jitter 360° / Jitter from Every Angle

Part 1: The Meaning of Total Jitter

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Jitter 360° / Jitter from Every Angle

Series Topics

1. The Meaning of Total Jitter ←
2. What the Dual-Dirac Model is and What it is Not
3. All About the Acronyms: RJ, DJ, DDJ, ISI, DCD, PJ, SJ,…
4. Jitter Analysis in Systems with Crosstalk
5. Clock Recovery in Serial-Data Systems
6. Reference Clock Jitter and Data Jitter

Introduction

In analyzing jitter we need…

1. A way to assure interoperability at some Bit Error Ratio
   – The reason for Total Jitter at a Bit Error Ratio

     TJ(BER)

2. Diagnostic information
   – Where is the jitter coming from and what can I do about it?
     – Assuring interoperability and performing diagnostics are not independent.

In this paper we explore TJ(BER), where it came from, what it's for, how its measured and how it can be estimated quickly and accurately.

In Search of Peak-to-Peak Jitter

Needed:

A quantity that links jitter to BER and is easily measured.

- The naïve solution, peak-to-peak jitter, doesn't work.
  - Peak-to-peak jitter measurements are not reproducible
    The longer it is measured the bigger it gets
  - Peak-to-peak jitter doesn't link jitter directly to BER

- To relate BER and jitter it's useful to distinguish jitter components that are unbounded from those that are bounded

In Search of Peak-to-Peak Jitter (2)

- Deterministic Jitter – DJ

  Is caused by predictable sources
  - Impedance mismatches
  - Electromagnetic interference
  - Filtering effects of transmission lines
  - …

  Can only shift the timing of a logic transition by a maximum amount ➔ bounded

Peak-to-peak DJ is well defined, call it DJ(p-p)

In Search of Peak-to-Peak Jitter (3)

- Random Jitter – RJ Is caused by huge number of small effects
  - Thermal oscillations
  - Flicker
  - Shot-noise
  - Variations in trace width on a printed circuit board
  - Fluctuations of conductivity caused by impurities
  - …
- The Central Limit Theorem makes it easy:

  "A large number of independent processes combine in such a way the result follows a Gaussian distribution"

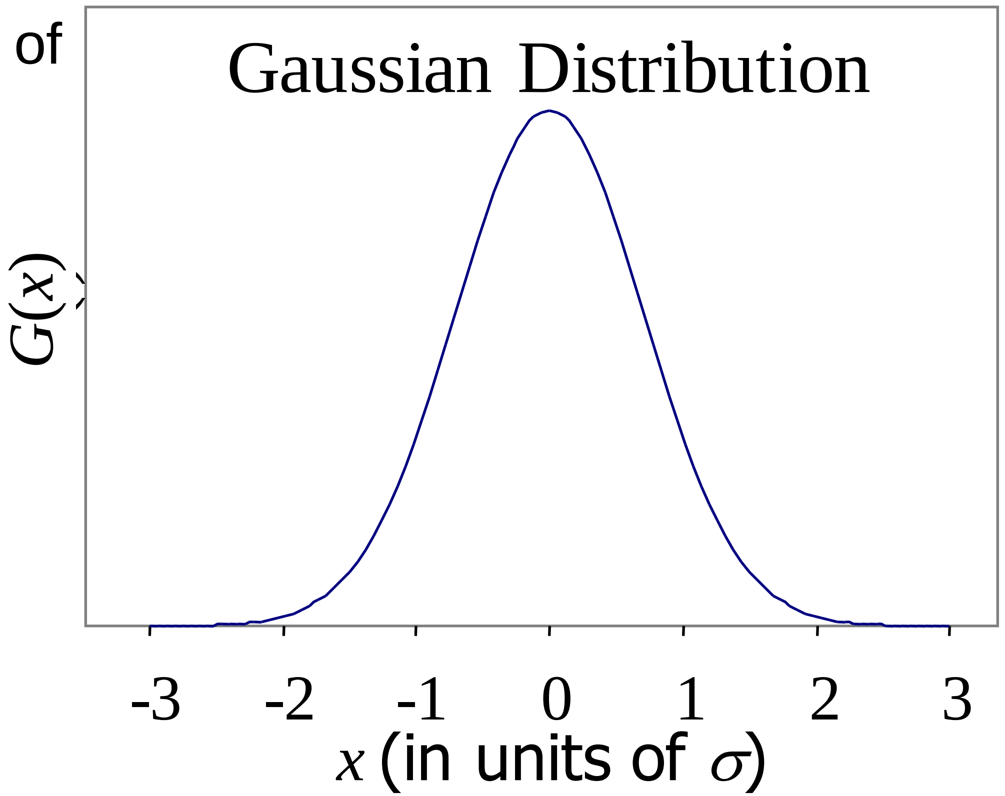
In Search of Peak-to-Peak Jitter (4)

- RJ follows a Gaussian Distribution

  Let x be the time-delay relative to the ideal time of a logic transition, then

$$G(x) = N \exp\left(-\frac{x^2}{2\sigma^2}\right)$$

  ➔ unbounded



A Gaussian is described by σ, the rms value of the RJ distribution,

  Define $\mathrm{RJ} = \sigma$

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TJ(BER) – Total Jitter at a Bit Error Ratio

Consider a peak-to-peak jitter measurement of a system whose BER is exactly 10^{-12}

- After about 10^{12} bits are transmitted the eye should be closed
  - Random fluctuations make it an unreliable measurement but it does tell us something about BER

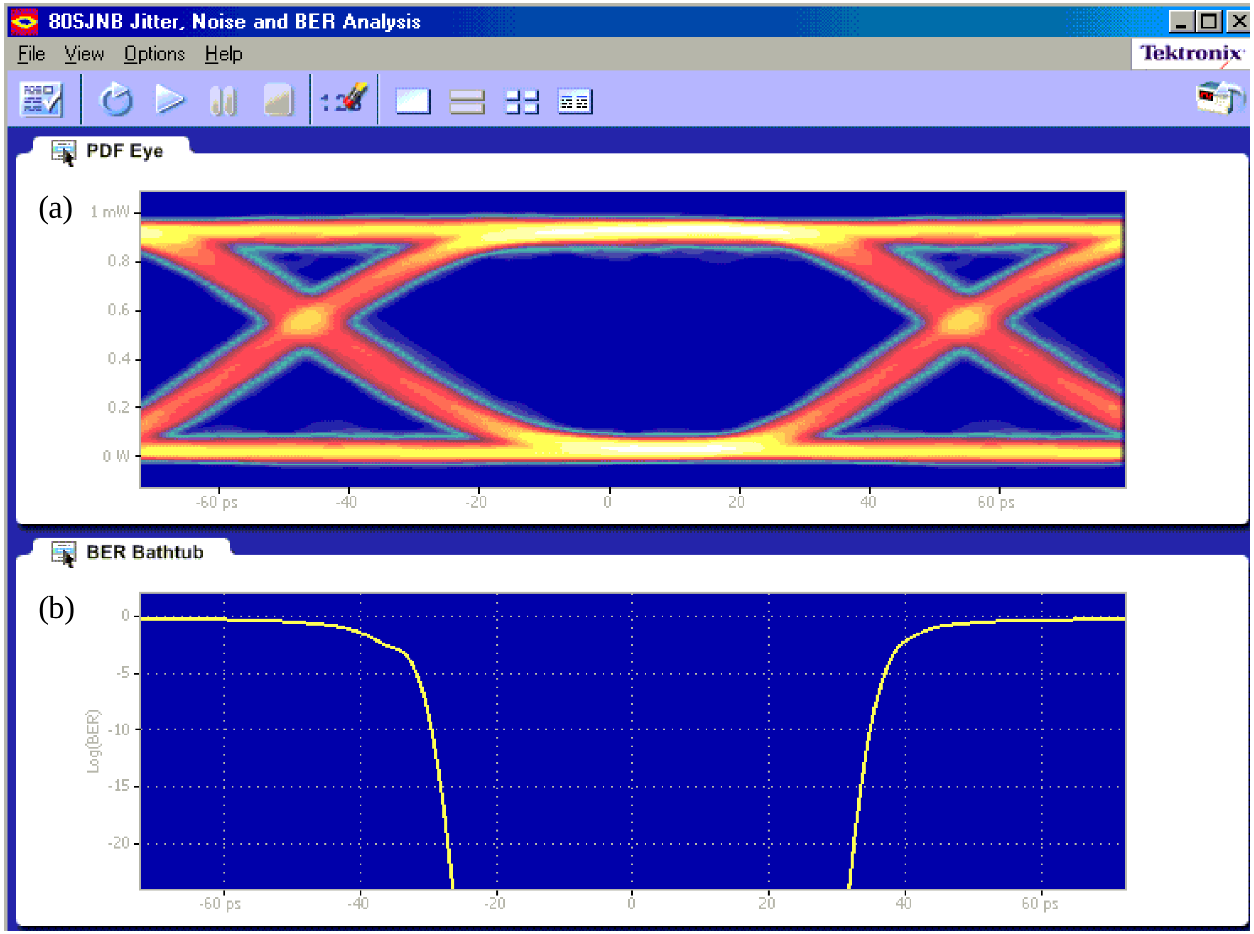
TJ(BER) relates the level of jitter directly to BER

- TJ(BER) is well defined
- Measurements of TJ(BER) are reproducible

In the example, $\mathrm{TJ}(10^{-12}) = T_B$

TJ(BER) – Total Jitter at a Bit Error Ratio (2)

- Eye diagram
- Corresponding "Bathtub Plot"
  - BER(*x*)



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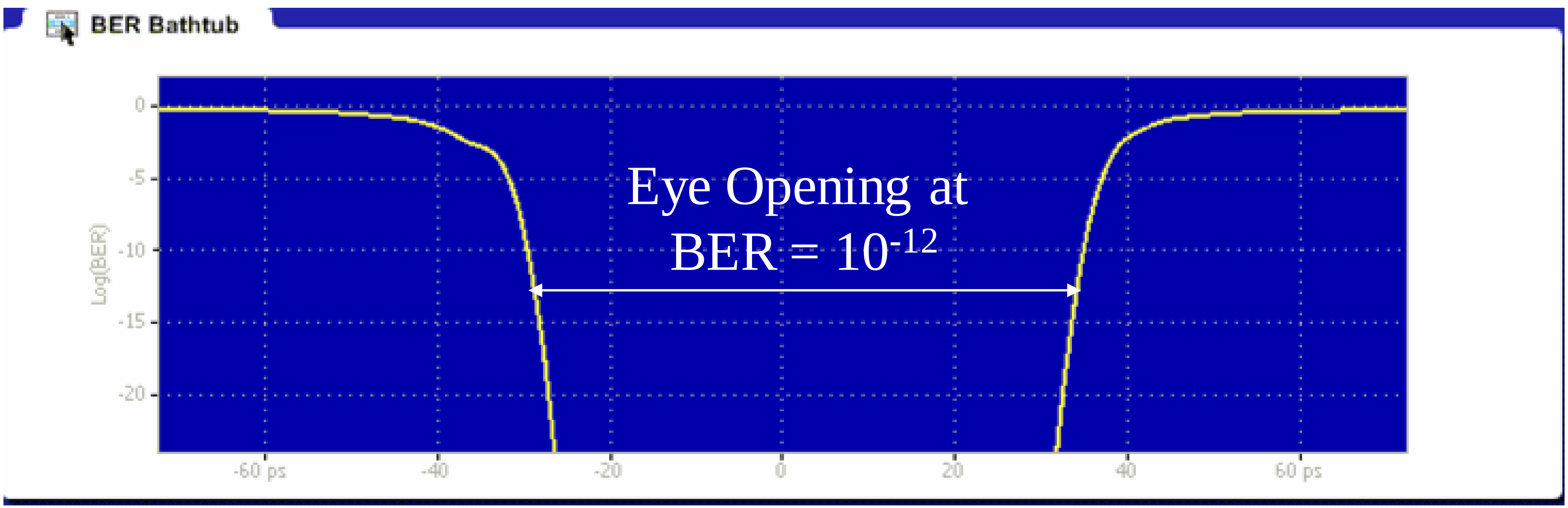
TJ(BER) – Total Jitter at a Bit Error Ratio (3)

- TJ(BER) is the total eye closure at a BER:

$$\text{TJ(BER)} = T_B - \text{eye opening (BER)}$$



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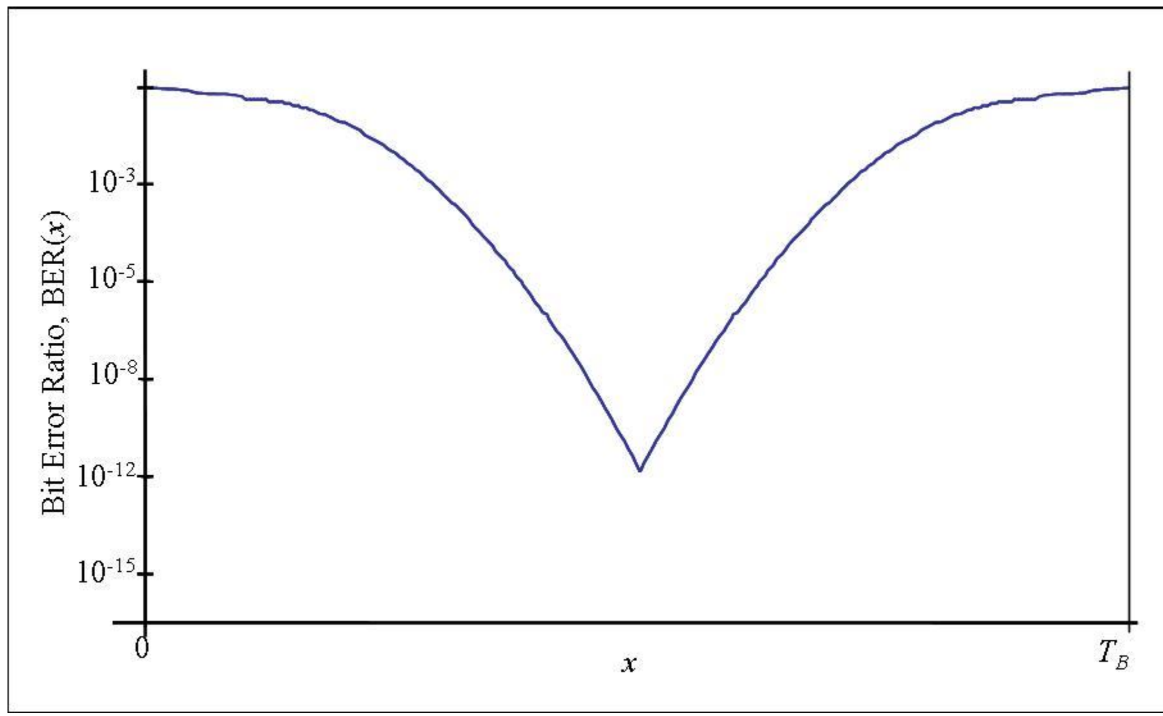
TJ(BER) – Total Jitter at a Bit Error Ratio (4)

The BER of this system is exactly 10^{-12}

- What is TJ(10^{-12})?
- What is TJ(10^{-18})?



TJ(BER) – Total Jitter at a Bit Error Ratio (5)

TJ(BER<10^{-8}) can only be *measured* on a Bit Error Ratio Tester

- Brute force measurement of BER(x) takes hours for BER=10^{-12} at 5 Gb/s
- Bracketing TJ(BER) takes about 30 minutes for BER=10^{-12} at 5 Gb/s

- Must sample at least 6/BER bits

  Can't measure the rate of a process without a statistical sample sufficient to observe the event

TJ(BER) – Total Jitter at a Bit Error Ratio (6)

- Time-base of modern BERTs are quite accurate, thus the largest uncertainty is from the BERT error detector sensitivity
  - between 20 and 50 mV, depending on the BERT
  - Much larger than voltage resolution/accuracy of an oscilloscope
- TJ(BER<10^{-8}) can only be *measured* on a BERT, but *estimates* on an oscilloscope can be more accurate

RJ and DJ

- There are two ways to estimate TJ(BER) without the 6/BER statistical requirement

1. Separate and measure the distributions of the jitter components, including RJ and all types of DJ
   – Convolve into a complete jitter PDF
   – Calculate BER(x) and extract TJ(BER)

   Only possible on simple jitter distributions

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RJ and DJ (2)

- There are two ways to estimate TJ(BER) without the 6/BER statistical requirement

2. Use the Dual-Dirac model
   - Measure RJ, σ, and a model-dependent form of DJ, DJ($\delta\delta$)
   - And use:

$$\mathrm{TJ(BER)} = 2Q_{BER} \times \mathrm{RJ} + \mathrm{DJ}(\delta\delta)$$

RJ and DJ (3)

In the Dual-Dirac model, DJ closes the eye a fixed amount, DJ($\delta\delta$), and the Gaussian RJ tails close it an amount that depends on the BER of interest.

$$\mathrm{TJ(BER)} = 2Q_{BER} \times \mathrm{RJ} + \mathrm{DJ}(\delta\delta)$$

- Q_{BER} relates the BER to the distance from the center of the RJ Gaussian
- DJ($\delta\delta$) Is easy to measure in many different ways

BER	Q_{BER}
10^{-10}	6.35
10^{-11}	6.70
10^{-12}	7.05
10^{-13}	7.35
10^{-14}	7.65

RJ and DJ (4)

In *any* estimate of TJ(BER) we must **assume**:

There are no rare processes whose observation would require a huge statistical sample.

