ECEN720: High-Speed Links Circuits and Systems Spring 2023

Lecture 10: Jitter

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Announcements

- Lab 6 Report due Apr 3

- Reference Material
  - Jitter application notes posted on website
  - Majority of today’s material from Hall reference

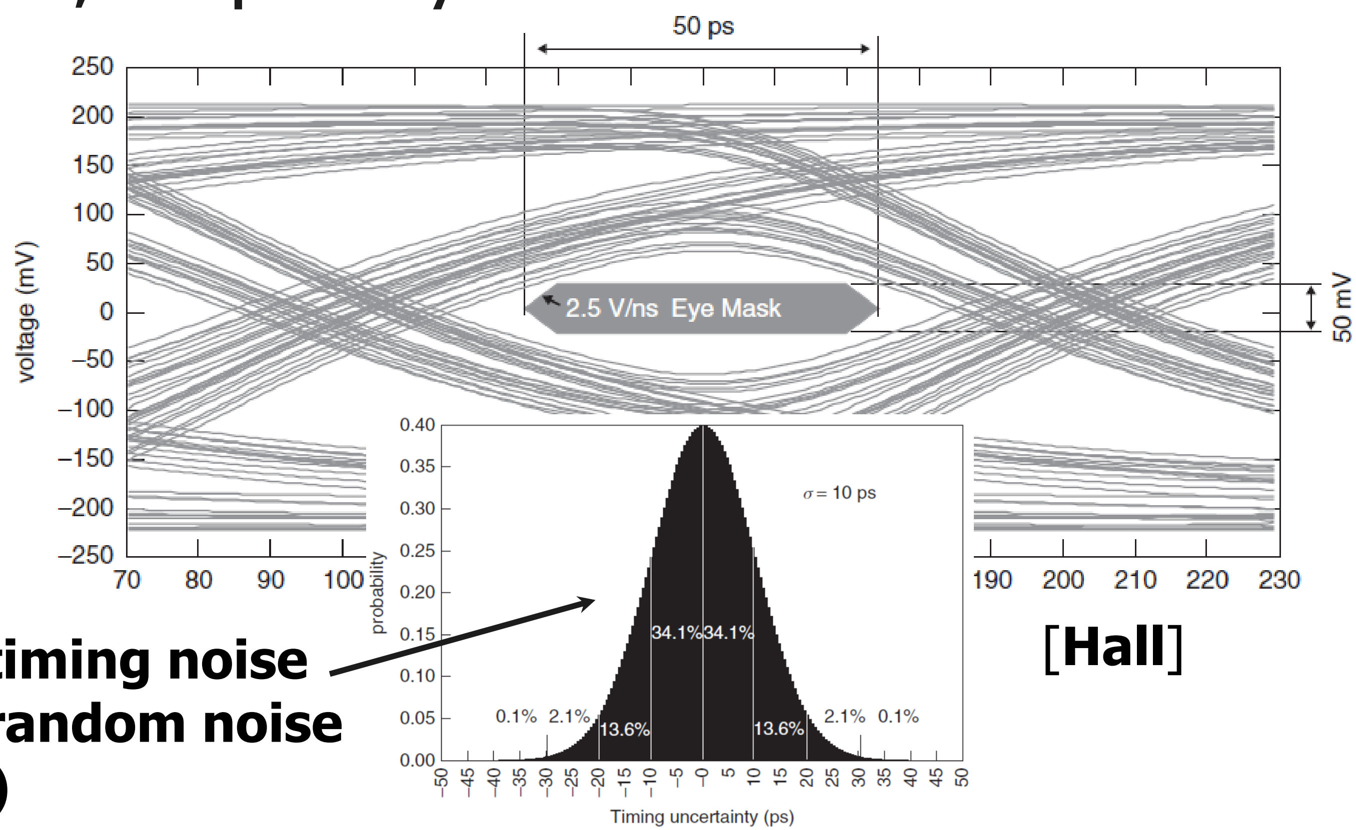
Agenda

- Jitter Definitions
- Jitter Categories
- Dual Dirac Jitter Model
- System Jitter Budgeting

Eye Diagram and Spec Mask

- Links must have margin in both the voltage AND timing domain for proper operation
- For independent design (interoperability) of TX and RX, a spec eye mask is used

Eye at RX sampler



[Hall]

RX clock timing noise or jitter (random noise only here)

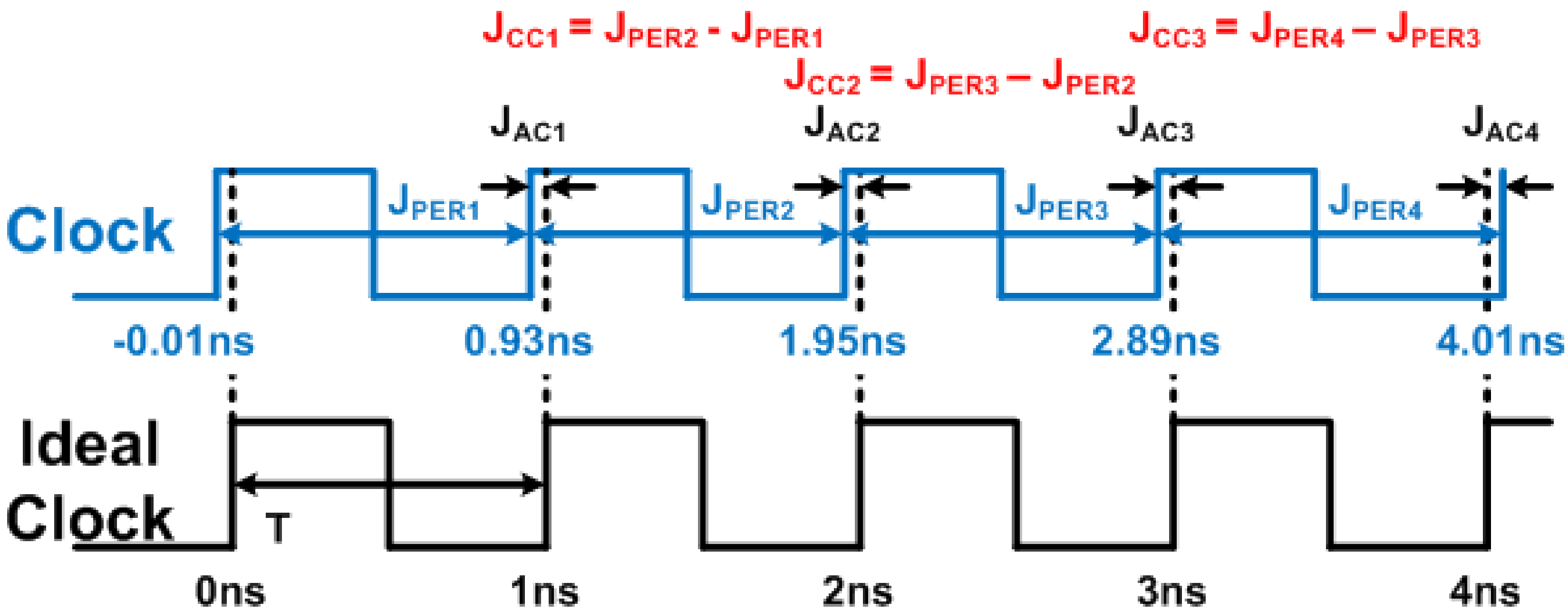
Jitter Definitions

- Jitter can be defined as "the short-term variation of a signal with respect to its ideal position in time"
- Jitter measurements
  - Period Jitter (J_{PER})
    - Time difference between measured period and ideal period
  - Cycle to Cycle Jitter (J_{CC})
    - Time difference between two adjacent clock periods
    - Important for budgeting on-chip digital circuits cycle time
  - Accumulated Jitter (J_{AC})
    - Time difference between measured clock and ideal trigger clock
    - Jitter measurement most relative to high-speed link systems

