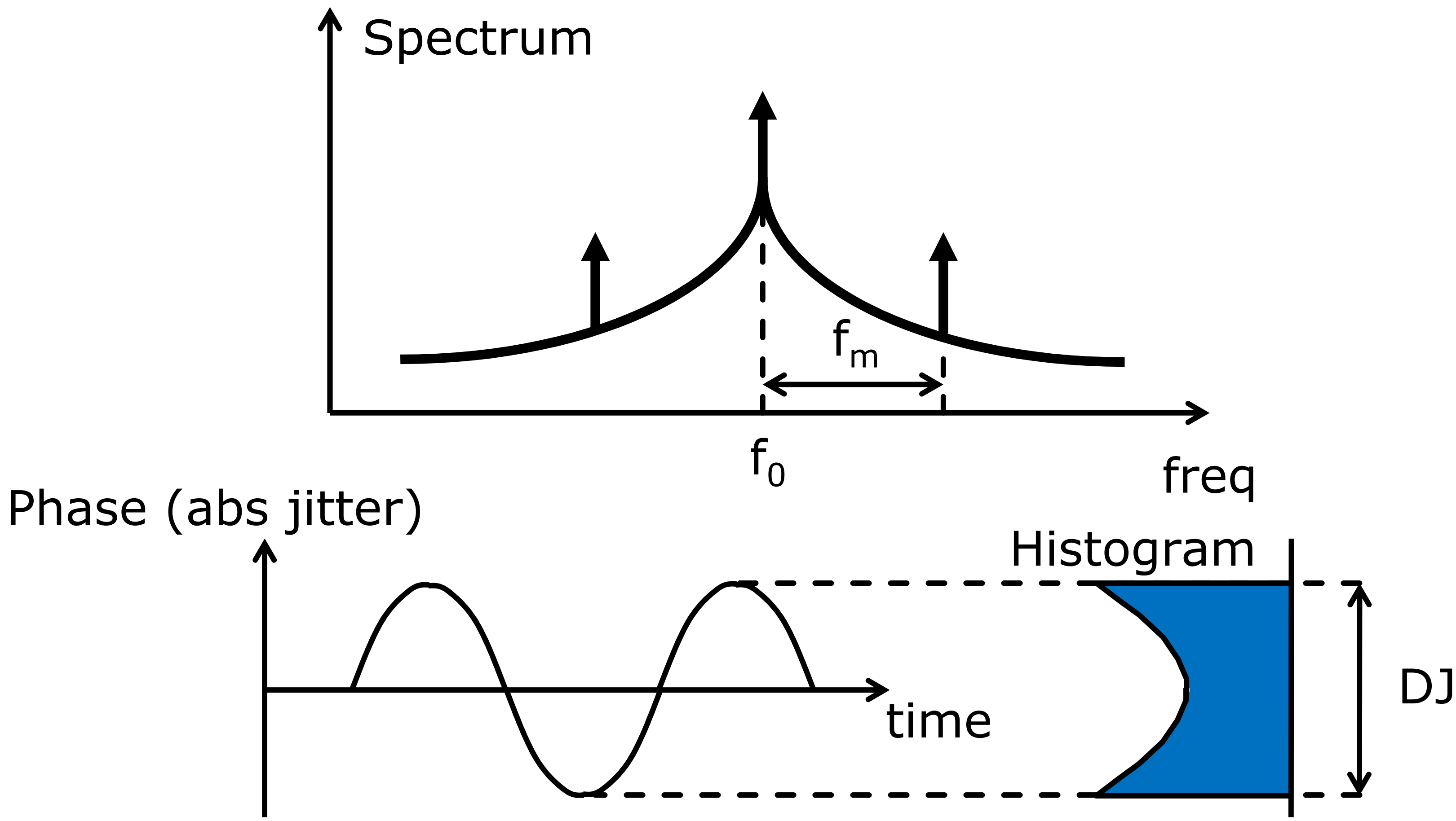
- Bathtub in Q-scale
- "Blue" has closed eye @ 1e-12 (system not working)
- "Red" system has > 30% eye opening @ 1e-12

Spurious Tones in Spectrum (1/4)