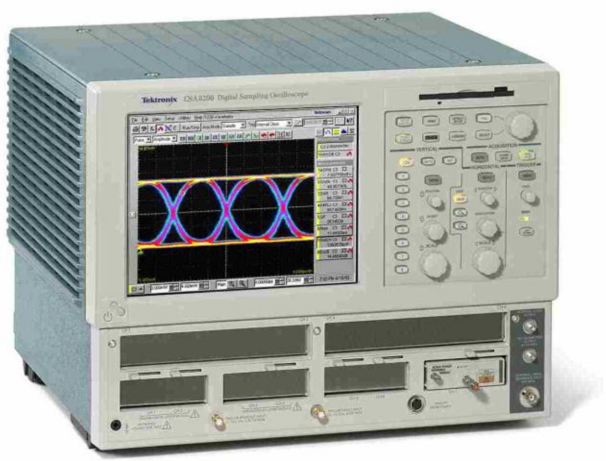
- The tails of the distribution follow the Gaussian of the underlying RJ distribution.

There is only one way to be absolutely certain the assumption is justified:

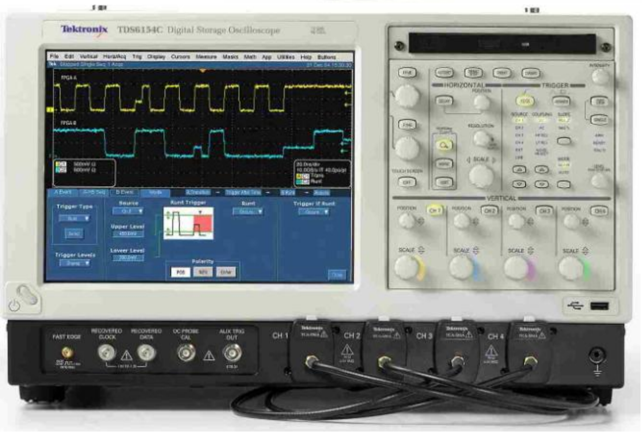
- Acquire a statistical sample of 100/BER transitions
  - For BER = 10^{-12} at 5 Gb/s would take 12 hours.

Fast Estimates of TJ(BER)

In most cases TJ(BER) can be accurately estimated in about ten seconds on an oscilloscope…



- Tektronix CSA8200 equivalent-time sampling oscilloscope with 80SJNB jitter and noise analysis



- Tektronix TDS6000 series real-time oscilloscope with TDSJIT3 jitter analysis

Conclusion (2)

1. TJ(BER) is an abstract form of peak-to-peak jitter referenced to a specific bit error ratio
2. TJ(BER) is useful for assuring interoperability, but not so useful for diagnosing jitter problems
3. While TJ(BER) can only be *measured* on a bit error ratio tester, but estimates on equipment with better voltage and timing accuracy are frequently more accurate

Conclusion (3)

- Jitter analysis is a simplification.

  Analyzing jitter independent of voltage noise can be useful, but…

No thorough signal integrity analysis neglects the relationship of Noise and Jitter.

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Conclusion (4)

What we *didn't* cover…

- What the dual-Dirac model is and what it is not
- The rest of the acronyms: DDJ, ISI, DCD, PJ, SJ
- Jitter analysis is a simplification.
  - Jitter and voltage noise are not really separable
  - E.g., Crosstalk can destroy all of our assumptions
- Clock recovery and the meaning of T_B
  - We only care about the jitter that can cause errors and receivers have limited bandwidth…
- Reference clock jitter and how it affects data jitter

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Part 2: What the Dual-Dirac Model is and What it is Not

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Introduction

The Dual-Dirac Model is…

1. Useful for estimating TJ(BER) of components and systems.
2. Frequently misunderstood because of the model-dependence of its parameters

Distinguish RJ from $RJ(\delta\delta)$ and DJ from $DJ(\delta\delta)$

$$TJ(BER) = 2Q_{BER} \times RJ(\delta\delta) + DJ(\delta\delta)$$

➔ The resulting TJ(BER) is model independent.

The Dual-Dirac Model

- We need three tools to describe the model

1st The **Dirac-delta** function

$$\delta(x - x_0) \equiv \begin{cases} 0, & x \neq x_0 \\ \to \infty, & x = x_0 \end{cases}$$ with $$\int \delta(x - x_0)dx = 1$$

2nd The RJ PDF is a **Gaussian**

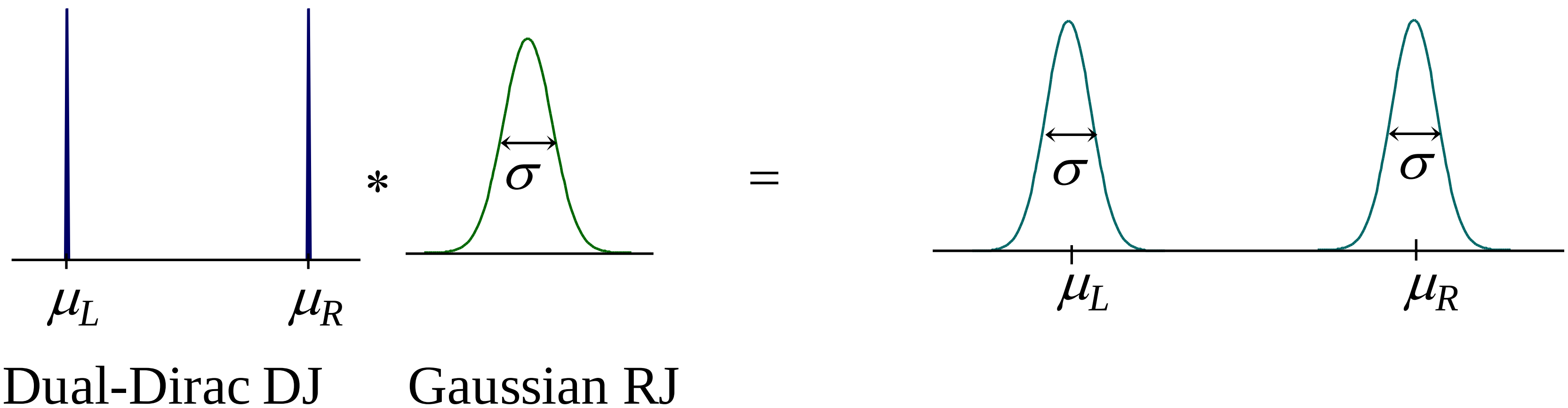
$$PDF_{RJ}(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{x^2}{2\sigma^2}\right]$$

3rd Different jitter components combine through **convolution**

$$\begin{aligned} \mathrm{PDF}(x) &= \mathrm{PDF}_{DJ}(x) * \mathrm{PDF}_{RJ}(x) \\ &= \int \mathrm{PDF}_{DJ}(u) * \mathrm{PDF}_{RJ}(x - u)du \end{aligned}$$

Elements of the Dual-Dirac Model

$$\left[\delta(x-\mu_L)+\delta(x-\mu_R)\right]*\frac{1}{\sqrt{2\pi}\sigma}\exp\left(-\frac{x^2}{2\sigma^2}\right)=\frac{1}{\sqrt{2\pi}\sigma}\left[\exp\left(-\frac{(x-\mu_L)^2}{2\sigma^2}\right)+\exp\left(-\frac{(x-\mu_R)^2}{2\sigma^2}\right)\right]$$



DJ(p-p) = $\mu_R - \mu_L$ RJ = σ

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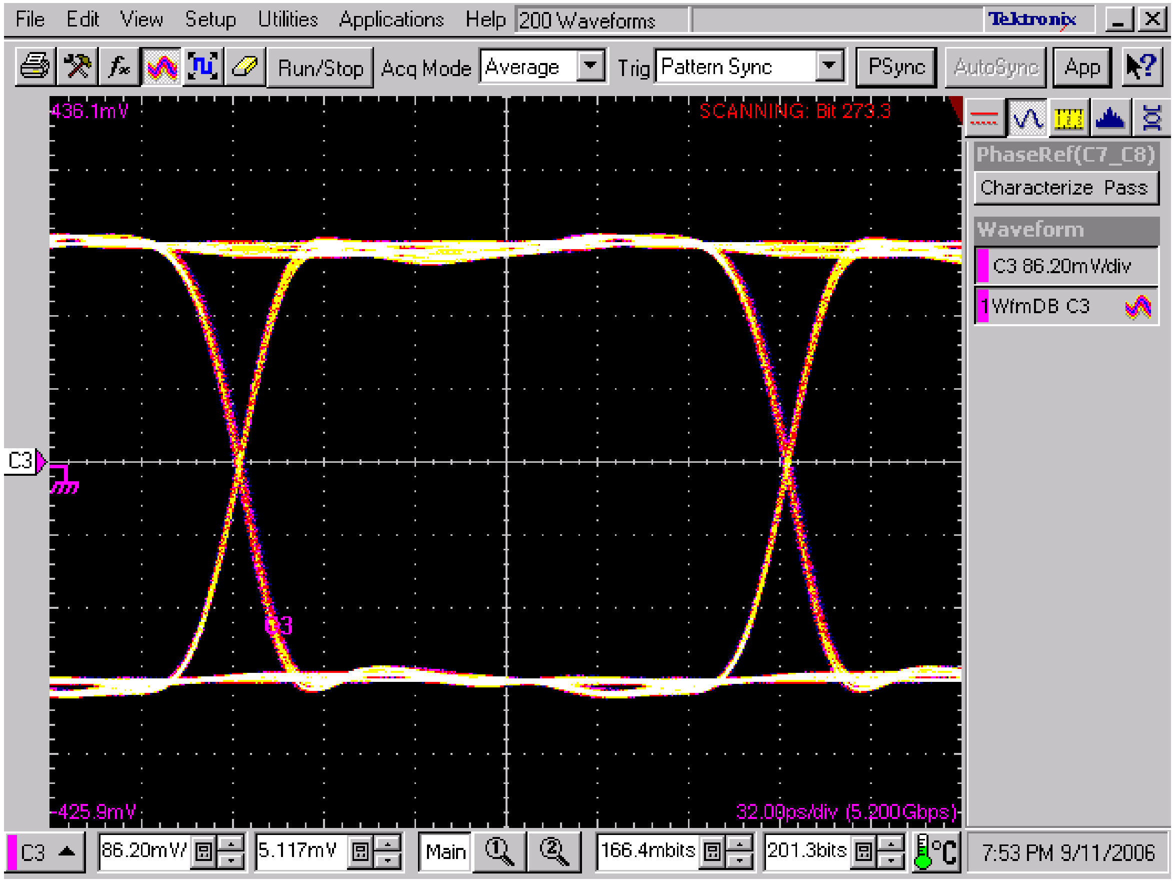
Elements of the Dual-Dirac Model (2)

- No jitter



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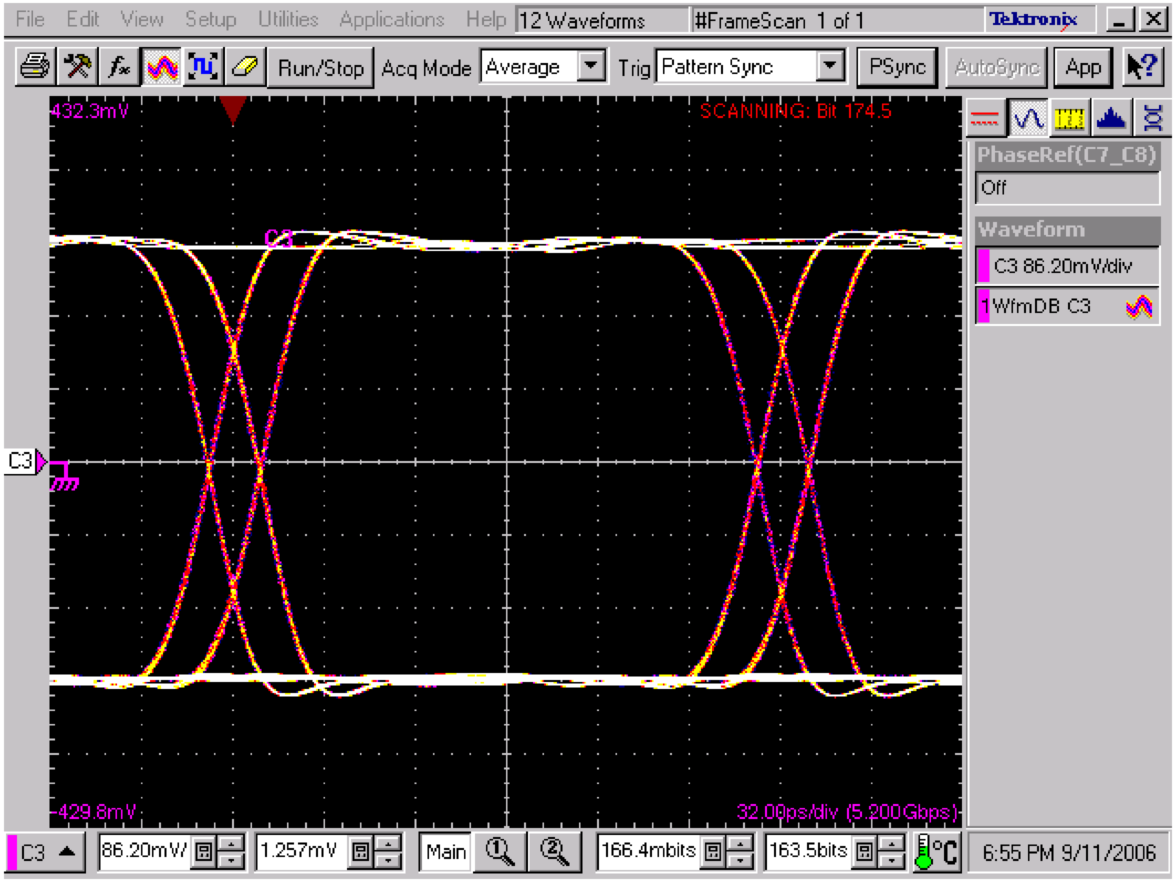
Elements of the Dual-Dirac Model (3)

- Dual-Dirac DJ, no RJ



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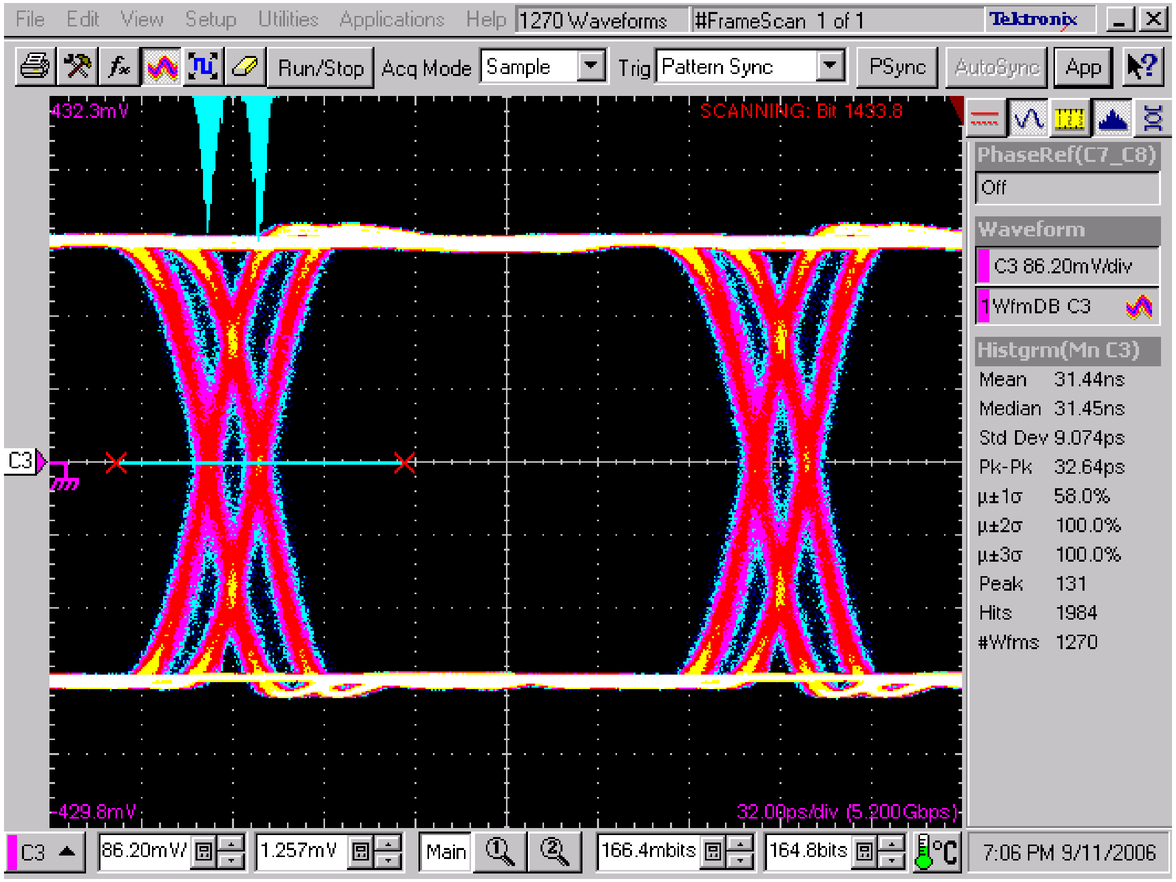
Elements of the Dual-Dirac Model (4)

- Dual-Dirac DJ with RJ



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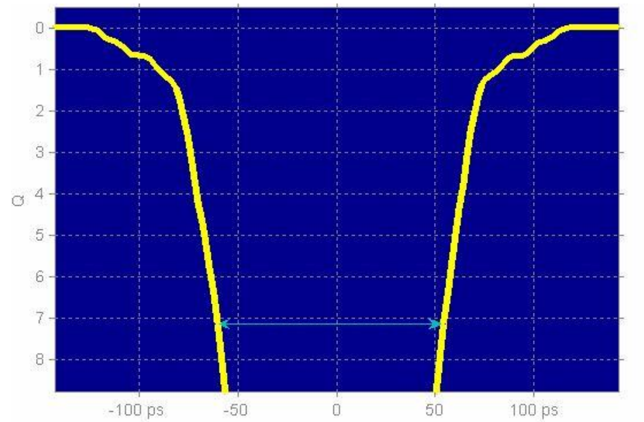
TJ(BER) in the Dual-Dirac Model

- The derivation of TJ(BER) in dual-Dirac…

Generally we can define the bathtub plot,



$$\mathrm{BER}(x) = \rho_T \int_x^{\infty} \mathrm{PDF}(x')dx' + \rho_T \int_{-\infty}^{x} \mathrm{PDF}(x'-T)dx'$$

Plug in dual-Dirac

$$\mathrm{BER}_{\delta\delta}(x) = \rho_T \left[\mathrm{erfc}\left(\frac{x-\mu_L}{\sqrt{2}\sigma} \right) + \mathrm{erfc}\left(\frac{(x-T)-\mu_R}{\sqrt{2}\sigma} \right) \right]$$

Evaluate the complementary error functions, $\mathrm{erfc}(x)$, and get

$$\mathrm{TJ(BER)} = 2Q_{BER} \times \mathrm{RJ}(\delta\delta) + \mathrm{DJ}(\delta\delta)$$

For BER $= 10^{-12}$, $Q_{BER} = 7$

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What the Dual-Dirac Model Is

But what about *real* jitter distributions?