Jitter Statistical Parameters

- Mean Value
  - Can be interpreted as a fixed timing offset or “skew”
  - Generally not important, as usually can corrected for
- RMS Jitter
  - Useful for characterizing random component of jitter
- Peak-to-Peak Jitter
  - Function of both deterministic (bounded) and random (unbounded) jitter components
  - Must be quoted at a given BER to account for random (unbounded) jitter

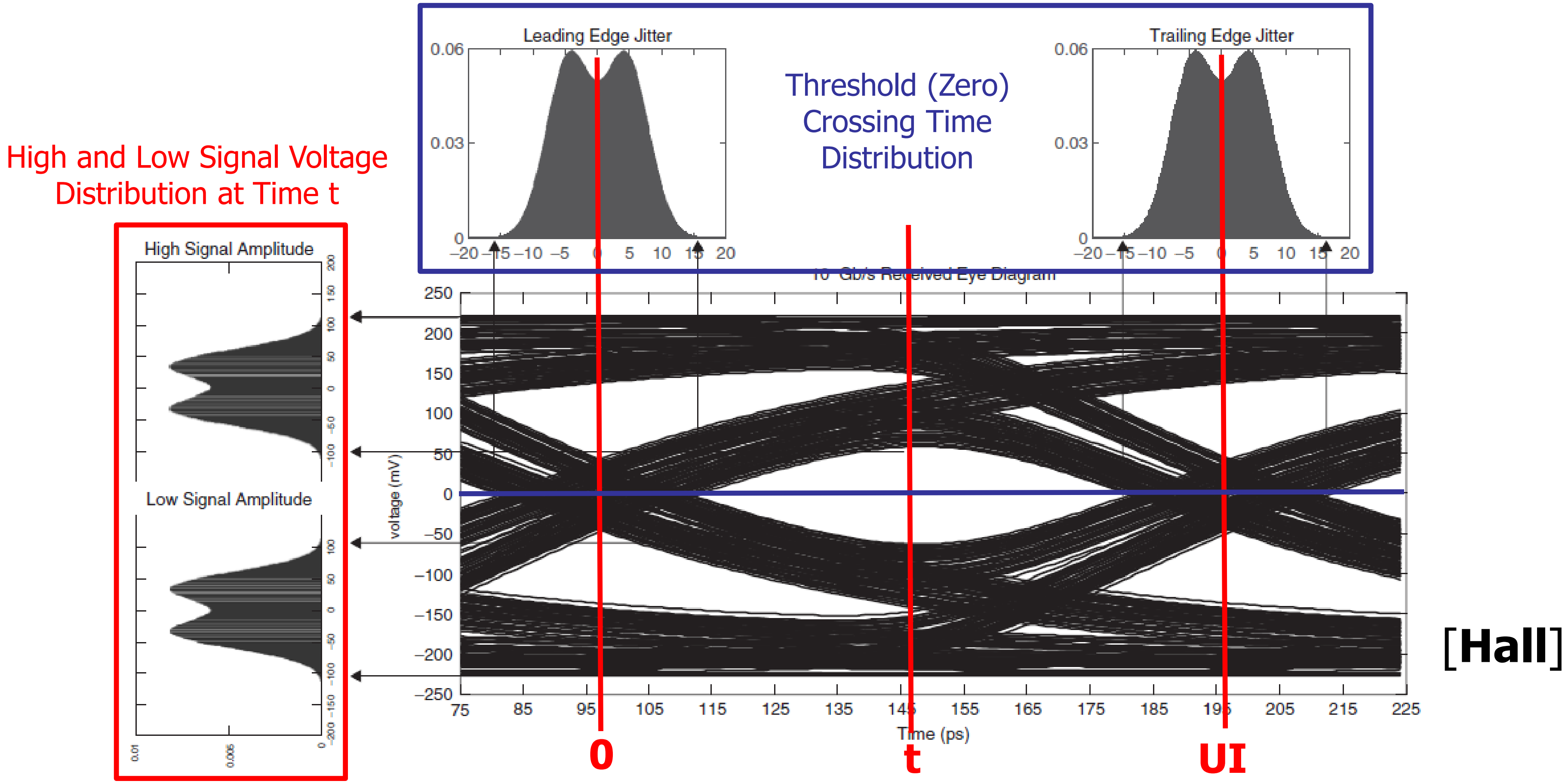
Jitter Calculation Examples



n	1	2	3	4	Mean	RMS	PP
J_{PER}	-0.06	0.02	-0.06	0.12	0.005	0.085	0.18
J_{CC}	0.08	-0.08	0.18	-	0.06	0.131	0.26
J_{AC}	-0.07	-0.05	-0.11	0.01	-0.055	0.05	0.12

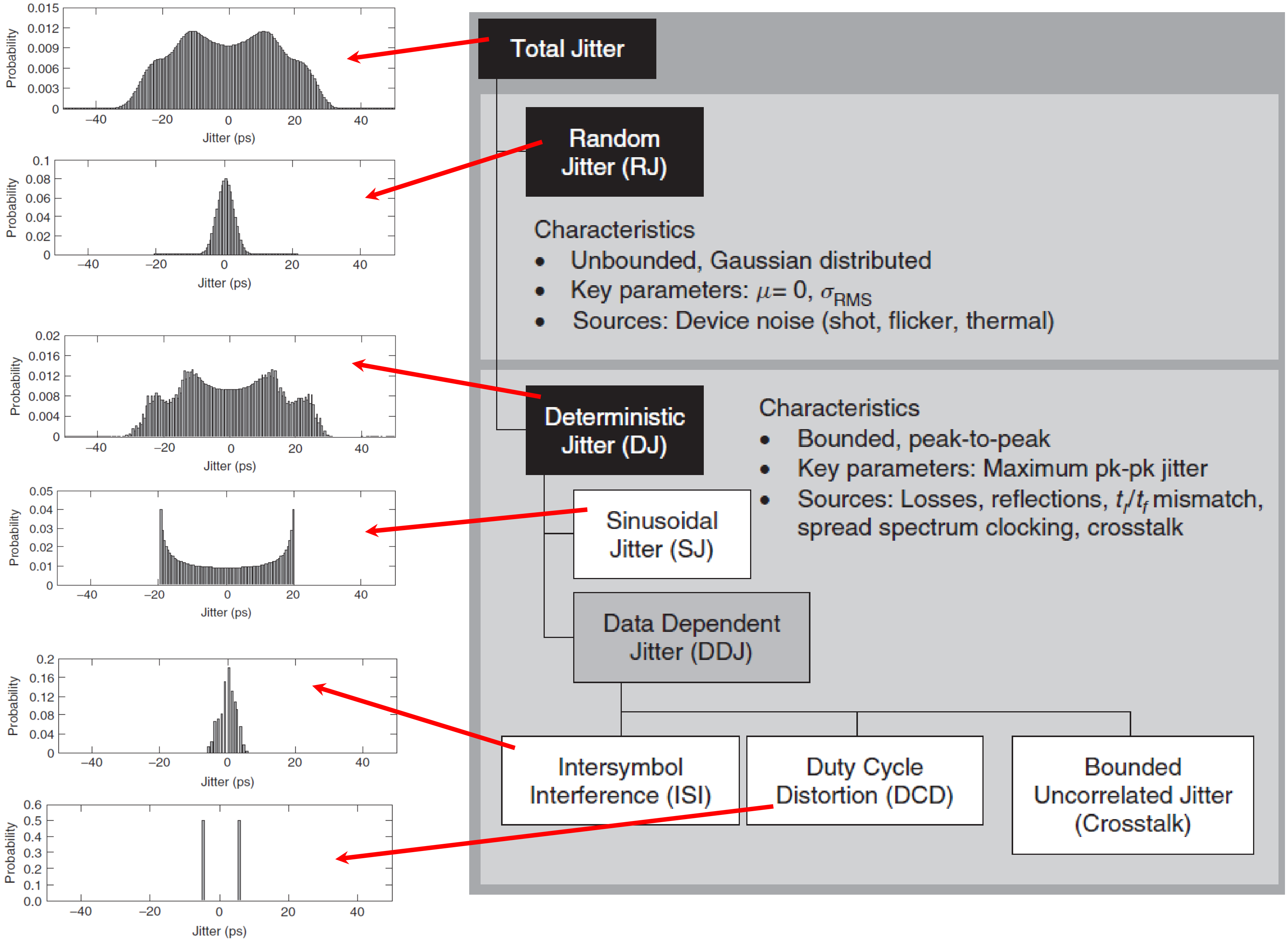
J_{PER} = time difference between measured period and ideal period
J_{CC} = time difference between two adjacent clock periods
J_{AC} = time difference between measured clock and ideal trigger clock