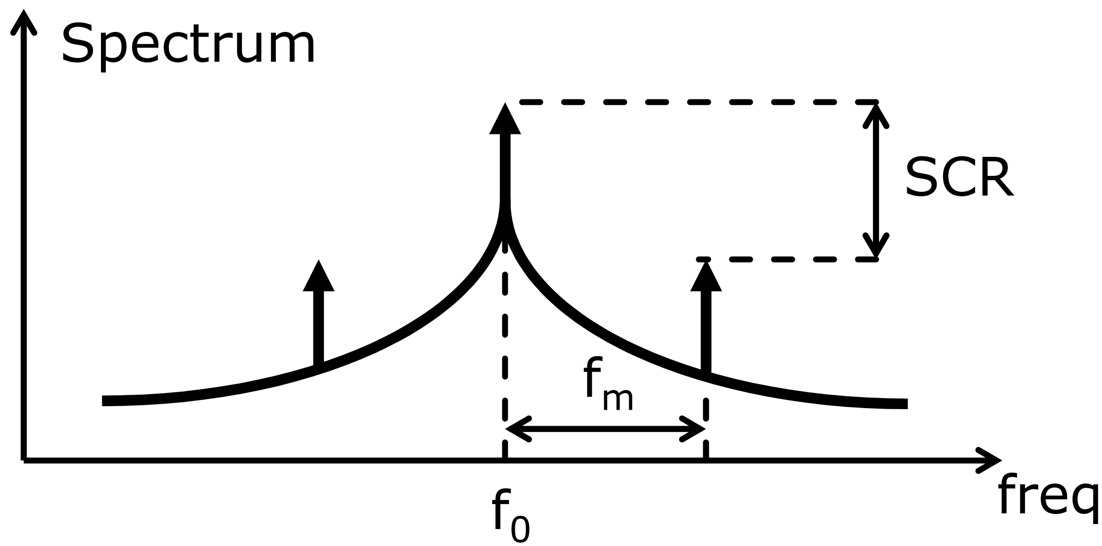
- Spurious tones indicate periodical phase modulation
- Periodic signals can be decomposed in sinusoidal components
- Each sinusoidal component contributes to bounded jitter (DJ)

Spurious Tones in Spectrum (2/4)



- Each sinusoidal component contributes to bounded jitter (DJ)

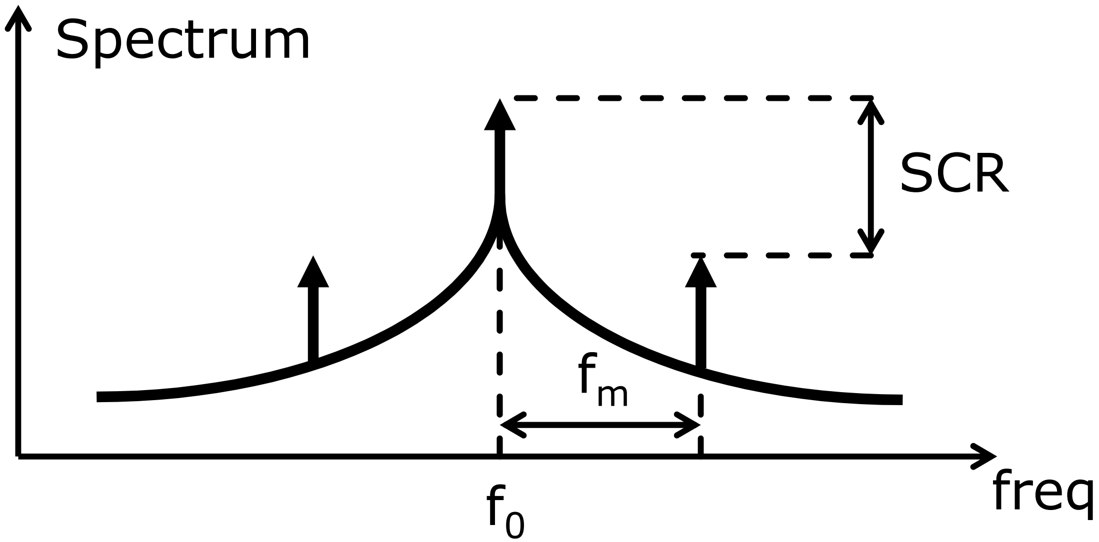
Spurious Tones in Spectrum (3/4)



$$V(t) = V_0 \sin\left(\omega_0 t + A\cdot\sin(\omega_m t)\right) = V_0 \cdot \begin{bmatrix} J_0(A)\sin\left(\omega_0 t\right) - J_1(A)\cos\left((\omega_0 - \omega_m)t\right) + \ldots \\ \ldots + J_1(A)\cos\left((\omega_0 + \omega_m)t\right) + \ldots \end{bmatrix}$$

$$\mathrm{SCR} = 20\log 10\left(\frac{J_1(A)}{J_0(A)}\right) = 20\log 10\left(\frac{A}{2}\right)$$ for small A

Spurious Tones in Spectrum (4/4)



$$\mathrm{DJ[s]} = \frac{2A}{2\pi f_0} = \frac{2}{\pi f_0} 10^{SCR/20}$$

$$\mathrm{DJ[UI]} = \frac{2}{\pi} 10^{SCR/20}$$

SCR [dBc]	DJ [UI]
-10	2.0E-01
-15	1.1E-01
-20	6.4E-02
-25	3.6E-02
-30	2.0E-02
-35	1.1E-02
-40	6.4E-03
-45	3.6E-03
-50	2.0E-03
-55	1.1E-03
-60	6.4E-04
-65	3.6E-04
-70	2.0E-04
-75	1.1E-04
-80	6.4E-05

- DJ depends on SCR and f_0, not on f_m

Summary

- Definition of several Jitter types (Absolute jitter, Period Jitter, Accumulated Jitter)
- Measurement in Time and Frequency Domain
- Phase Noise and relationship to Jitter
- Jitter in typical applications
- Analysis of statistical properties of Jitter for gaussian and non-gaussian distributions
- Jitter decomposition in RJ and DJ
- DJ in High Speed Data Communication (PJ/SJ,DDJ/ISI,DCD,…)
- Tail fitting
- Bathtub plots
- Extrapolation of eye opening @ very low BER

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