- The calculation of $\mathrm{TJ(BER)}$ depends only on the *tails* of the distribution, thus…

$$\mathrm{TJ(BER)} = 2Q_{BER} \times \mathrm{RJ}(\delta\delta) + \mathrm{DJ}(\delta\delta)$$

… applies for *any* jitter distribution… as long as

1. We can neglect amplitude noise
2. The tails of the distribution are dominated by RJ

In other words,

As long as the tails of the distribution follow the RJ Gaussian at the BER we care about, $\mathrm{TJ(BER)} = 2Q_{BER} \times \mathrm{RJ}(\delta\delta) + \mathrm{DJ}(\delta\delta)$

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RJ($\delta\delta$): Model Dependence of RJ

- If the rising and falling edges are symmetric, then

$$RJ(\delta\delta) = RJ = \sigma$$

Else,

$$RJ(\delta\delta) \equiv \tfrac{1}{2} (\sigma_L + \sigma_R)$$

- Unless the asymmetry is huge, it's safe to assume

$$RJ(\delta\delta) = RJ = \sigma$$

Combining the RJ of Different Components

Since…

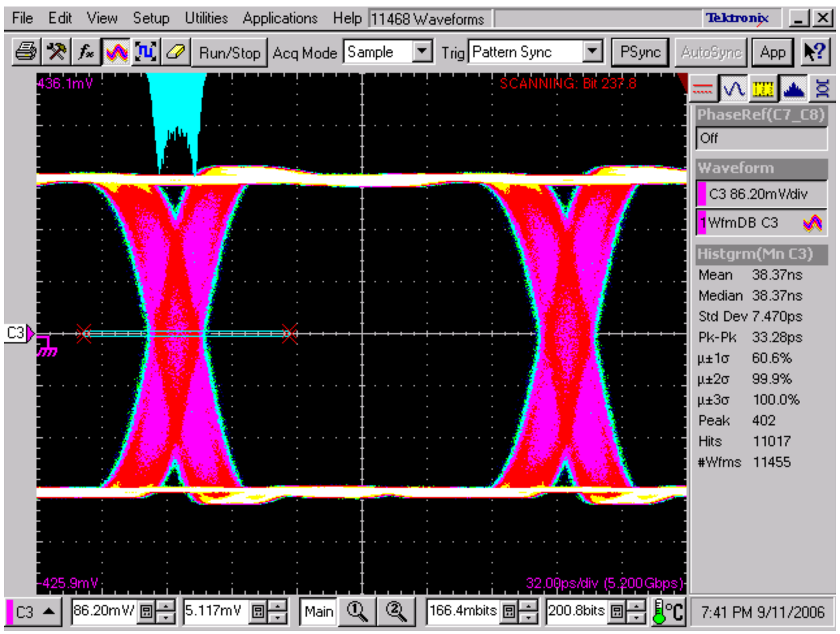
1. The RJ of one component is independent of the RJ of another
2. The convolution of two Gaussians is a Gaussian…

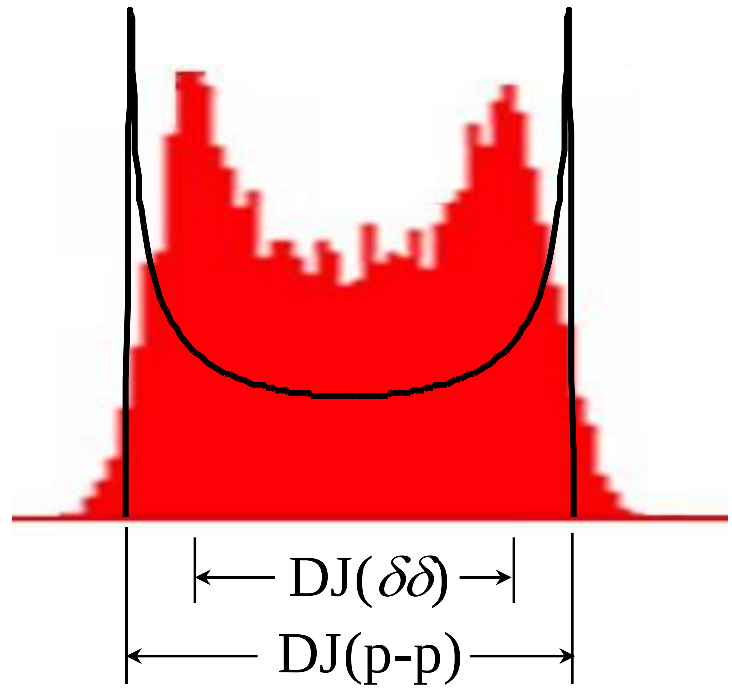
$$\sigma_{system} = \sqrt{\sigma_1^2 + \sigma_2^2 + \ldots + \sigma_N^2}$$

DJ(dd): Model Dependence of DJ

- The model dependence of DJ is rarely negligible

Consider the case of sinusoidal DJ…





$$DJ(\delta\delta) \leq DJ(p\text{-}p)$$

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DJ(dd): Model Dependence of DJ (2)

$$DJ(\delta\delta) \leq DJ(p\text{-}p)$$

… Is the reason dual-Dirac is controversial

- It's okay for a model to have model-dependent parameters
- Make sure to use $DJ(\delta\delta)$ in $TJ(BER) = 2Q_{BER} \times RJ + DJ$

Besides

- It's easier to measure $DJ(\delta\delta)$ than $DJ(p\text{-}p)$
- For getting TJ(BER), $DJ(\delta\delta)$ is more useful than $DJ(p\text{-}p)$

Combining the DJ of Different Components

- The p-p value of the convolution of two independent distributions is the $(\text{p-p})_1 + (\text{p-p})_2 + \ldots$

But DJ sources are not usually independent!

$$DJ_{system}(\text{p-p}) \leq DJ_1(\text{p-p}) + DJ_2(\text{p-p}) + \ldots + DJ_N(\text{p-p})$$

Two problems:

1. Summing $DJ_i(\text{p-p})$ overestimate $DJ_{System}(\text{p-p})$
2. $DJ(\text{p-p})$ is the wrong parameter for estimating TJ(BER)!

Consider

$$DJ_{system}(\delta\delta) \approx DJ_1(\delta\delta) + DJ_2(\delta\delta) \ldots + DJ_N(\delta\delta)$$

Combining the DJ of Different Components (2)

$$\mathrm{DJ}_{system}(\delta\delta) \approx \mathrm{DJ}_1(\delta\delta) + \mathrm{DJ}_2(\delta\delta) \ldots + \mathrm{DJ}_N(\delta\delta)$$

is an approximation

Rationale:

- More DJ sources
  → more convolutions
  → smoother DJ distribution
- Smoother DJ
  → greater discrepancy between $\mathrm{DJ}(\delta\delta)$ and $\mathrm{DJ(p\text{-}p)}$

Expect $\mathrm{DJ}_{system}(\delta\delta)$ to be close to the sum,

maybe smaller, maybe even conservative…

Conclusion: What Dual-Dirac is…

$$\mathrm{TJ(BER)} = 2Q_{BER} \times \mathrm{RJ}(\delta\delta) + \mathrm{DJ}(\delta\delta)$$

- Fast estimate of TJ(BER) that is as accurate as the measurements of σ and $\mathrm{DJ}(\delta\delta)$
  – RJ and DJ may be model dependent, but $\mathrm{TJ(BER)}$ isn't

$$\sigma_{system} = \sqrt{\sigma_1^2 + \sigma_2^2 + \ldots + \sigma_N^2}$$

$$\mathrm{DJ}_{system}(\delta\delta) \approx \mathrm{DJ}_1(\delta\delta) + \mathrm{DJ}_2(\delta\delta) \ldots + \mathrm{DJ}_N(\delta\delta)$$

- Easy to combine σ and $\mathrm{DJ}(\delta\delta)$ of different components to estimate TJ of a system

Conclusion: What Dual-Dirac is not…

It's a model, it's assumptions can be debated

- Most techniques for measuring RJ fail if there's crosstalk
- What if RJ doesn't follow a Gaussian?
- What if there are many small DJ sources that look Gaussian?
  – "Truncated Gaussian" could upwardly bias RJ and, hence, TJ(BER)
- What about Amplitude noise?
  – Jitter is just one dimension of a two dimensional problem

No thorough signal integrity analysis neglects the relationship of Noise and Jitter.

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Part 3: All About the Acronyms: RJ, DJ, DDJ, ISI, DCD, PJ, SJ, …

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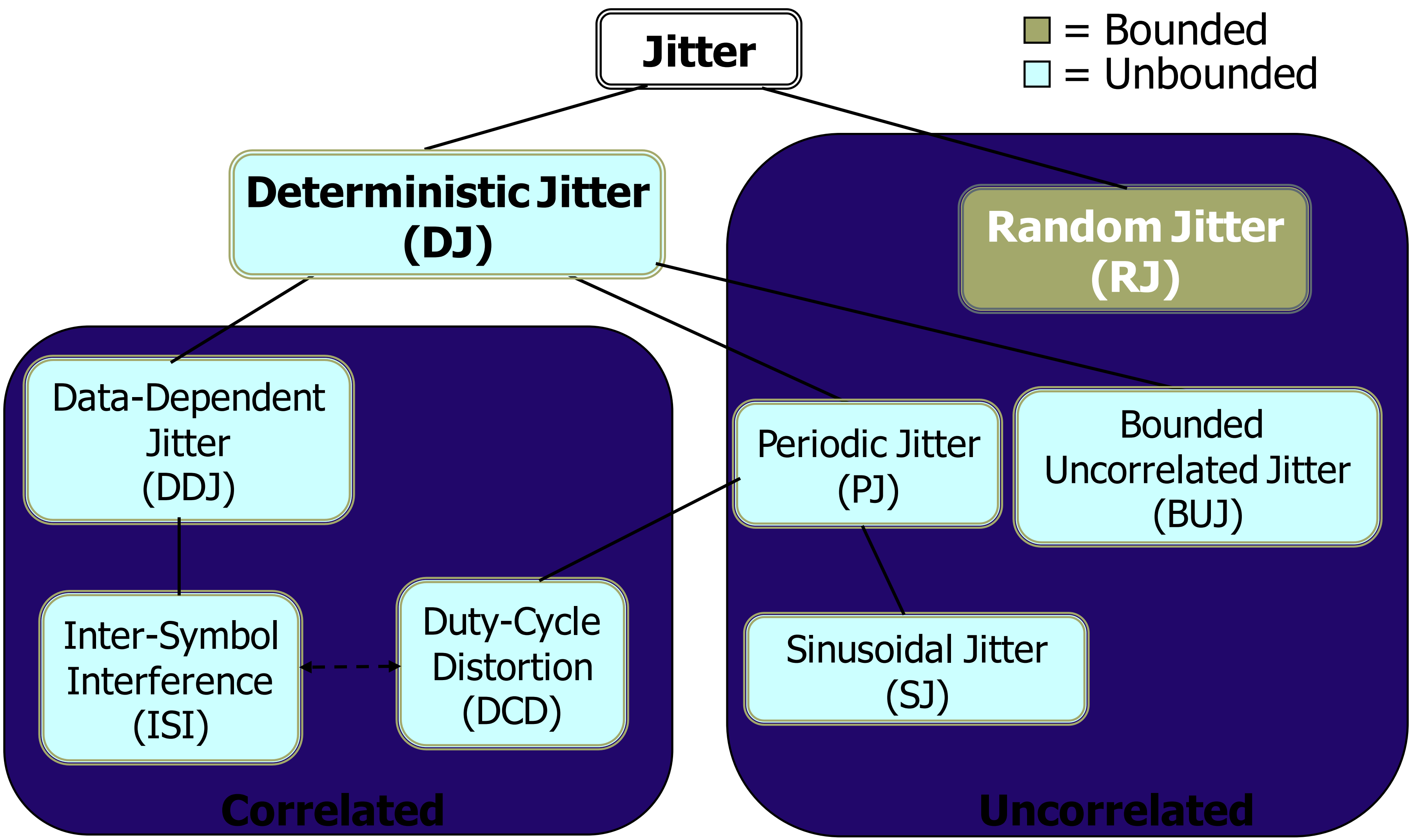
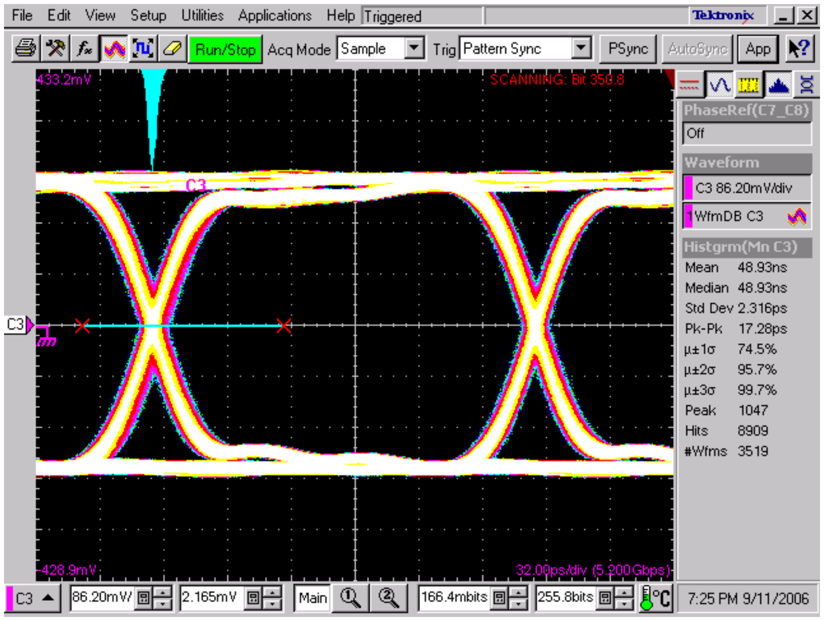
Introduction

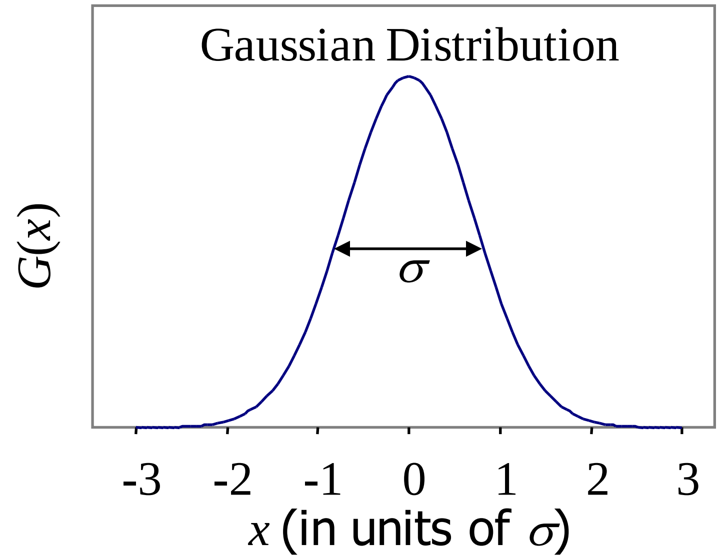
- Jitter analysis is riddled with acronyms
  - Good acronyms are convenient abbreviations like "laser" everyone really does know what they mean without needing to know what it stands for
- To understanding a complicated system it helps to break things into small pieces
  - Knowing that TJ(10^{-12}) is too large for your jitter-budget doesn't help you fix the problem
  - Knowing that the dominant type of jitter is Inter-Symbol Interference (ISI) does