Jitter Histogram



- Used to extract the jitter PDF
- Consists of both deterministic and random components
  - Need to decompose these components to accurately estimate jitter at a given BER

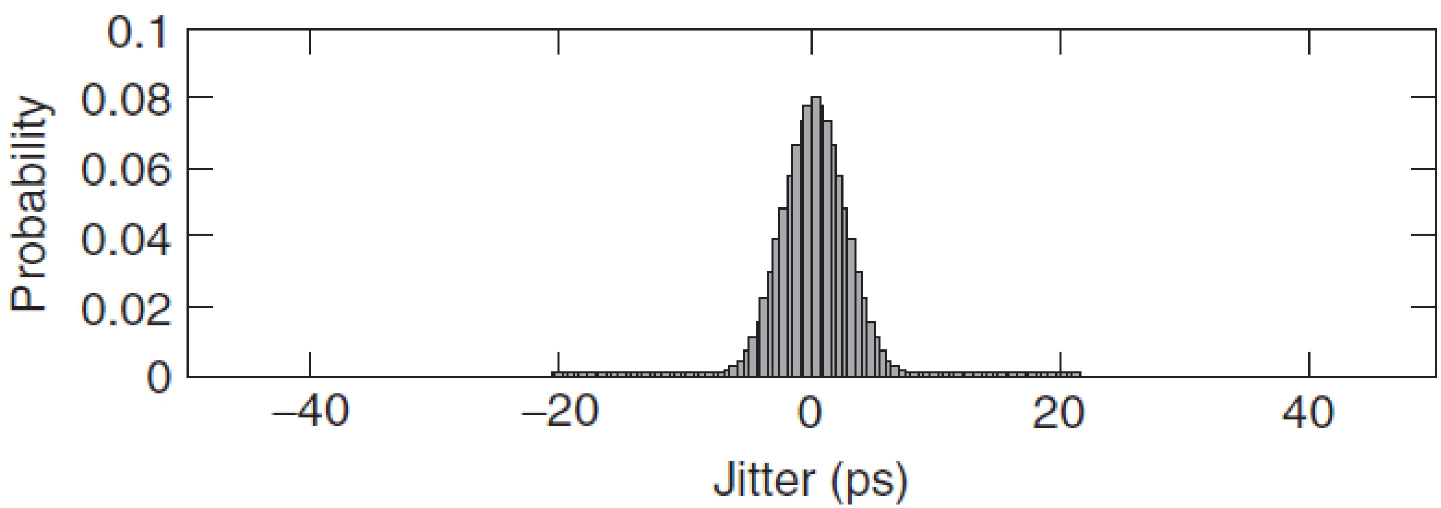
Jitter Categories



Random Jitter (RJ)

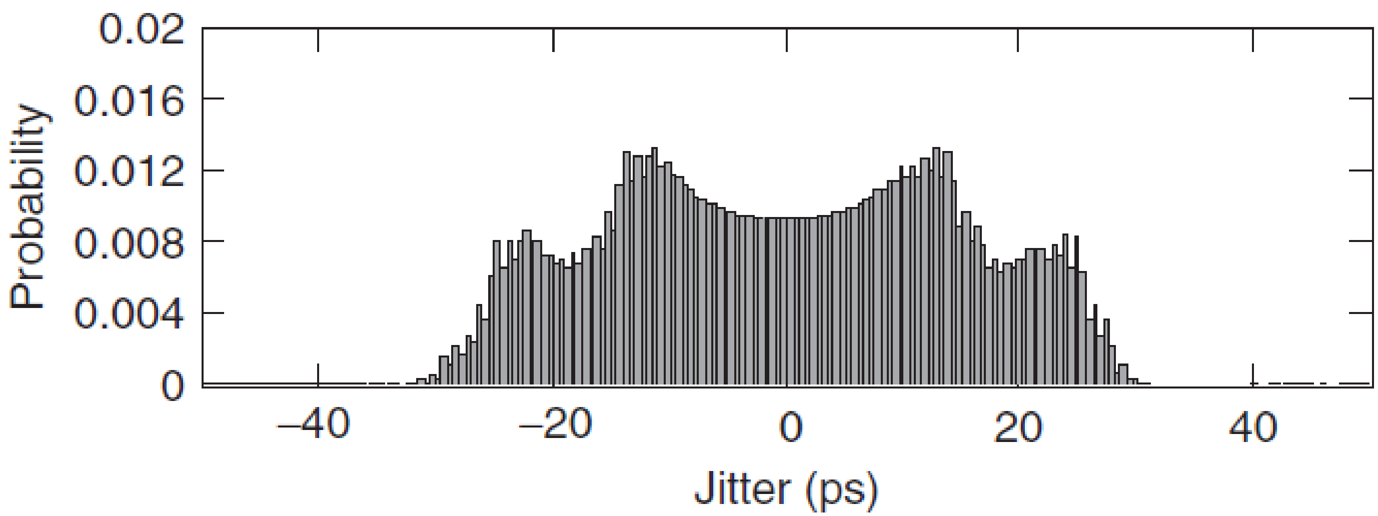
- Unbounded and modeled with a gaussian distribution
  - Assumed to have zero mean value
  - Characterized by the rms value, σ_{RJ}
  - Peak-to-peak value must be quoted at a given BER
- Originates from device noise
  - Thermal, shot, flicker noise

$$RJ(t) = \frac{1}{\sqrt{2\pi}\sigma_{RJ}} e^{\frac{-t^2}{2\sigma_{RJ}^2}}$$



Deterministic Jitter (DJ)

- Bounded with a peak-to-peak value that can be predicted
- Caused by transmission-line losses, duty-cycle distortion, spread-spectrum clocking, crosstalk
- Categories
  - Sinusoidal Jitter (SJ or PJ)
  - Data Dependent Jitter (DDJ)
    - Intersymbol Interference (ISI)
    - Duty Cycle Distortion (DCD)
    - Bounded Uncoirrelated Jitter (BUJ)