The Jitter Family Tree



Random Jitter – RJ





$$G(x) = N \exp\left(-\frac{x^2}{2\sigma^2}\right)$$

RJ = σ

Random Jitter – RJ

- RJ is unbounded
- RJ is uncorrelated to the data
- RJ is aperiodic
- RJ is independent of the other sources of jitter

Deterministic Jitter

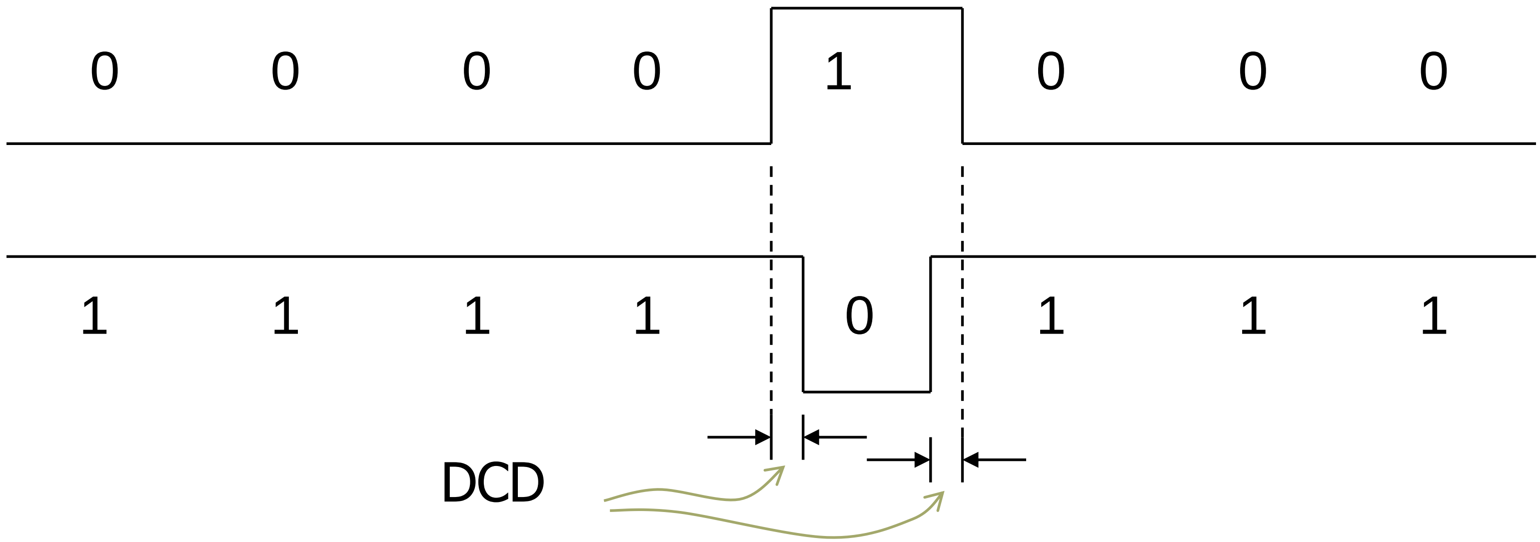
Deterministic Jitter (DJ) is the jitter that remains after Random Jitter (RJ) has been removed

$$DJ = DJ(p\text{-}p) \text{ or } DJ(\delta\delta)$$

- DJ is bounded
- DJ may include both periodic and aperiodic components

Duty Cycle Distortion – DCD

- DCD is the asymmetry in the duty-cycle of a the transmitter



- DCD is correlated with Inter-Symbol Interference (ISI)
  – DCD and ISI interfere with each other

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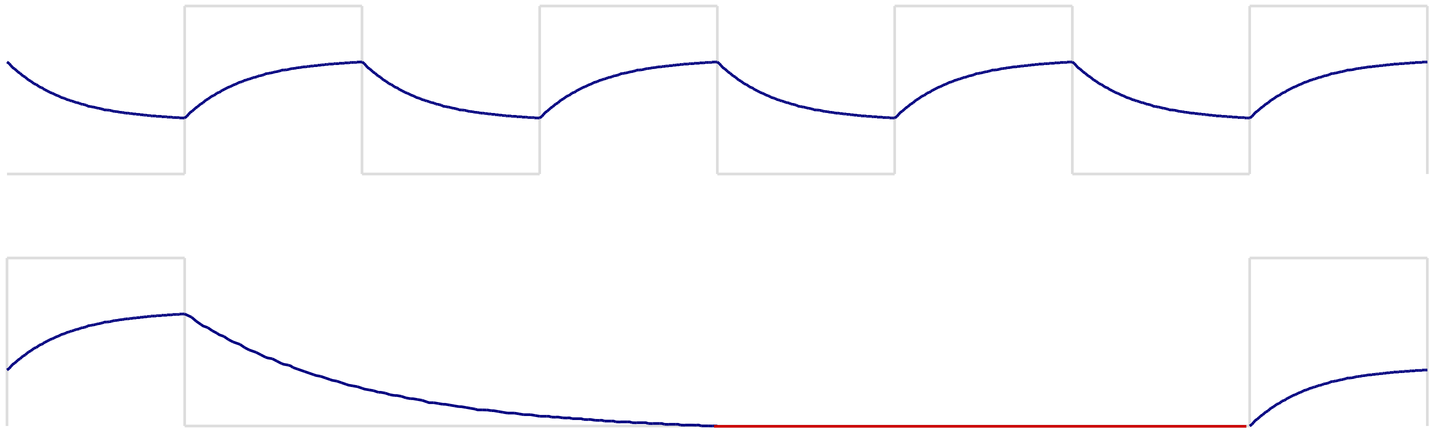
Duty-Cycle Distortion – DCD

- DCD is bounded
- DCD follows a simple bimodal distribution
- DCD is usually caused by a clock asymmetry or limiting amplifier imperfection and so is periodic at the data-rate
- DCD is correlated with Inter-Symbol Interference (ISI) – a change in DCD causes a change in ISI and vice versa

Data-Dependent Jitter – DDJ

- DDJ is all jitter whose magnitude is affected by the transmitted data signal



- DDJ is caused by
  - macroscopic impedance mismatches
  - resistance and frequency response of the transmission path

  and is affected by DCD

Aside – Correlation

- Correlation of two random variables:

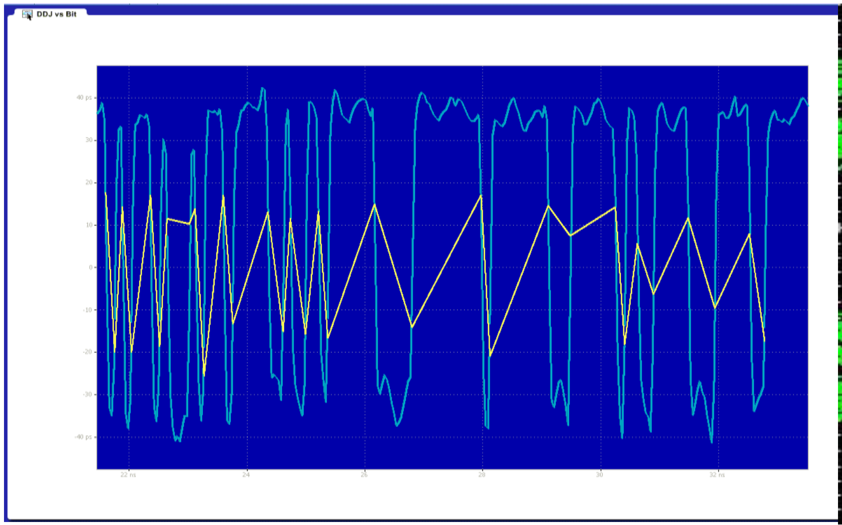
  If changing one variable causes a change in the other

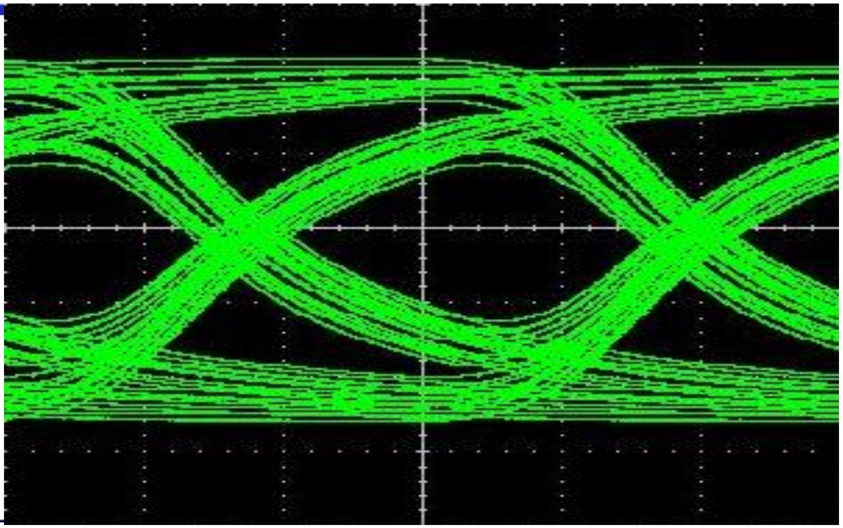
Two types of correlation in jitter analysis:

1. Jitter is said to be *correlated* to the data if the amplitude of jitter is affected by the transmitted data signal or the data rate
2. The level of one type of jitter is affected by the level of another type of jitter
   – E.g., Inter-Symbol Interference (ISI) is correlated to Duty-Cycle Distortion (DCD)

   correlation ⇔ interference

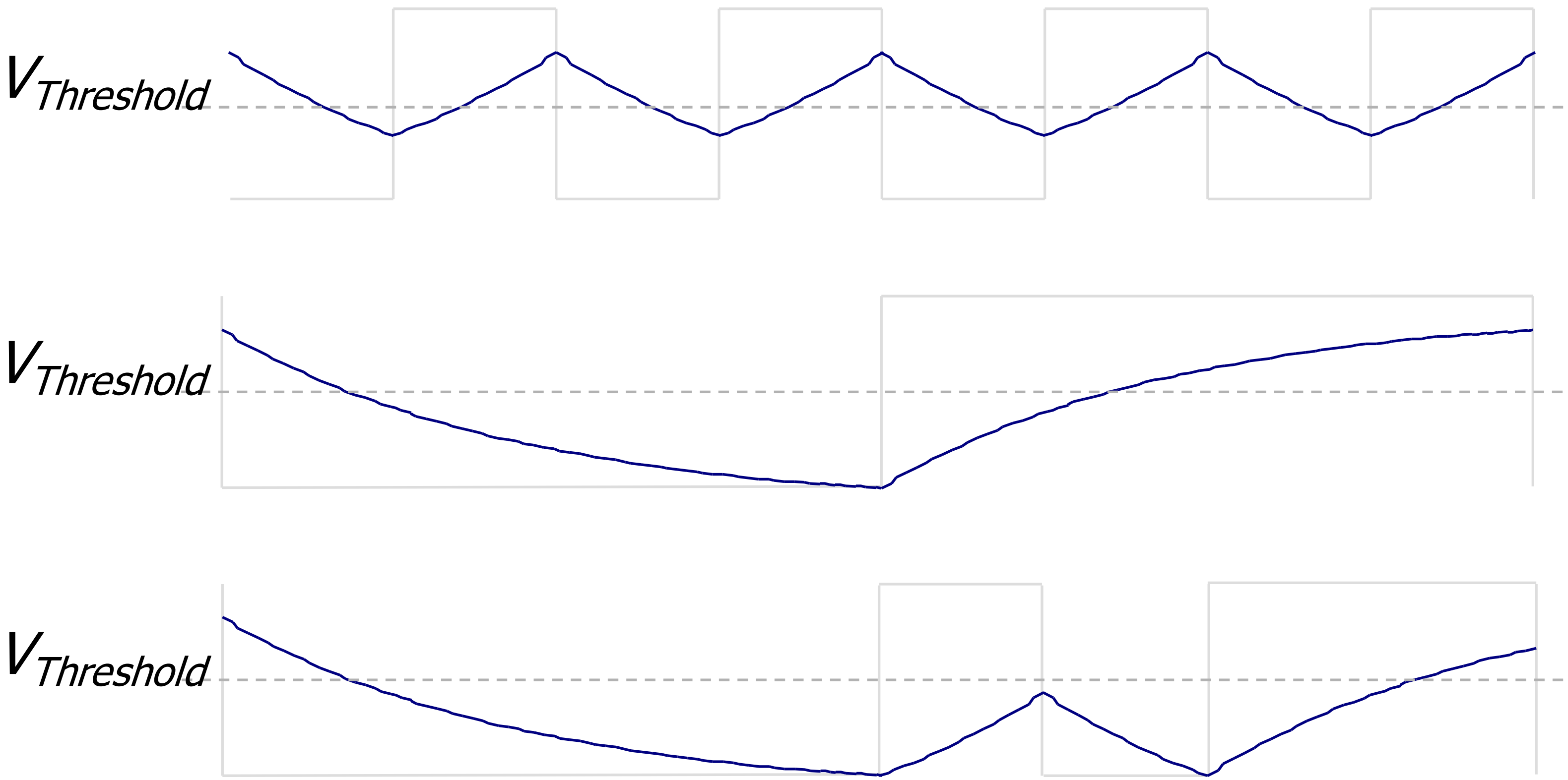
Data-Dependent Jitter – DDJ (2)



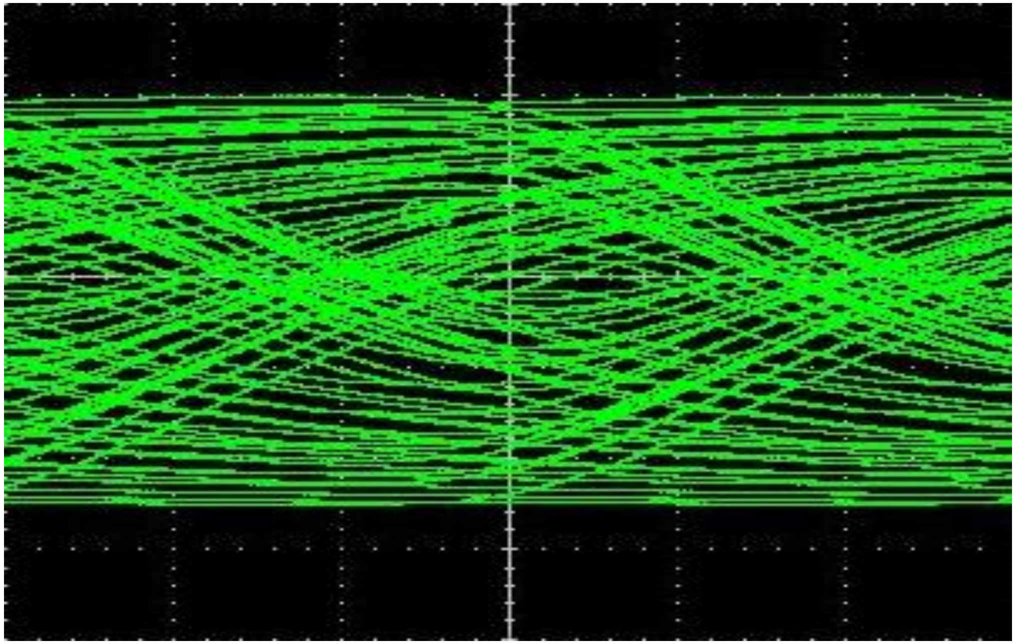


Inter-Symbol Interference – ISI

- The primary cause of Data Dependent Jitter



Inter-Symbol Interference – ISI (2)



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Inter-Symbol Interference – ISI (3)

- ISI is bounded
- ISI is only periodic if the signal is a repeating pattern
- ISI is caused by the geometry and media of the conductor and dielectric and discrete impedance mismatches that cause multiple reflections
- ISI can be introduced by the transmitter
- ISI of different circuit elements are correlated to each other – they interfere
- ISI can be predicted from the impulse response
  - The impulse response can be derived from the *S*-parameters measured through Time Domain Reflectometry (TDR)

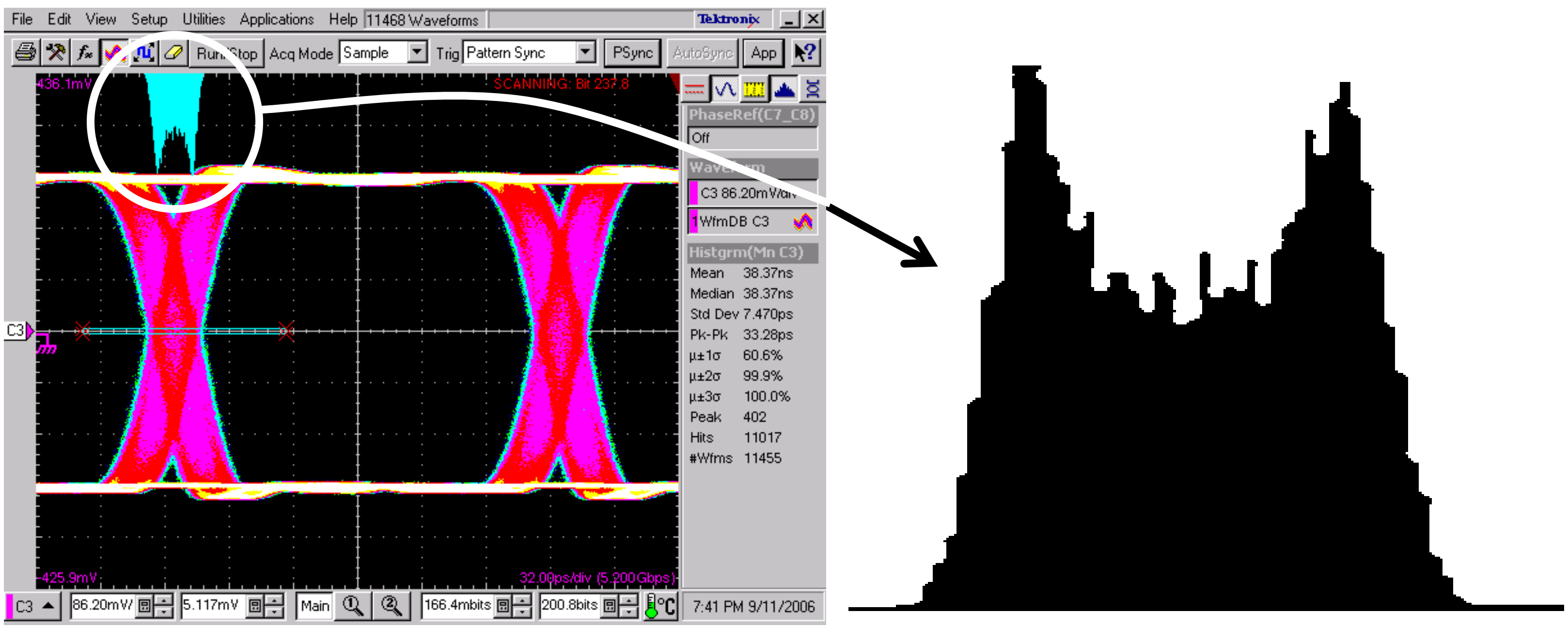
Periodic Jitter – PJ

PJ is any jitter that occurs at a fixed frequency

- PJ is easy to measure accurately
- PJ can have a variety of wave shapes (e.g., square-wave phase modulation is PJ that results in a dual-Dirac distribution) with corresponding jitter-frequency spectra
- PJ is useful in diagnosing jitter problems
- PJ is bounded and follows a distribution that can be calculated if the amplitudes, frequencies, and relative phases of all harmonics and PJ sources are measured

Sinusoidal Jitter – SJ

- SJ is Periodic Jitter (PJ) at just one frequency
- SJ is bounded and uncorrelated to the data
- SJ can be applied to a signal for use in calibrating test equipment



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Bounded Uncorrelated Jitter – BUJ

- BUJ bounded and uncorrelated to the data
- BUJ is usually used as a receptacle for the jitter we can't measure
- The two most commonly discussed sources of BUJ are non-stationary jitter and the jitter effects of crosstalk

Jitter Categories

Lots of ways to categorize jitter

- Random Jitter (RJ) vs Deterministic Jitter (DJ) which is equivalent to unbounded vs bounded
- correlated vs uncorrelated
- data-dependent vs data-independent
- periodic vs aperiodic

But it’s more important to understand jitter types than to know how to organize them

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Summary

Random Jitter	RJ	Unbounded	Uncorrelated	Aperiodic	Thermal noise
Deterministic Jitter	DJ	Bounded	Either	Either	Inter-Symbol Interference
Periodic Jitter	PJ	Bounded	Either	Periodic	Power supply feed-through
Sinusoidal Jitter	SJ	Bounded	Uncorrelated	Periodic	Electromagnetic interference
Data-Dependent Jitter	DDJ	Bounded	Correlated	Aperiodic	Impedance mismatch
Duty-Cycle Distortion	DCD	Bounded	Correlated	Periodic	Clock asymmetry
Inter-Symbol Interference	ISI	Bounded	Correlated	Aperiodic	Non-uniform frequency response of a transmission line
Bounded Uncorrelated Jitter	BUJ	Bounded	Uncorrelated	Aperiodic	Crosstalk

jitter 360° / Jitter from Every Angle

Part 4: Jitter Analysis in Systems With Crosstalk

Ransom Stephens, Ransom's Notes, LLC

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Jitter 360° / Jitter from Every Angle

Series Topics

1. The Meaning of Total Jitter
2. What the Dual-Dirac Model is and What it is Not
3. All About the Acronyms: RJ, DJ, DDJ, ISI, DCD, PJ, SJ, …
4. **Jitter Analysis in Systems with Crosstalk ←**
5. Clock Recovery in Serial-Data Systems
6. Reference Clock Jitter and Data Jitter

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Introduction

- Crosstalk doesn't come under a tidy jitter analysis acronym like RJ, PJ, DDJ

Crosstalk is Bounded Uncorrelated Jitter - BUJ

- Crosstalk
  - tends to confound jitter analysis algorithms
  - should be analyzed as a two dimensional noise problem
  - is reduced by using differential signaling

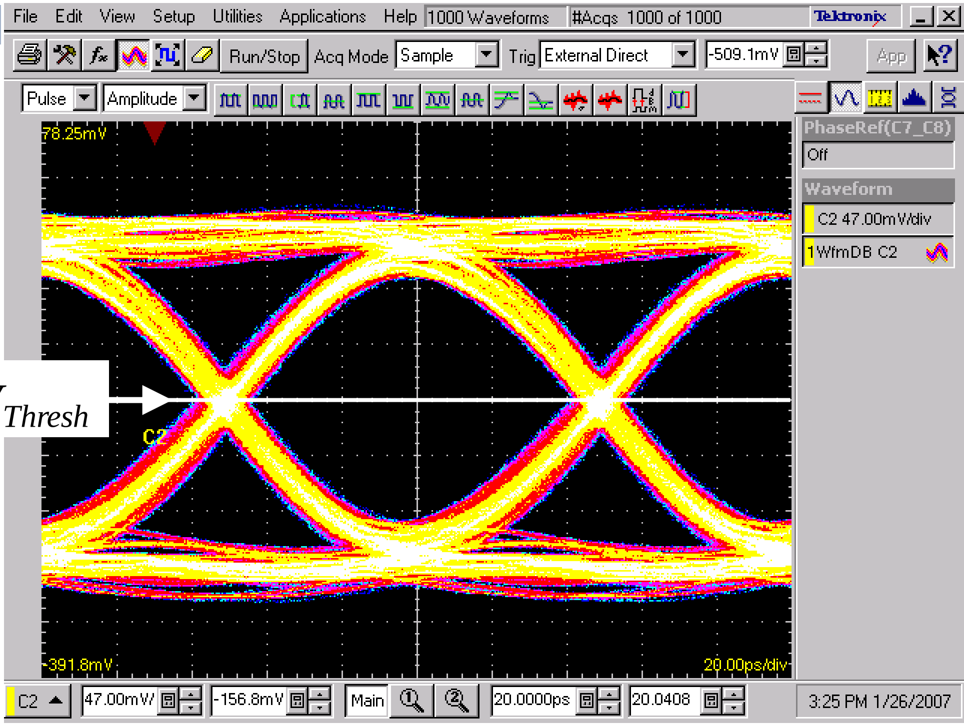
Noise is noise

- Voltage noise in the vertical
- Phase noise in the horizontal

Jitter analysis only considers one dimension of the two-dimensional noise problem

Jitter is the variation in the timing of the significant instants of a digital signal

- A “significant instant” is when th signal crosses V_{Thresh}



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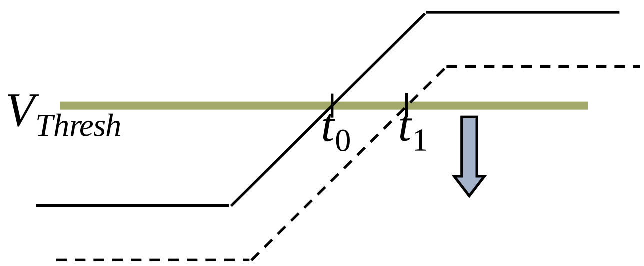
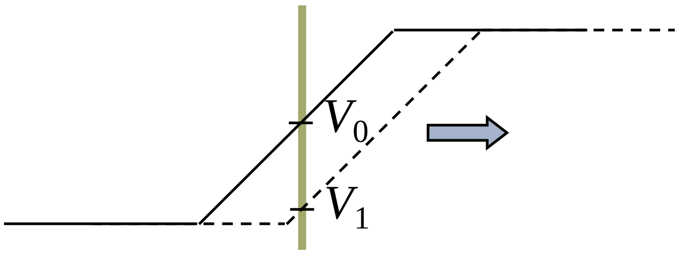
Phase noise vs amplitude noise
jitter vs voltage noise

$$f(x) = (A + \delta A)\sin(x + \delta x)$$

amplitude noise   phase noise

- Phase noise is the variation of the phase
  - Noise that moves the signal back and forth horizontally
- Amplitude noise moves the signal vertically up and down





$$J_{PP} \approx \frac{\delta V}{dV/dt}$$

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Voltage noise gets acronyms too!

- RJ → RN Random Noise
- DJ → DN Deterministic Noise
- DDJ → DDN Data-Dependent Noise
- PJ → PN Periodic Noise

(But *never* say “voltage jitter”)

- PLUS discriminate between the phase-noise and amplitude noise contributions:

RJ ➔ RJ(h) and RJ(v)

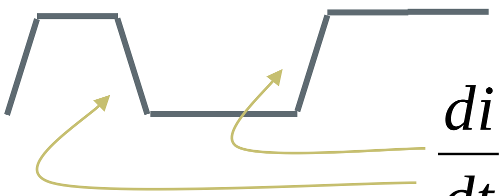
Crosstalk

In a system with more than one signal…

- Crosstalk is
  - the electromagnetic interference (EMI) of an *aggressor* imposed on the *victim*
  - usually capacitive coupling between nearest neighbors
  - ran be reduced by
    - shielding
    - increasing distance between victim and aggressor traces
    - limiting signal slew rates
    - using differential signaling
- At GHz, signals are more like guided waves than DC currents
  - the circuit board is the dielectric, trace is the waveguide
- Circuit discontinuities - connectors and vias – generate crosstalk like antennas

Crosstalk (2)

- The magnitude of crosstalk is the voltage of the aggressor signal at the victim
- Maxwell ➔ radiation is caused by accelerated charges
  - Most acceleration during a transition ➔ a jolt of crosstalk



$$\frac{di}{dt} \propto \frac{dV_{agg}}{dt}$$

is a maximum at transitions

- The amount of crosstalk is measured as

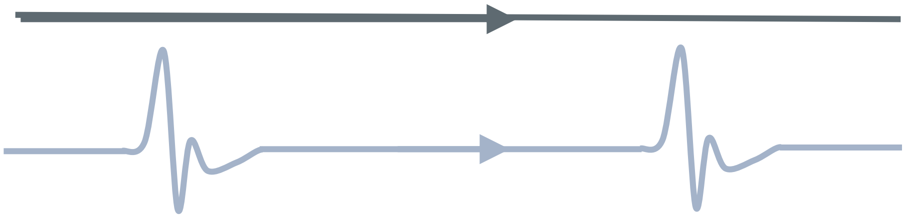
$$\frac{V_{agg}(\text{at the signal trace})}{V_{signal}}$$

In dB

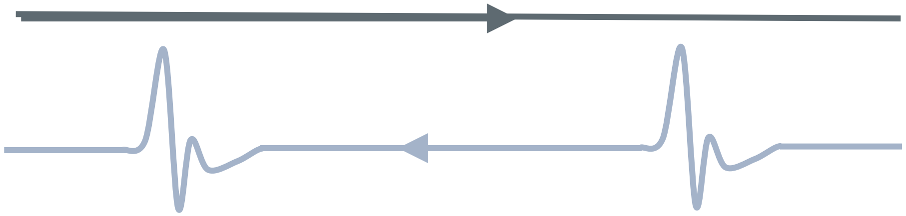
NEXT and FEXT

Crosstalk is directional

- Near End Crosstalk – NEXT
  – Signal and noise propagate in the same direction



- Far End Crosstalk – FEXT
  – Signal and noise propagate in opposite directions



- FEXT is usually worse than NEXT

Differential Signaling

Transmit s(t) on one line and –s(t) on the other

- *Ideal* system the net signal in the dielectric is zero
- Signal at the receiver is s(t) – [-s(t)] = 2 s(t)

Ideal means

  - zero skew
  - perfect overlap
  - identical but inverse signals

none of which are possible in real systems

Case 1: victim and aggressor are frequency and phase locked

If the victim and aggressor are controlled by the same reference clock…

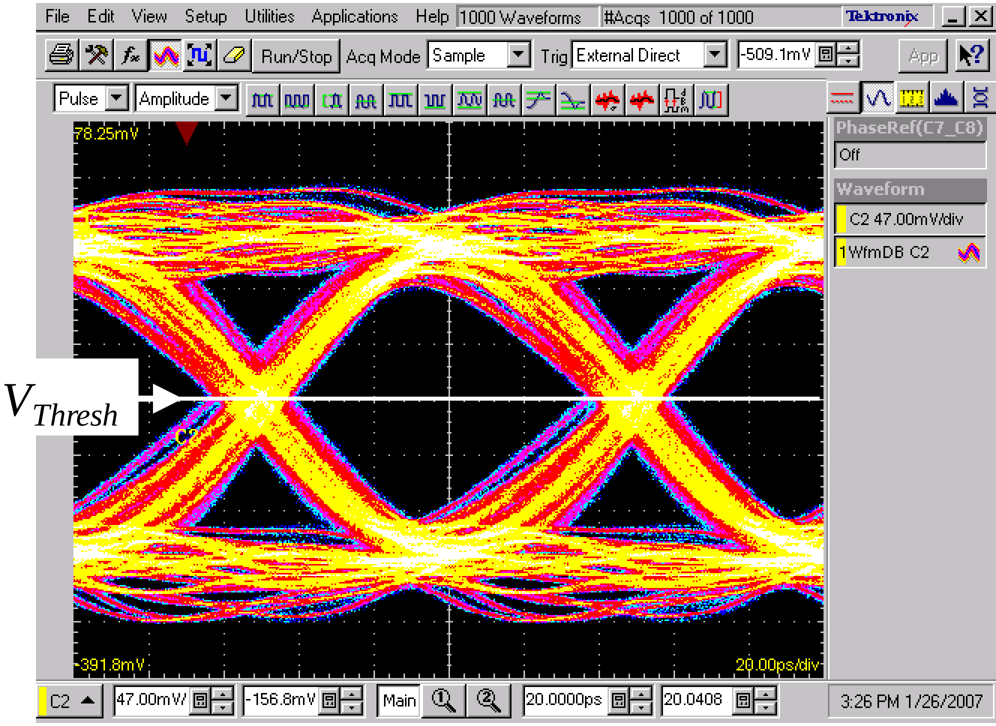
- Crosstalk signature

  +pulse during aggressor 0 → 1

  no noise during 0 → 0 or 1 → 1

  - pulse during aggressor 1 → 0

- Design so that the mess occurs at the crossing point
  - Minimize voltage noise, maximize jitter



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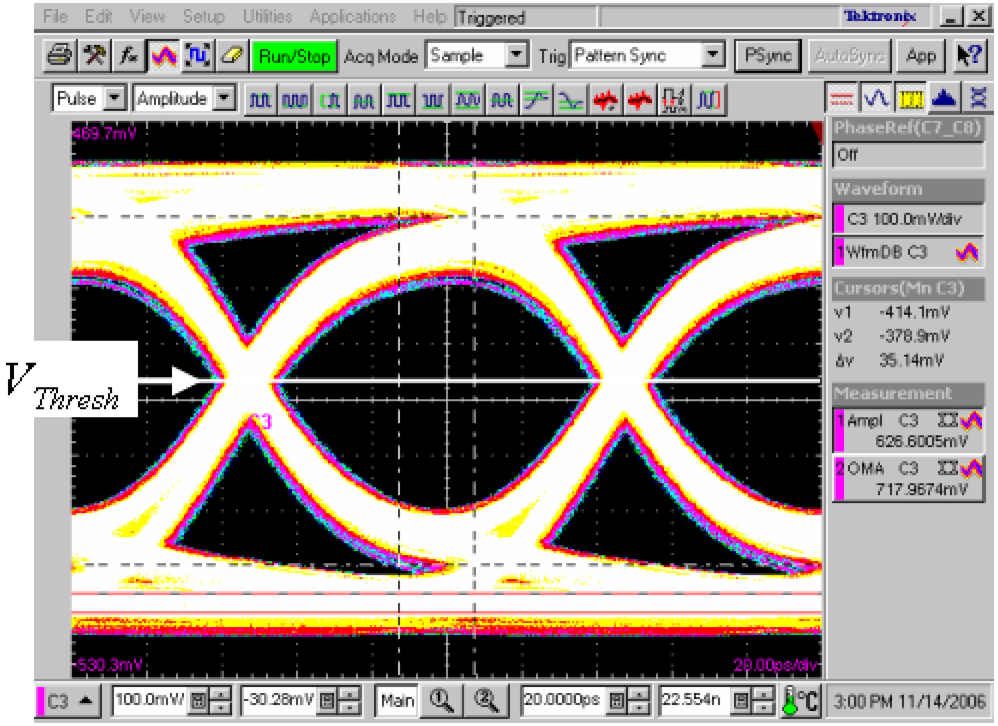
Case 2: victim and aggressor are NOT frequency and phase locked