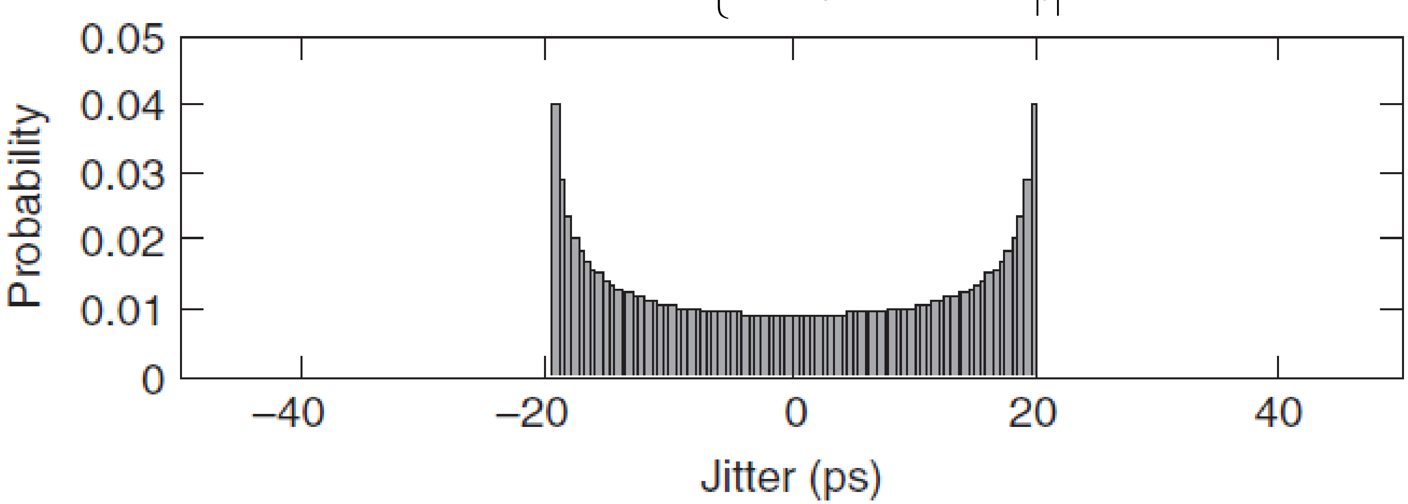
Sinusoidal or Periodic Jitter (SJ or PJ)

- Repeats at a fixed frequency due to modulating effects
  - Spread spectrum clocking
  - PLL reference clock feedthrough
- Can be decomposed into a Fourier series of sinusoids

$$SJ(t) = \sum_i A_i \cos(\omega_i t + \theta_i)$$

- The jitter produced by an individual sinusoid is

$$PDF_{SJ}(t) = \begin{cases} \dfrac{1}{\pi\sqrt{A^2 - t^2}} & A > |t| \\ 0 & A \le |t| \end{cases}$$



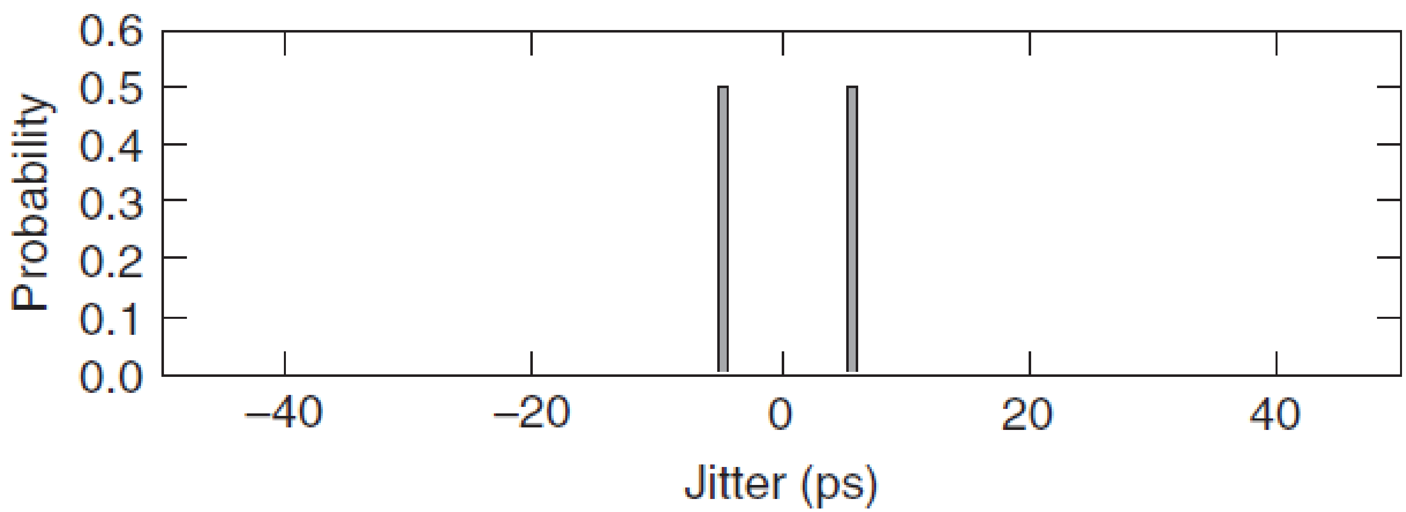
Data Dependent Jitter (DDJ)

- Data dependent jitter is correlated with either the transmitted data pattern or aggressor (crosstalk) data patterns
- Caused by phenomena such as phase errors in serialization clocks, channel filtering, and crosstalk
- Categories
  - Duty Cycle Distortion (DCD)
  - Intersymbol Interference (ISI)
  - Bounded Uncorrelated Jitter (BUJ)

Duty Cycle Distortion (DCD)

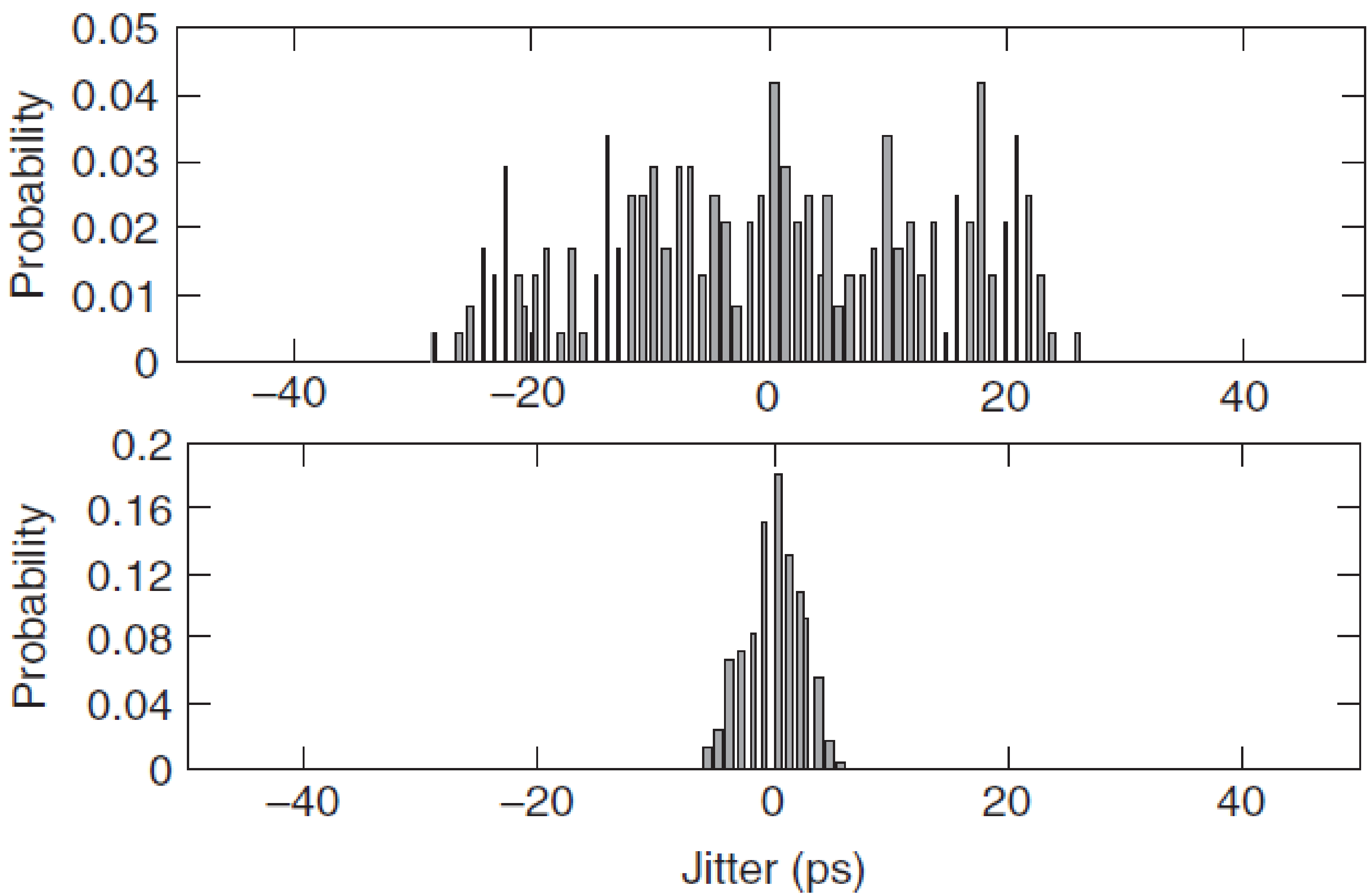
- Caused by duty cycle errors in TX serialization clocks and rise/fall delay mismatches in post-serialization buffers
- Resultant PDF from a peak-to-peak duty cycle distortion (α_{DCD}) is the sum of two delta functions

$$PDF_{DCD}(t) = \frac{1}{2}\left[\delta\left(t - \frac{\alpha_{DCD}}{2}\right) + \delta\left(t + \frac{\alpha_{DCD}}{2}\right)\right]$$



Intersymbol Interference (ISI)

- Caused by channel loss, dispersion, and reflections
- Equalization can improve ISI jitter



No Equalization

2-tap
TX Equalization

Bounded Uncorrelated Jitter (BUJ)

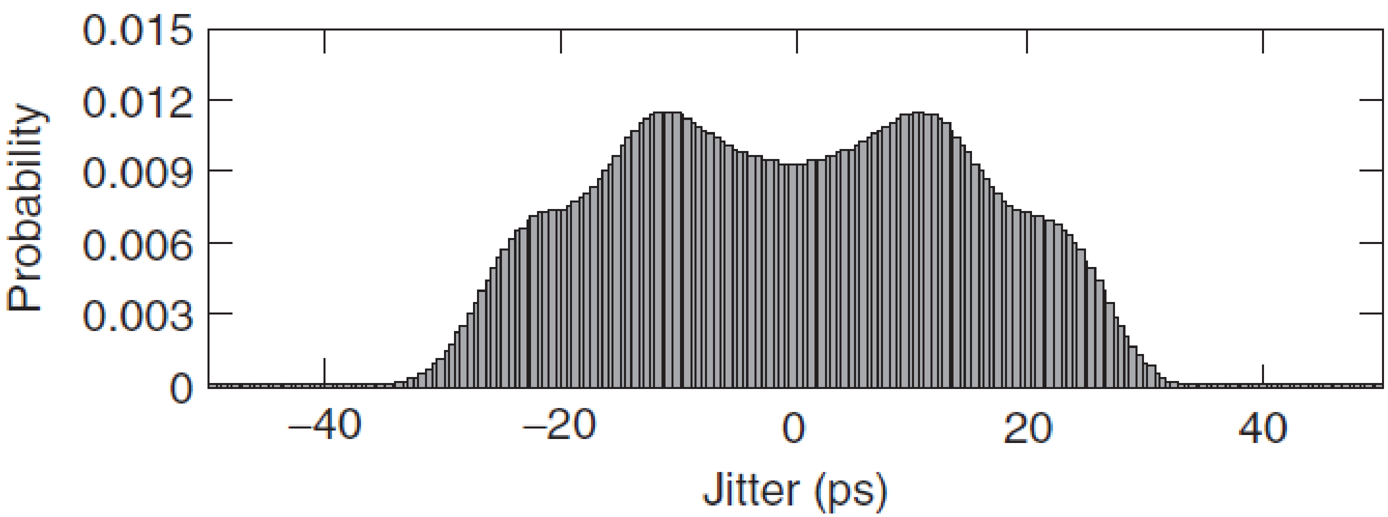
- Not aligned in time with the data stream
- Most common source is crosstalk
- Classified as uncorrelated due to being correlated to the aggressor signals and not the victim signal or data stream
- While uncorrelated, still a bounded source with a quantifiable peak-to-peak value

Total Jitter (TJ)

- The total jitter PDF is produced by convolving the random and deterministic jitter PDFs

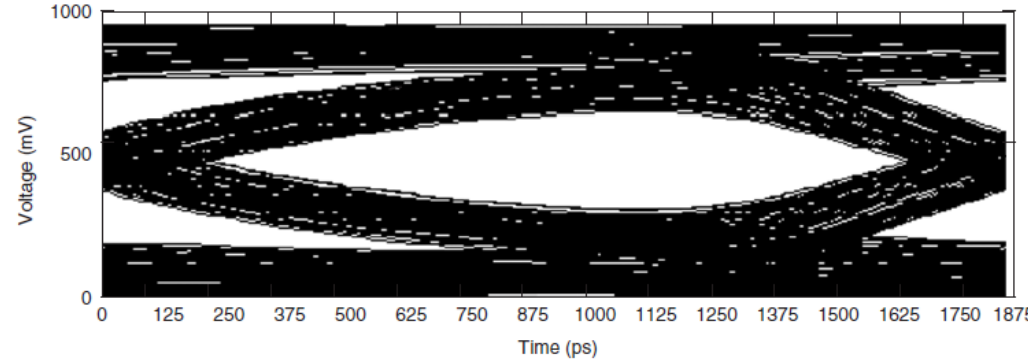
$$PDF_{JT}(t) = PDF_{RJ}(t) * PDF_{DJ}(t)$$

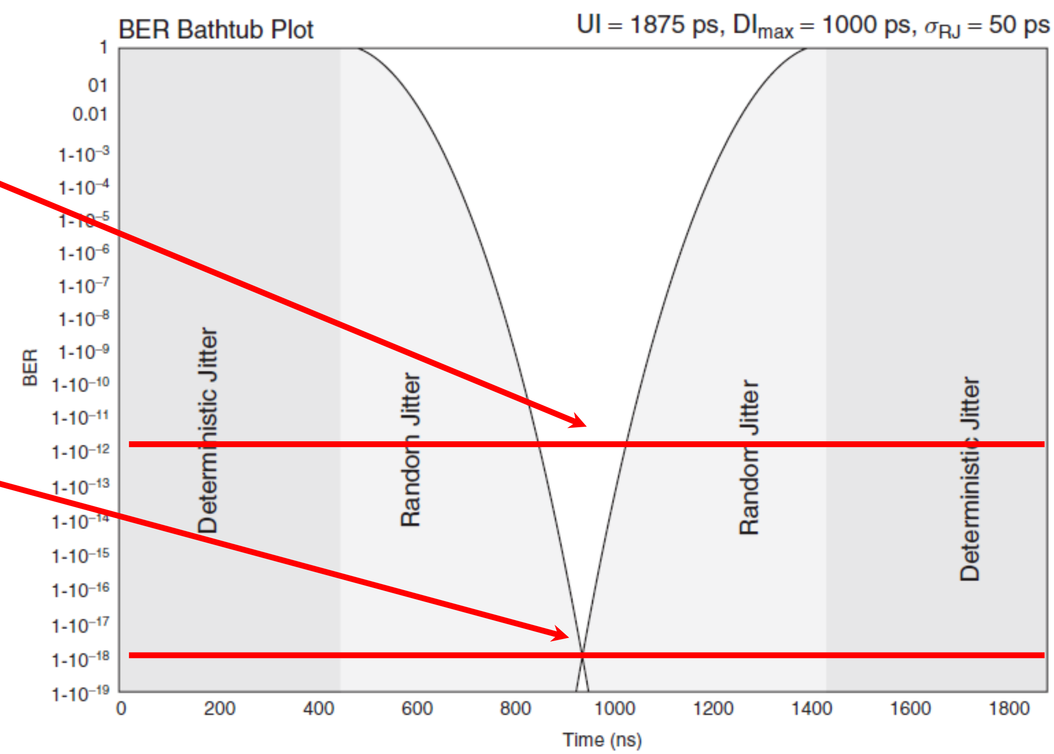
where $PDF_{DJ}(t) = PDF_{SJ}(t) * PDF_{DCD}(t) * PDF_{ISI}(t) * PDF_{BUJ}(t)$