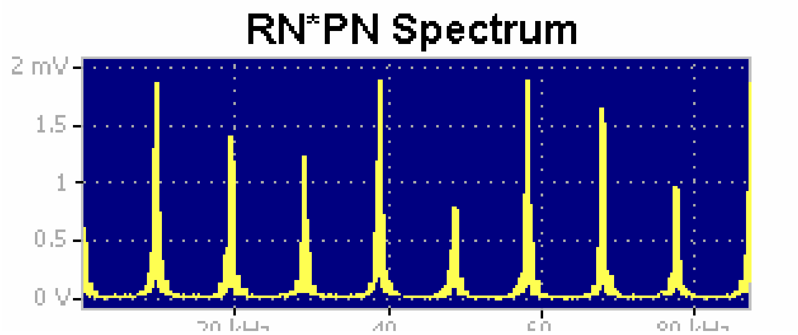
- Time domain view of crosstalk looks like excess voltage noise



Frequency domain view

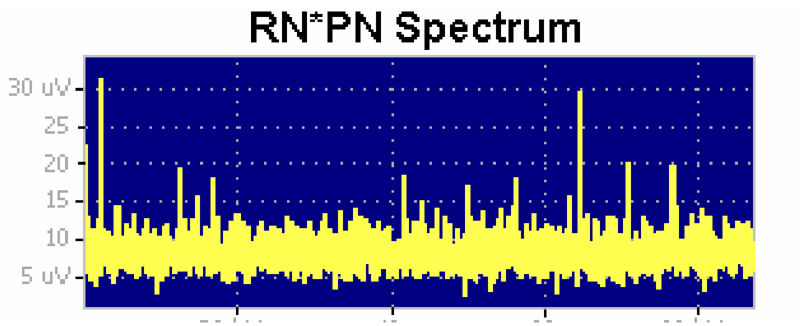
- Frequency and phase-locked
  - Spectrally based analyses confuses crosstalk for PJ and PN
  - Tail-fitting techniques mistake crosstalk for RJ

    → overestimate TJ(BER)



- Not locked
  - Real-time sampling equipment sees broadened resonant spectra
  - Under-sampling equipment see an increase in the continuum
  - Spectrally based as well as tail-fitting techniques mistake crosstalk for RJ

    → overestimate TJ(BER)



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Signal analysis with crosstalk

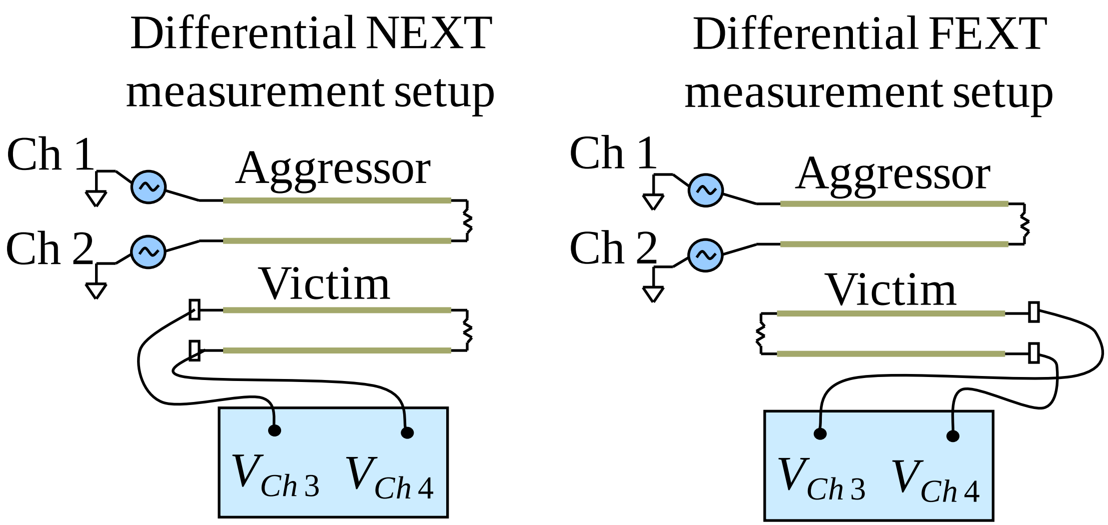
- Anticipate the problem and design around it
- Measure S-parameters between victim and aggressor lanes or evaluate them in a simulation
  - Calculate the aggressor voltage at the victim trace, V_{NEXT} or V_{FEXT}

$$\text{Crosstalk} = \frac{V_{xEXT}}{V_{signal}}$$

Usually in dB

Signal analysis with crosstalk (2)

Measure the response on the victim trace of an aggressor signal



$$V_{NEXT} = V_{Ch\,3} - V_{Ch\,4}$$

$$V_{FEXT} = V_{Ch\,3} - V_{Ch\,4}$$

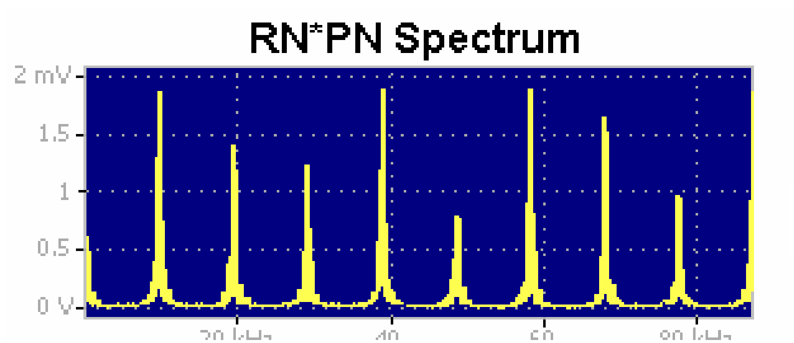
Use smallest slew rate in

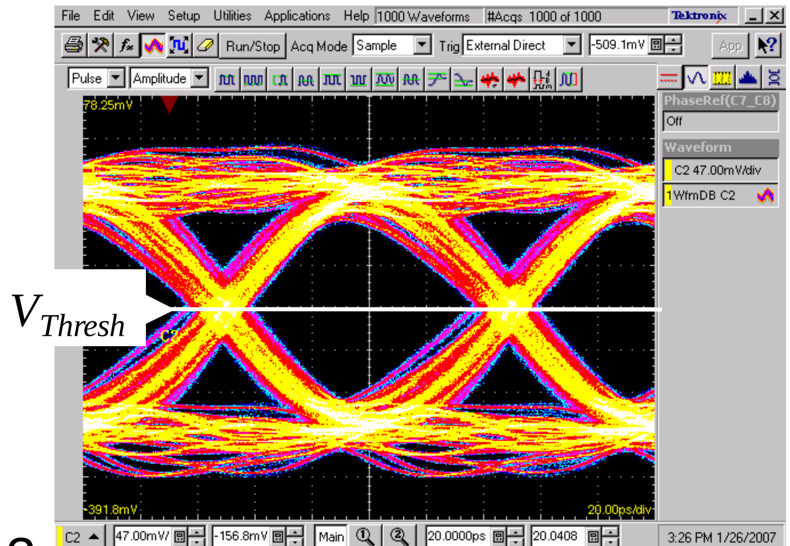
$$J_{PP} \approx \frac{V_{xEXT}}{dV/dt}$$

Signal analysis with crosstalk (3)

All we know is that the Bit Error Ratio is too high

- If neighboring traces are governed by the same reference clock
  - Look for characteristic splintering or bulge at some time-delay point in the eye-diagram





- Do a jitter analysis…
  - If RJ is abnormally large (> 3 ps) might mean crosstalk

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Signal analysis in two dimensions

Use both voltage noise *and* jitter analysis!

(Tektronix's JNB software option)

– Get RJ, RN, DDJ, DDN, PJ, PN, …

with both vertical and horizontal contributions

If RN(v)/RN(h) >> RJ(h)/RJ(v) ➔ amplitude noise is the problem

- Since crosstalk appears to the analysis techniques as random noise, it's probably crosstalk.

Other ways to identify crosstalk

- Turn off suspected aggressors
  - Compare RJ with and without aggressor if RJ-with > RJ-without then it's crosstalk
    - Use the RJ-without measurement and DJ-with measurement in the dual-Dirac model to estimate TJ(BER)
- Crosstalk is BUJ – it's *bounded*
- Transmit a 1010… signal on the aggressor
  - Frequency/phase-locked case – get a single PJ, PN peak
  - Unlocked case uncorrelated jitter and noise distributions (RJ∗PJ and RN∗PN) not Gaussian

    PLUS no peaks in the PJ or PN spectra

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Conclusion

- There is no one-button push way to identify crosstalk
- Crosstalk is *amplitude* noise, not *phase* noise
- With simultaneous jitter and voltage noise analysis it is at least possible to identify crosstalk

Thank You!

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Part 5: Clock Recovery in Serial-Data Systems

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6. Reference Clock Jitter and Data Jitter

Introduction

- The unit interval…

  $UI = 1/T_{Bit}$ right?

  … only if we want jitter at every frequency to cause errors

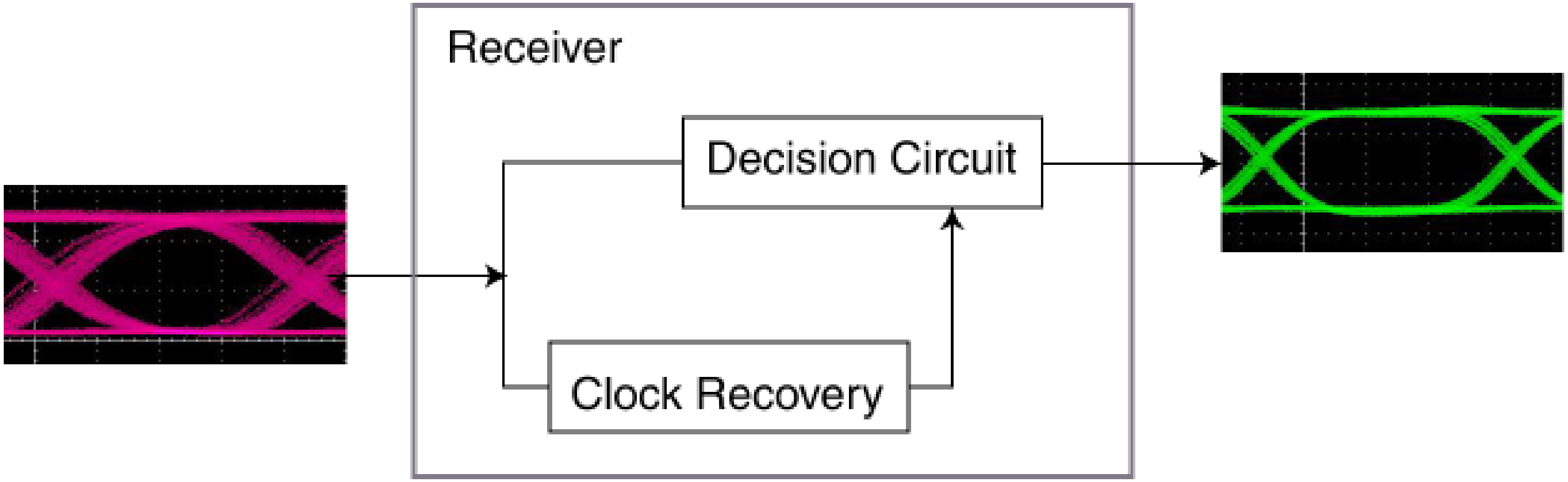
- Clocks recovered from data, "embedded clocks," can reduce the Bit Error Ratio (BER)
  – But complicate what we mean by a Unit Interval

Introduction (2)

In a receiver

- The clock positions the sampling point
- Comparator determines logic level

How can we reduce the effect of jitter in the decision circuit?



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Introduction (3)

"Obvious approach" with an absolute reference clock:

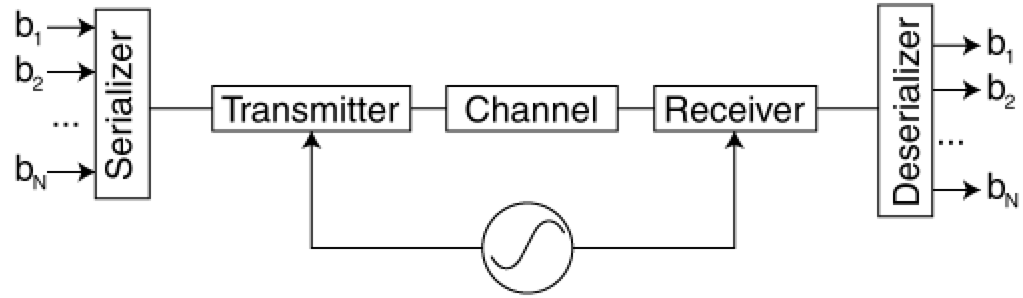
$UI = 1/T_{Bit}$

$Skew = mod(\Delta t, T_{BIT})$

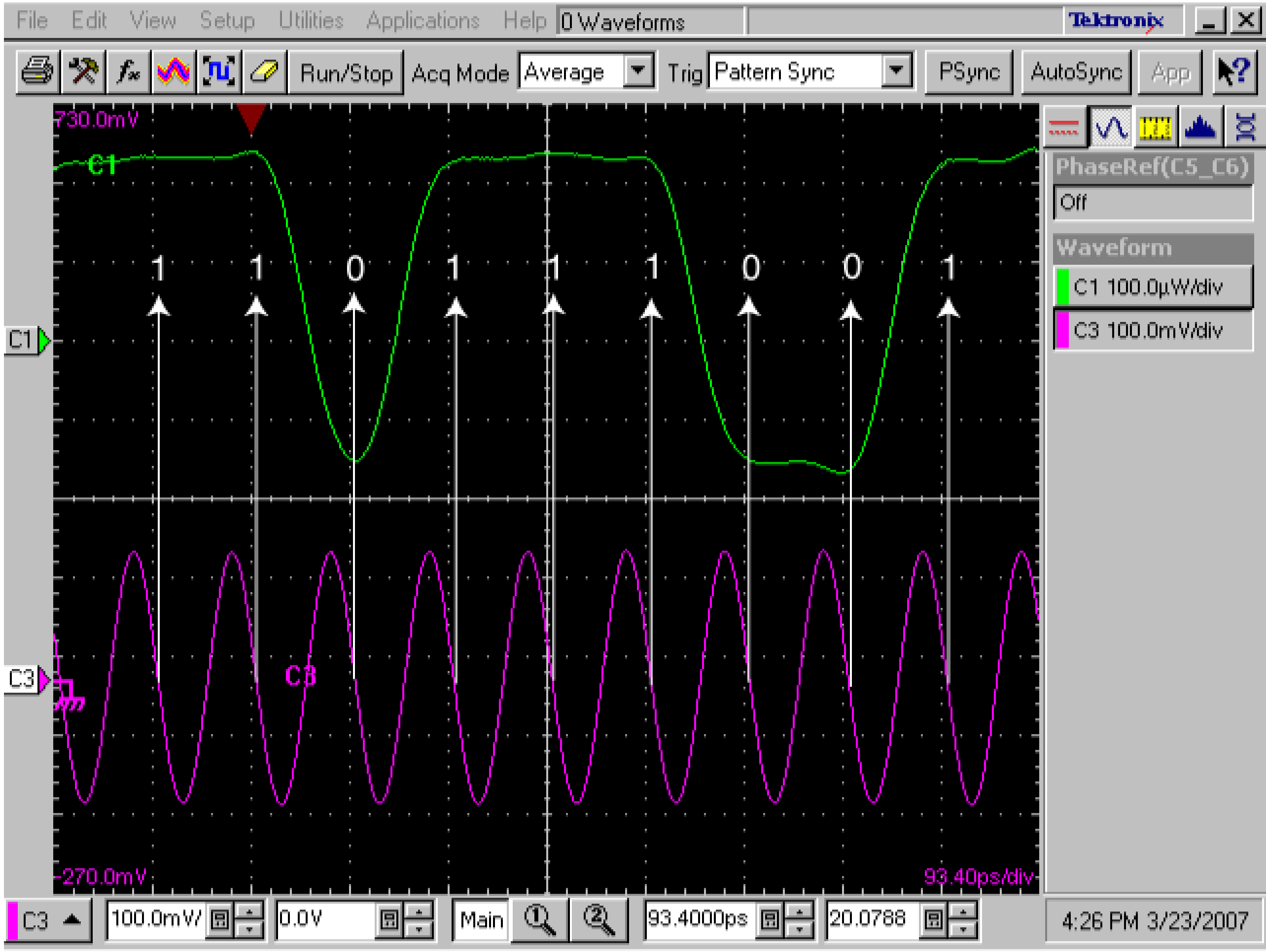
Rx samples at the center of each bit…

doesn't it?

a)



b)



The ideal world

What if …

- …we could set the sampling point half a bit period after a logic transition, regardless of how much jitter is on the signal?
- … the sampling point had the same jitter as the data?

What if we could build an infinite bandwidth clock recovery circuit?

If the data and clock have the same jitter…

they dance in harmony

- Bits would be identified not at *ideal* times but at the *best* times

“the jitter on the clock *tracks* the jitter on the data”

BER would not be affected by jitter

Clock Recovery

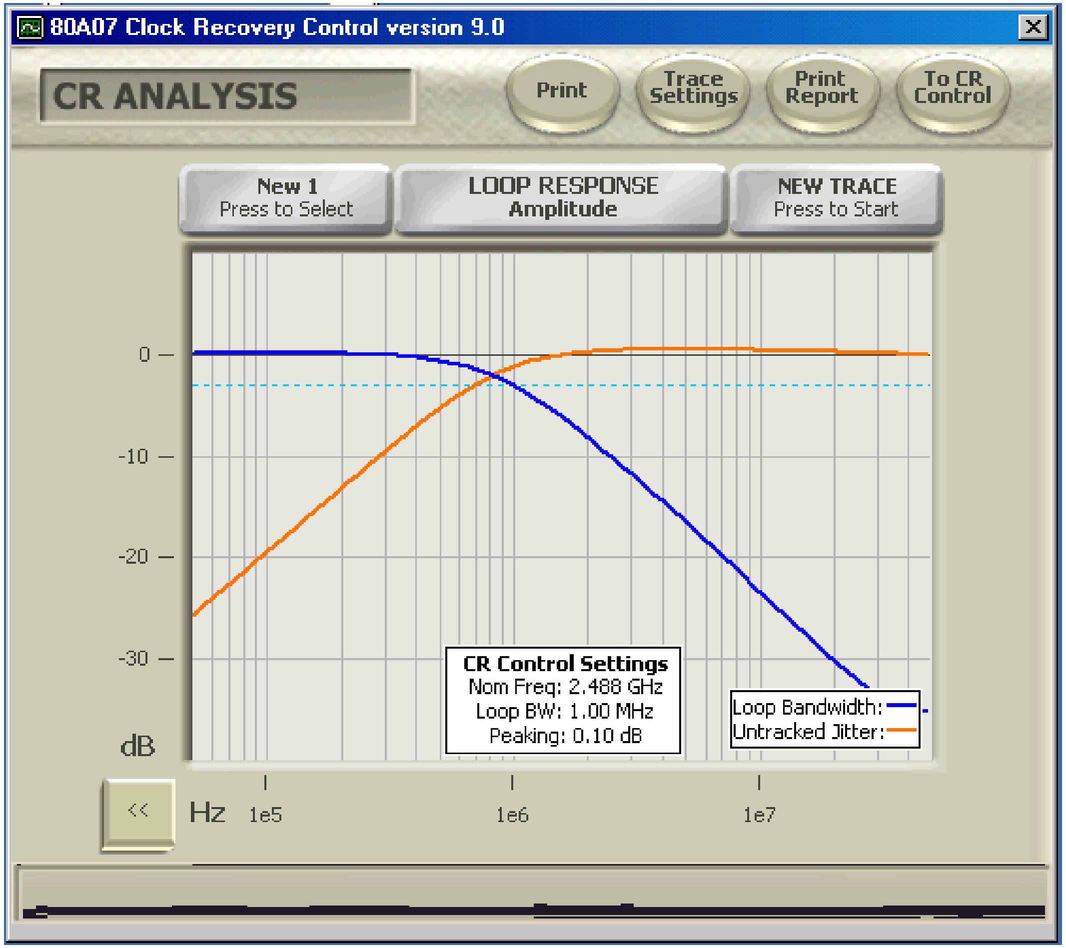
- Phase Locked Loop (PLL) clock recovery
- Phase Interpolator (PI) clock recovery
  - Uses sampling – “digital” techniques
  - Faster lock time, less power, less PCB area
  - Harder to model than PLLs, harder to debug
- Standards use parameters from PLL theory
  - 2nd order PLL transfer function:

$$H(s) = \frac{2s\zeta\omega_n + \omega_n^2}{s^2 + 2s\zeta\omega_n + \omega_n^2}$$

  - Key parameters: peaking, ζ, and ω_n bandwidth, ω_{3dB}:

$$\omega_{3dB} = \omega_n \sqrt{1 + 2\zeta^2 + \sqrt{(1 + 2\zeta^2)^2 + 1}}$$

Clock Recovery Frequency Response



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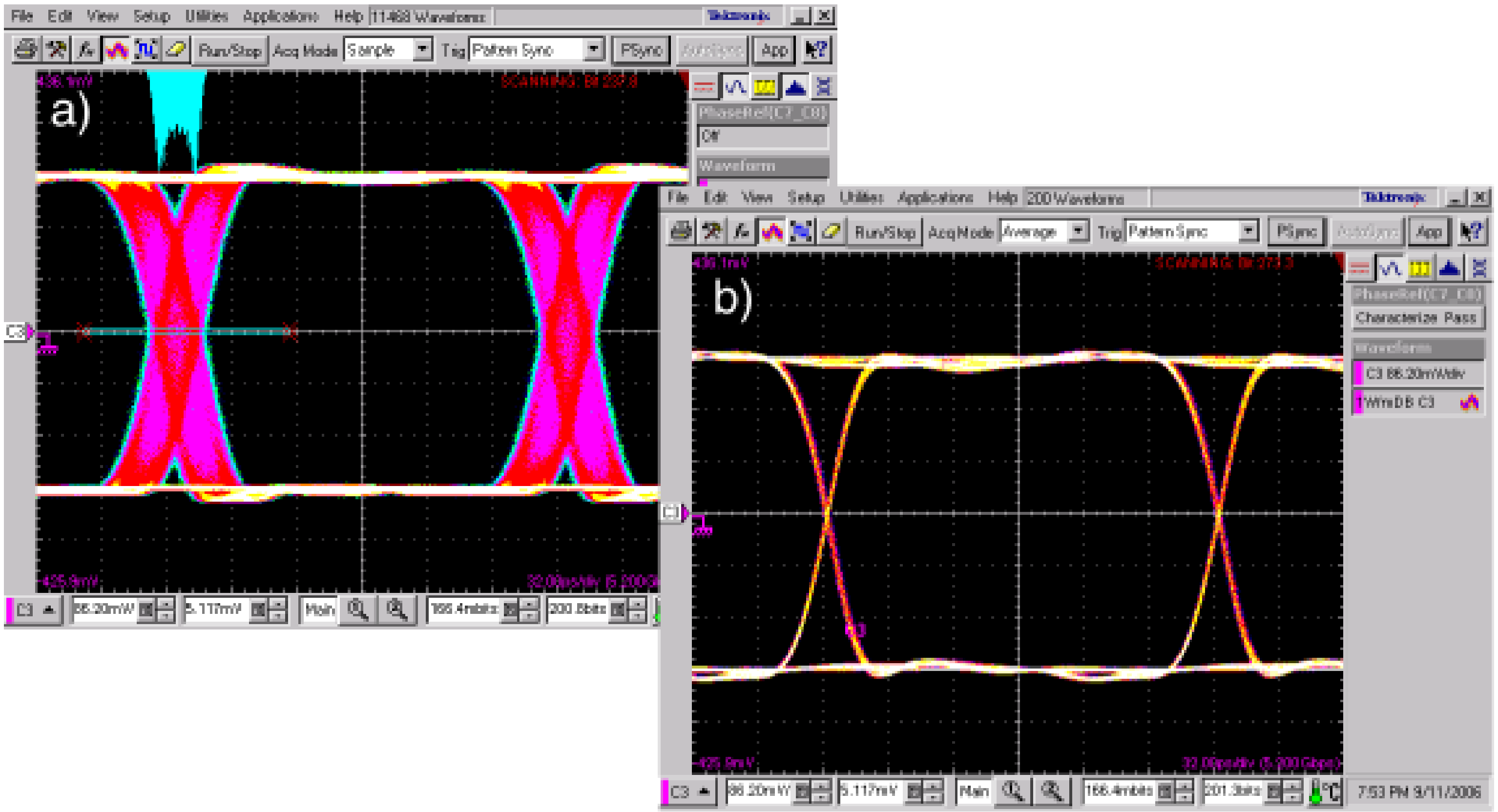
Effect of CR Bandwidth on Eye Opening



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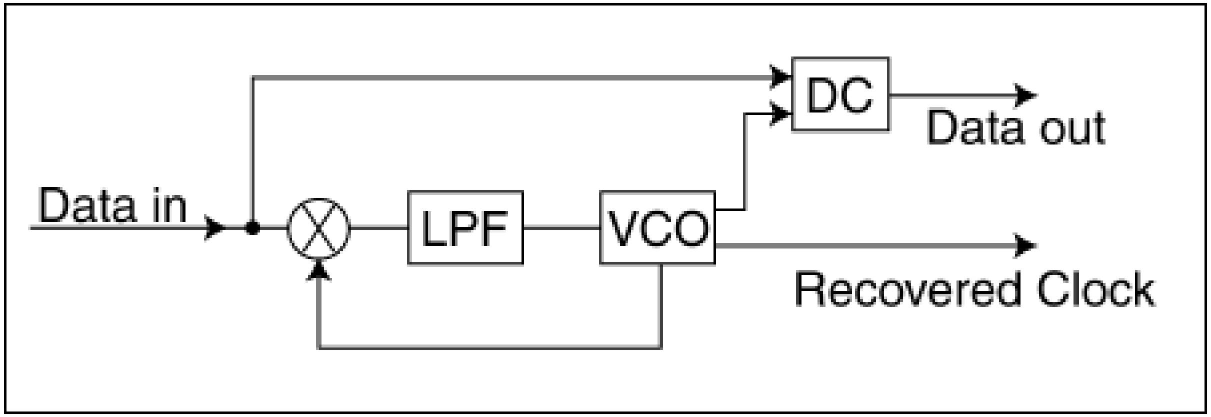
Phase Locked Loop Clock Recovery

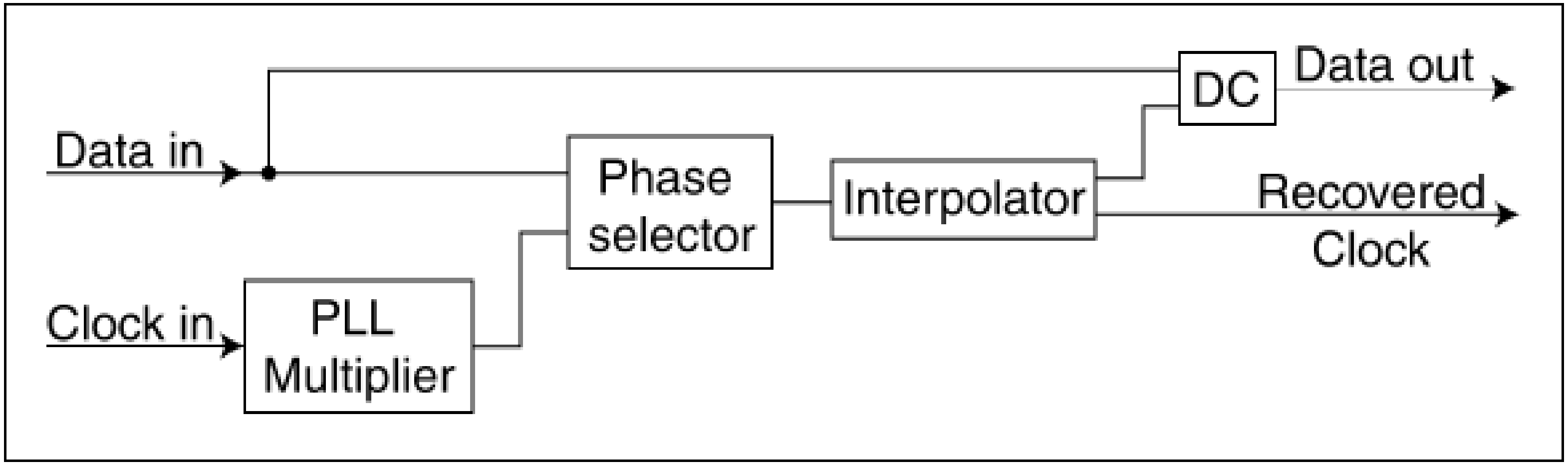


To extract a useful clock, the data must…

- Have plenty of logic transitions
  - No long runs of identical bits
- Be DC balanced

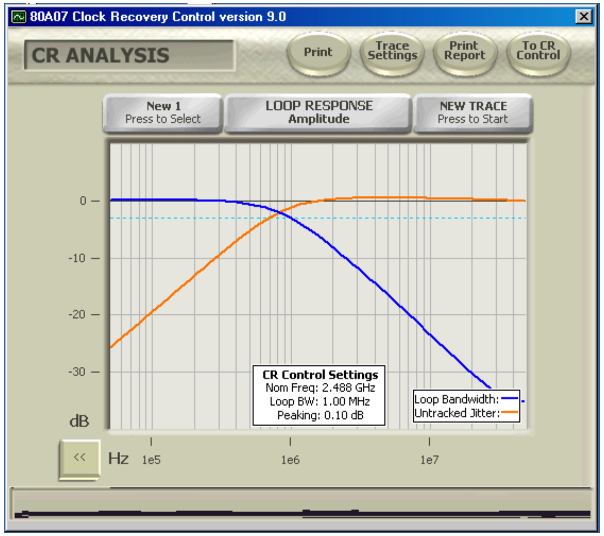
Data signals are encoded, e.g., 8B/10B encoding

Phase Interpolator Clock Recovery



The Problem of Delay

- Net delay between the recovered clock and data is bad!
  - Jitter on the clock is only “good” if it’s the same jitter as on the data
- There is a coherence phenomenon between the jitter on the recovered clock and data – the longer the delay, the less correlated is the jitter.
- As the delay increases, lower frequencies of jitter cause more problems.



Spread Spectrum Clocking

- Low frequency clock modulation
  - 33 kHz FM at amplitudes of 0 to -0.5% of data rate
  - Typically triangle-wave or “Lexmark Hershey’s Kiss” shape
- Smears radiated energy into larger frequency band
  - Easier to pass FCC EMI requirements
- Clock recovery bandwidth must be >> modulation bandwidth to prevent SSC from causing errors
- Delay at the transition point from positive to negative changing frequency can cause errors!

(More on SSC in *Part 6: Reference Clock Jitter and Data Jitter*)

Conclusion

- Clock Recovery reduces the BER
- Specifications require

  CR bandwidth larger than some limit

  CR peaking smaller than some limit
- E.g., for FibreChannel 4x at 4.25 Gb/s

  $\omega_{3\ \mathrm{dB}} > 2.55$ MHz

  $\zeta < 0.3$ dB
- We'll revisit clock recovery in Part 6 so, stay tuned…

Thank You!