Jitter and Bit Error Rate

- Jitter consists of both deterministic and **random** components
- Total jitter must be quoted at a given BER
  - At BER=10^{-12}, jitter ~1675ps and eye width margin ~200ps
  - System can potentially achieve BER=10^{-18} before being jitter limited





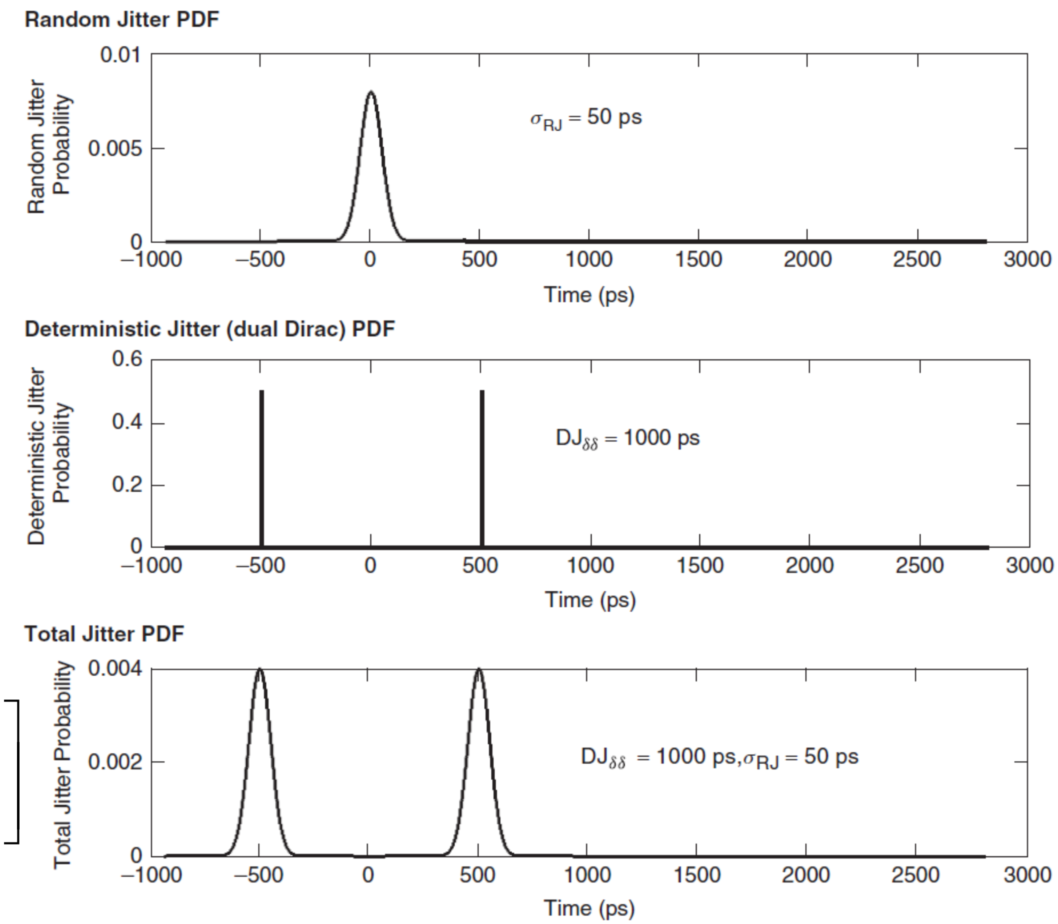
Dual Dirac Jitter Model

- For system-level jitter budgets, the dual Dirac model approximates the complex total jitter PDF and allows for the budgeting of deterministic and random jitter components

$$RJ(t) = \frac{1}{\sqrt{2\pi}\sigma_{RJ}} e^{\frac{-t^2}{2\sigma_{RJ}^2}}$$

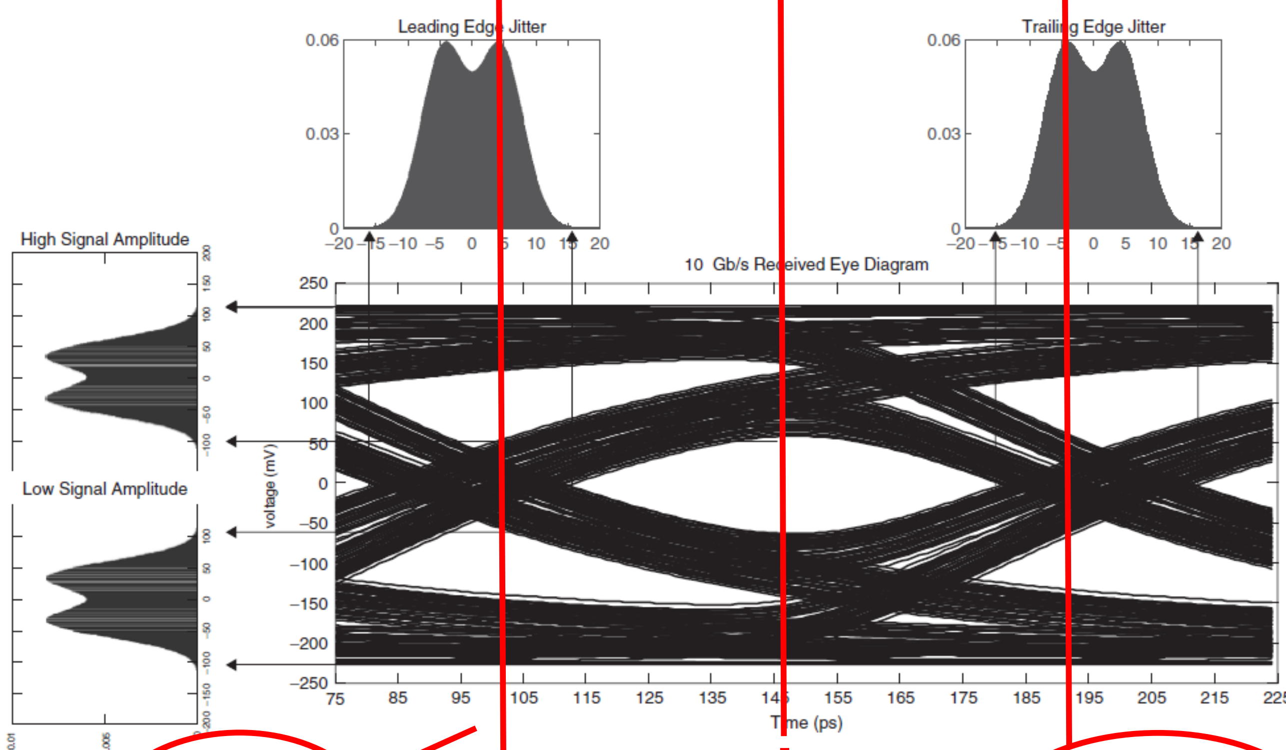
$$DJ(t) = \frac{\delta(t - DJ_{\delta\delta}/2)}{2} + \frac{\delta(t + DJ_{\delta\delta}/2)}{2}$$

$$JT(t) = RJ(t) * DJ(t) = \frac{1}{2\sqrt{2\pi}\sigma_{RJ}} \left[e^{-\frac{t - DJ_{\delta\delta}/2}{2\sigma_{RJ}^2}} + e^{-\frac{t + DJ_{\delta\delta}/2}{2\sigma_{RJ}^2}} \right]$$