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Part 6: Reference Clock Jitter and Data Jitter

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6. **Reference Clock Jitter and Data Jitter** ←

Introduction

Just as most

- DDJ is generated in the transmission path
- PJ is caused by electromagnetic interference of some sort

Most Random Jitter (RJ) is generated by the reference clock

For rates > 2 Gb/s,

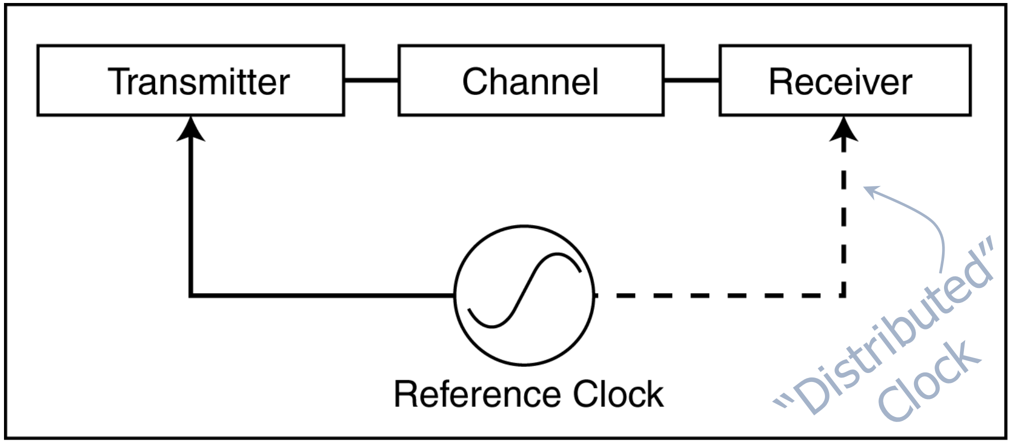
- Need to specify reference clock jitter separate from transmitter jitter

Introduction (2)

- *Four* primary components of a serial-data system

The reference clock

1. Defines the timing of logic transitions at the transmitter
2. Provide the timing reference necessary for the receiver to set the time-delay of the sampling point



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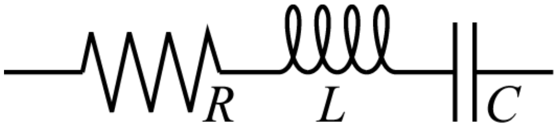
Oscillators

The oscillator provides the periodic structure of a digital system

- Oscillator parameters, based on an under-damped LRC oscillator:

Resonant frequency: $$f_R = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \left(R/2L\right)^2} \approx \frac{1}{2\pi\sqrt{LC}}$$

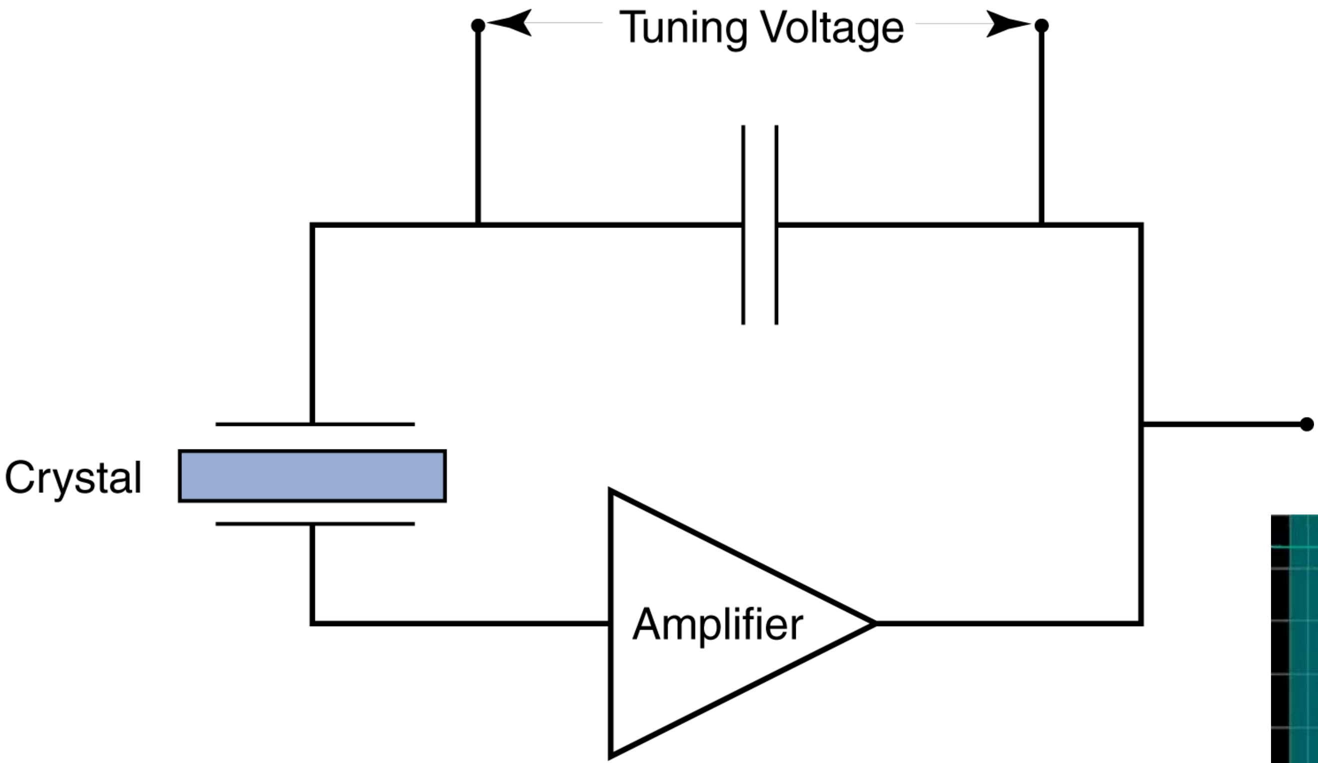


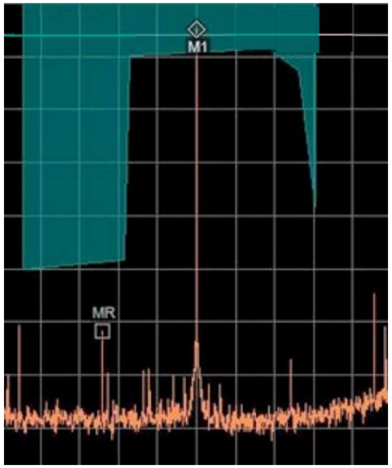
Damping factor: $$\zeta = R/2L$$

Bandwidth: $$\Delta f = \frac{\zeta}{\pi} = \frac{R}{2\pi L}$$

Quality: $$Q = \frac{f_R}{\Delta f} = \frac{1}{R}\sqrt{\frac{L}{C}}$$

Crystal Oscillators





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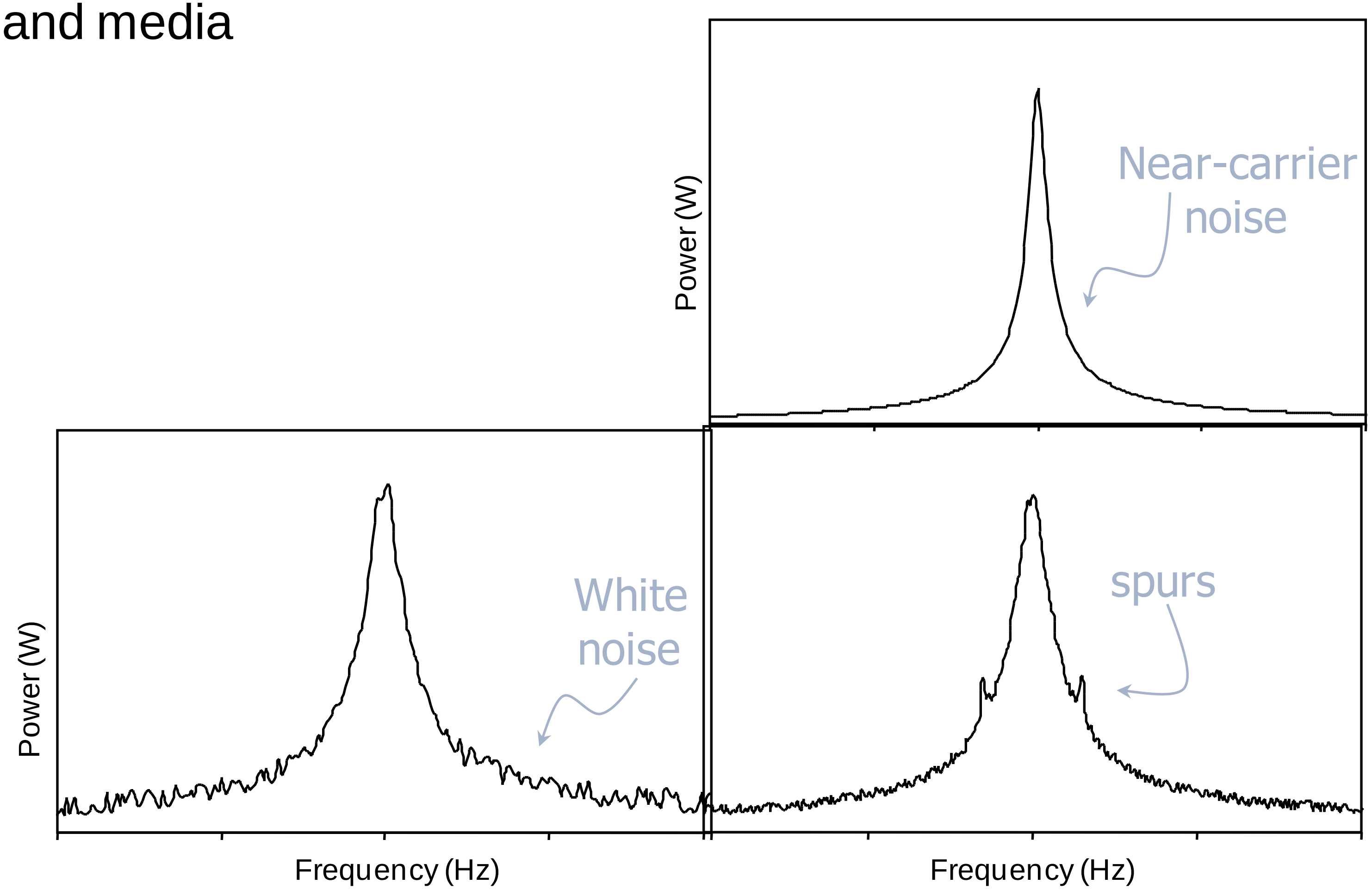
Crystal Oscillators (2)

- f_R comes from geometry and media



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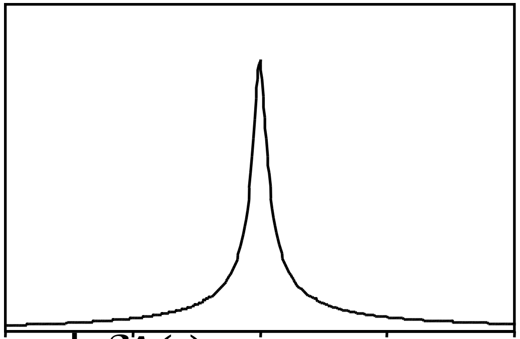
Crystal Oscillators (3)

Ideal: $$\psi(t) = A\sin(2\pi f t)$$

Real: $$\psi(t) = (A + \delta A(t))\sin(2\pi f t + \varphi(t))$$

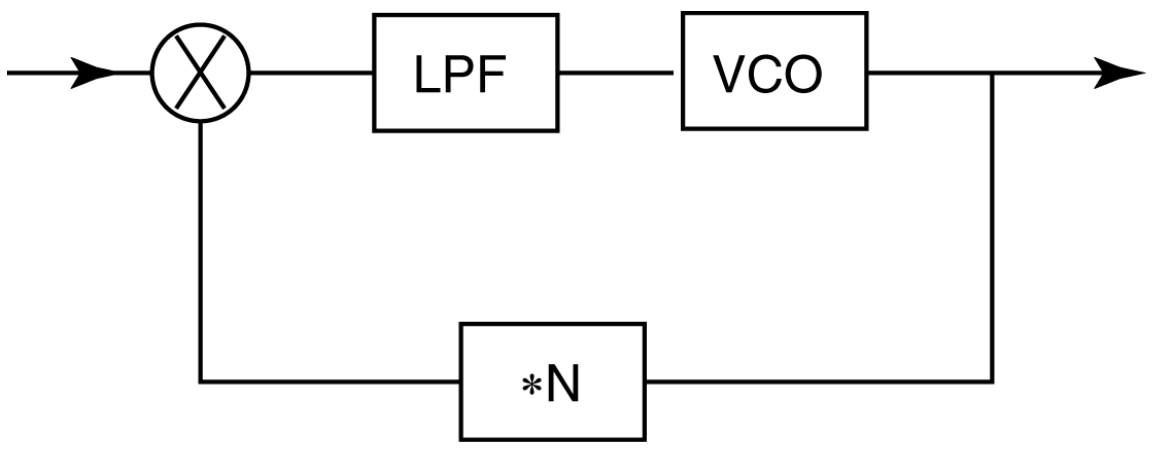


- RJ comes from the continuum background of $\varphi(t)$ and $\delta A(t)$
- RJ is most difficult to debug
  - Broad resonance → vibration, shock, temperature variations,
  - Lorentzian shape → flicker
  - Asymmetric, flat-topped → bad crystal
  - Wide, lumpy resonance → noisy electronics
  - White Noise → thermal noise in electrical components
- RJ can't be reduced by a limiting amp
- RJ can be reduced by a filter

At the Transmitter

To convert reference clock to data-rate → PLL multipler

- Frequency multiplication increases 20 dB for each 10 dB increase
- PLL multiplier adds more RJ
- PLL nonlinearities cause Duty Cycle Distortion (DCD)



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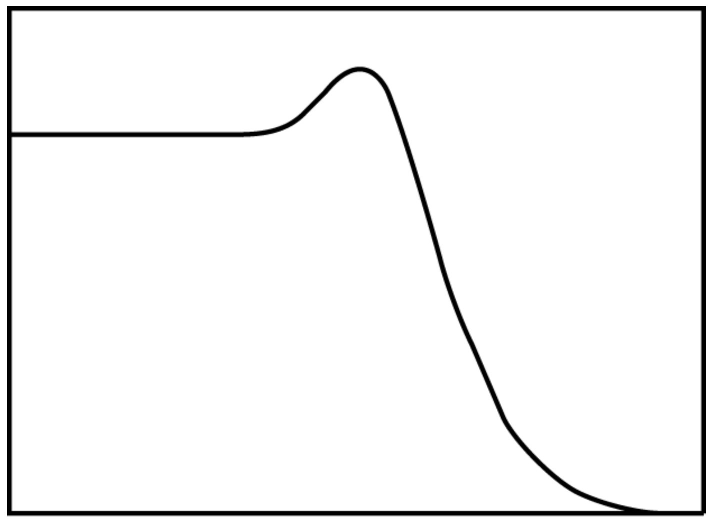
At the Transmitter (2)

- The PLL multiplier is also a filter:



- What jitter frequencies can affect BER?

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At the Receiver

- Data-rate clock is recovered at the receiver
  – With or without a distributed reference clock

Does the jitter on the recovered clock track the jitter on the data?

- If **Yes** → jitter is irrelevant to BER
- IF **No** → Jitter degrades BER

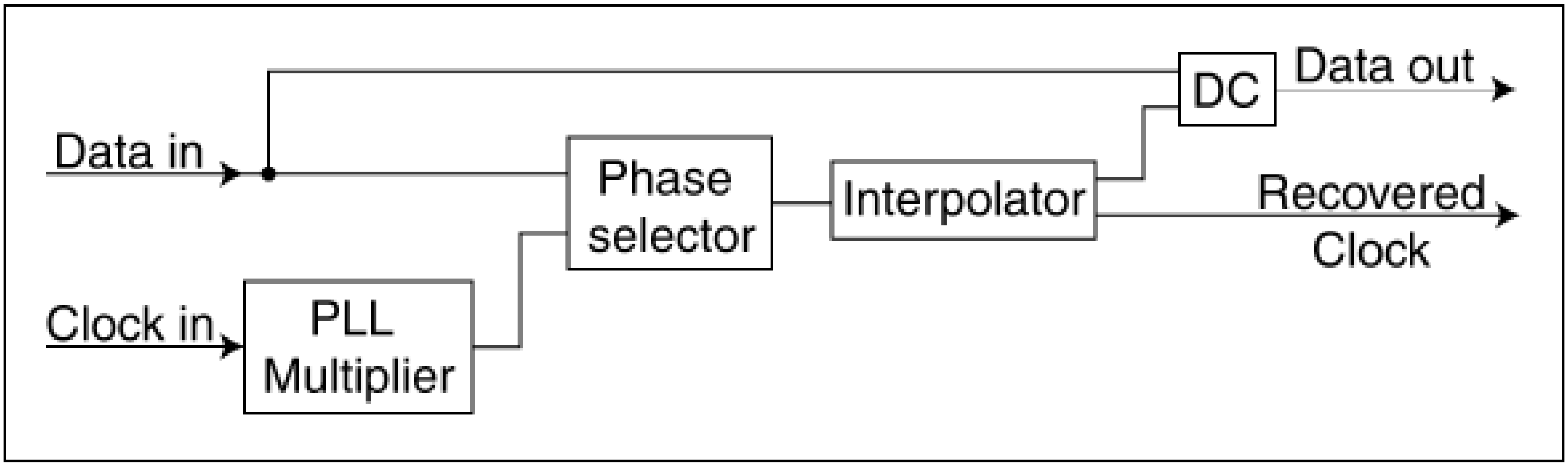
Ideal situation:

Low bandwidth transmitter PLL multiplier

Wide bandwidth receiver clock recovery

At the Receiver (2)

- Phase Interpolator clock recover has an additional PLL-multiplier



- Mismatched transmitter/receiver multipliers have different jitter-frequency response → jitter on data not tracked by receiver.

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Analyzing Clock Jitter

- Traditional clock spec's – like cycle-to-cycle jitter – don't answer the only relevant question:

What impact does the clock have on the Bit Error Ratio?

- Clocks *should* be spec'ed with their RJ and DJ under different Transmitter/Receiver assumptions so that the clock TJ(BER) can be estimated during system design.

Analyzing Clock Jitter (2)

Real-time Oscilloscopes and Spectrum Analyzers can simulate the bandwidth effects by applying transmitter/receiver transfer functions to captured data

- Apply DSP to the timing of logic transitions, $\{t_n\}$ or frequency spectrum $\{f_n\}$ → apply jitter analysis techniques (e.g. JIT3) to get the relevant RJ, DJ
- Use TJ(BER) = $2Q_{BER} \times$RJ + DJ

Conclusion

1. Reference clock jitter has a major effect on system BER
2. Ref Clock is the primary RJ source
3. The transmitter PLL-multiplier amplifies jitter by the square of the multiplication factor
4. Narrow bandwidth transmitter PLL-multipler + wide bandwidth receiver clock recovery → minimum clock TJ(BER)
5. Reference clocks can be evaluated under different Transmitter/Receiver assumptions → clock RJ and DJ, TJ(BER) estimates

Thank You!