Dual Dirac Jitter Model

- Jitter at a given BER is computed considering both leading and trailing edges



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Dominant Terms

$$BER_{lead}(t) = 0.5\left[erfc\left(\frac{t - DJ_{\delta\delta}/2}{\sqrt{2}\sigma_{RJ}}\right) + erfc\left(\frac{t + DJ_{\delta\delta}/2}{\sqrt{2}\sigma_{RJ}}\right)\right], \quad BER_{trail}(t) = 0.5\left[erfc\left(\frac{UI - t - DJ_{\delta\delta}/2}{\sqrt{2}\sigma_{RJ}}\right) + erfc\left(\frac{UI - t + DJ_{\delta\delta}/2}{\sqrt{2}\sigma_{RJ}}\right)\right]$$

$$\textbf{where } erfc(t) = \frac{2}{\sqrt{\pi}}\int_t^{\infty} e^{-x^2}\,dx$$

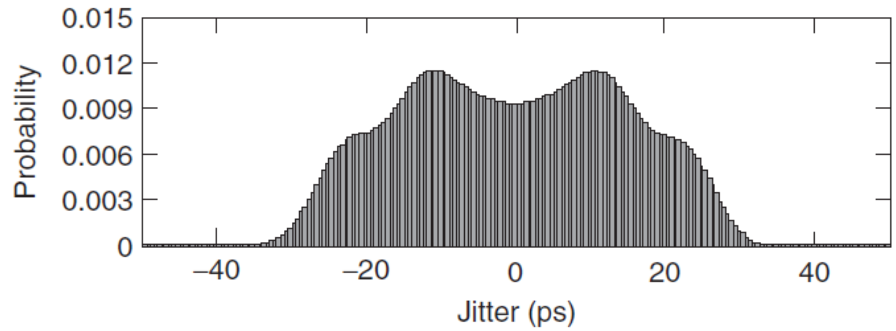
Dual Dirac Jitter Model Example

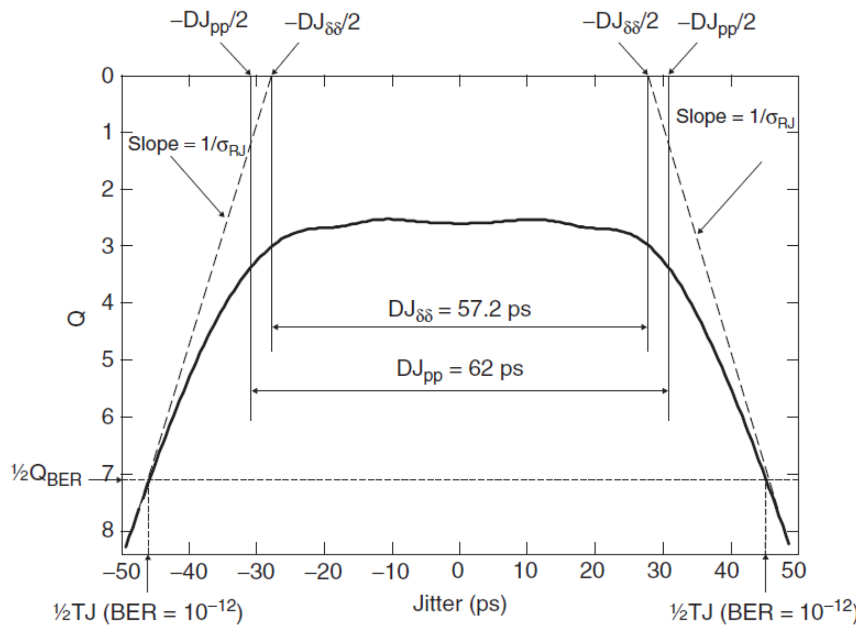
- Plot measured jitter PDF vs Q-scale

$$Q_{BER}(BER) = \sqrt{2}erf^{-1}\left(1 - \frac{BER}{\rho_T}\right)$$

where ρ_T is the transition density, typically 0.5

- Tails are used to extract σ_{RJ}
- Extrapolate to Q(0) to extract separation of dual-Dirac delta functions

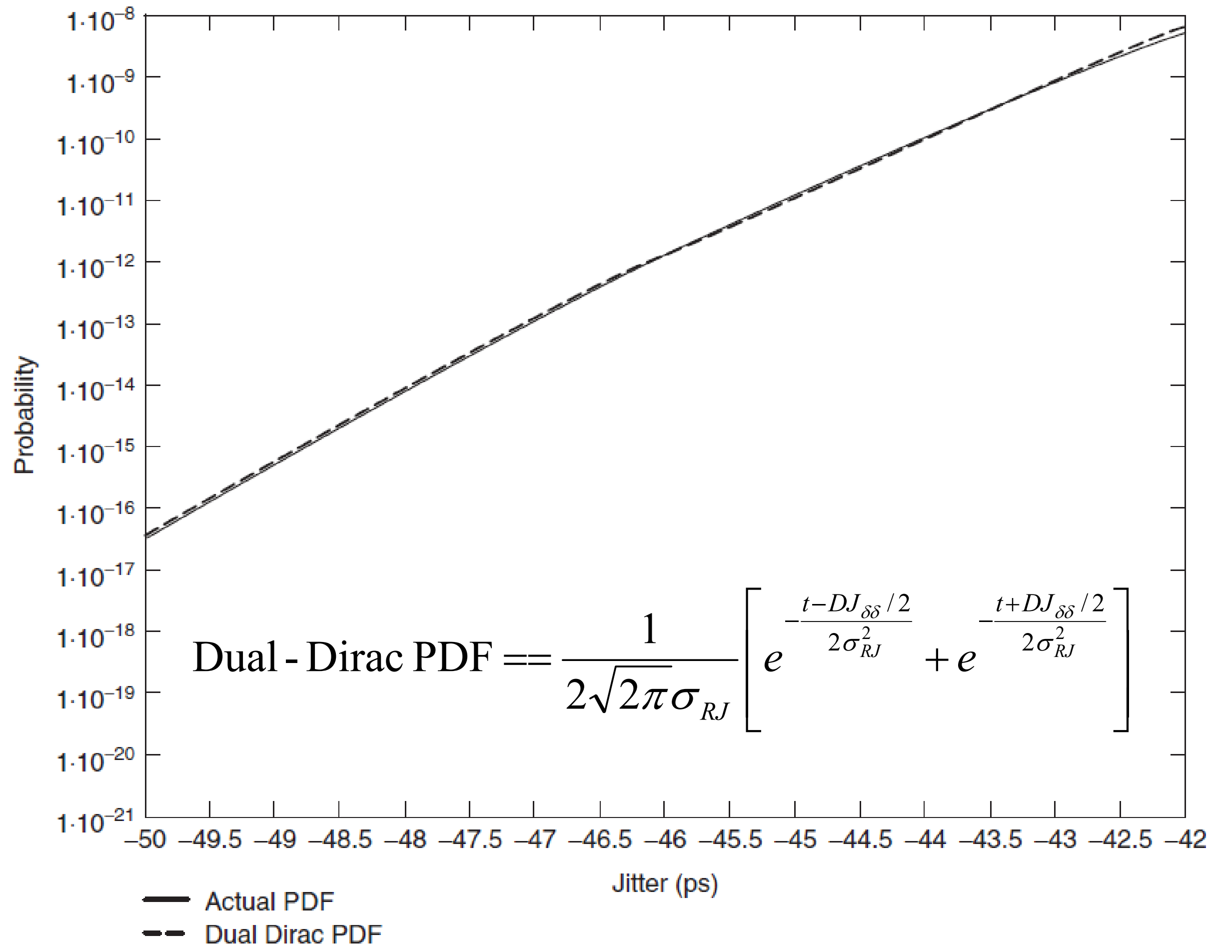




$DJ_{\delta\delta}$ = Extracted seperation of dual - Dirac delta functions

DJ_{pp} = Actual deterministic jitter peak - to - peak value

Dual Dirac Jitter Model Example



- Extracted dual Dirac model matches well with measured jitter PDF

System Jitter Budget

- For a system to achieve a minimum BER performance

$$UI \geq DJ_{\delta\delta}(sys) + Q_{BER}\sigma_{RMS}(sys)$$

- The convolution of the individual deterministic jitter components is approximated by linear addition of the terms

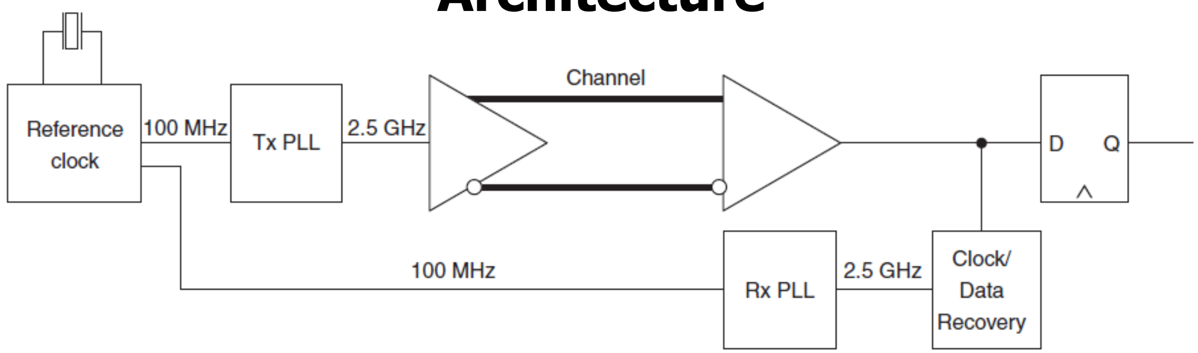
$$DJ_{\delta\delta}(sys) = \sum_i DJ_{\delta\delta}(i)$$

- The convolution of the individual random jitter components results in a root-sum-of-squares system rms value

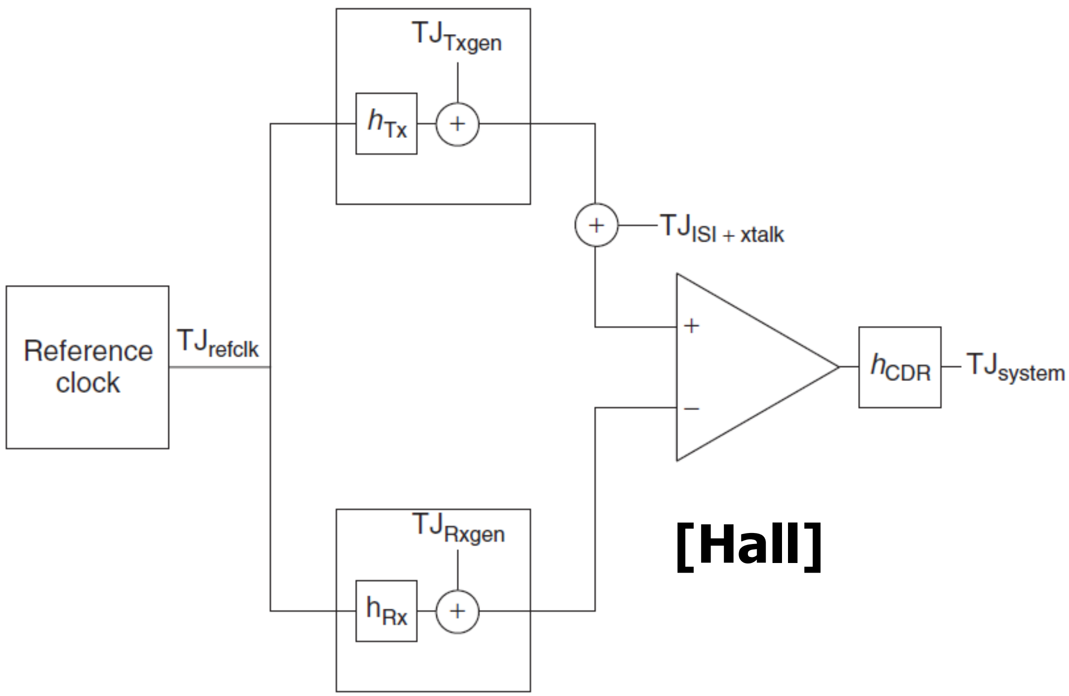
$$\sigma_{RMS}(sys) = \sqrt{\sum_i \sigma_{RMS}^2(i)}$$

Jitter Budget Example – PCI Express System

Architecture



Jitter Model



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Jitter Budget Example – PCI Express System

$$DJ_{\delta\delta}(sys) = DJ_{\delta\delta}(TX) + DJ_{\delta\delta}(channel) + DJ_{\delta\delta}(RX) + DJ_{\delta\delta}(clock)$$

$$\sigma_{RMS}(sys) = \sqrt{\sigma_{RMS}^2(TX) + \sigma_{RMS}^2(channel) + \sigma_{RMS}^2(RX) + \sigma_{RMS}^2(clock)}$$

TABLE 13-2. PCI Express 2.5-Gb/s Jitter Budget at 10^{-12} BER

Component	Term	σ_{RJ} (ps)	$DJ_{\delta\delta}$ (ps)	TJ (ps)
Reference clock	TJ_{clock}	4.7	41.9	108
Transmitter	TJ_{TX}	2.8	60.6	100
Channel	$TJ_{channel}$	0	90	90
Receiver	TJ_{Rx}	2.8	120.6	~~147~~ → 160
Linear TJ				458
RSS TJ		6.15 * 14.069 = 86.5	313.1	399.6

[Hall]

TABLE 13-1. Q_{BER} as a Function of the Bit Error Rate

BER	Q_{BER}	BER	Q_{BER}	BER	Q_{BER}
1×10^{-3}	6.180	1×10^{-10}	12.723	1×10^{-17}	16.987
1×10^{-4}	7.438	1×10^{-11}	13.412	1×10^{-18}	17.514
1×10^{-5}	8.530	1×10^{-12}	14.069	1×10^{-19}	18.026
1×10^{-6}	9.507	1×10^{-13}	14.698	1×10^{-20}	18.524
1×10^{-7}	10.399	1×10^{-14}	15.301	1×10^{-21}	19.010
1×10^{-8}	11.224	1×10^{-15}	15.882	1×10^{-22}	19.484
1×10^{-9}	11.996	1×10^{-16}	16.444	7.7×10^{-24}	20.000

Next Time

- Clocking Architectures