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Jitter Measurements in Digital Circuits

January 24th, 2003

presented by:

Brian Fetz

Agenda Topics

- Introduction to Jitter
  - Jitter Basics
  - Random and Deterministic Jitter
  - A Signal Case Study
- Jitter Measurement Views
  - A Generalized Device Under Test Model
  - Important Views of Jitter
- Jitter Evaluation Tools
  - Jitter Solution Types
  - Strengths and Weaknesses
- Summary

Introduction to Jitter

- **Dictionary:**

  Jitter (verb) – show nervousness or apprehension.
  Jittery (adj) – anxious and quaking

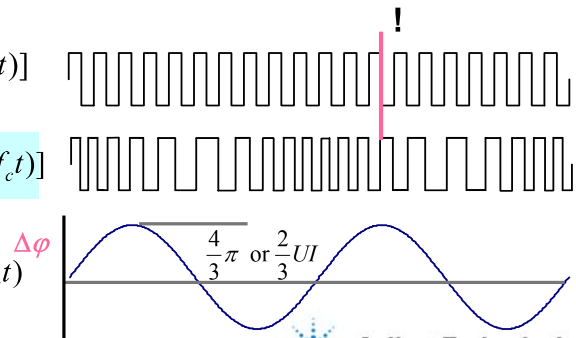
- **Electrical:**

  Jitter (noun) – the short term phase variation of the significant instants of a digital signal from their ideal positions in time.

$$P[\sin(2\pi f_c\, t)]$$

$$P[\sin(2\pi f_c\, t + \frac{4}{3}\pi \sin(\frac{1}{10} 2\pi f_c t)]$$

$$\frac{4}{3}\pi \sin(\frac{1}{10} 2\pi f_c t)$$



Jitter as Phase Deviation

$$S(t) = P(2\pi f_d t + \varphi(t)) \rightarrow \text{!!!}$$

- **Jitter**
  - **Is Phase Noise---Time, Modulation, Frequency Domains!**
  - **Is the variation of the actual from the ideal phase:** $J \propto \Delta\varphi$
  - **Is represented in various equivalent dimensions**

$$J[\mathrm{UI}] = \frac{1}{2\pi}\Delta\varphi[\mathrm{rad}]$$

$$J[\mathrm{s}] = \frac{1}{2\pi f_d}\Delta\varphi[\mathrm{rad}]$$

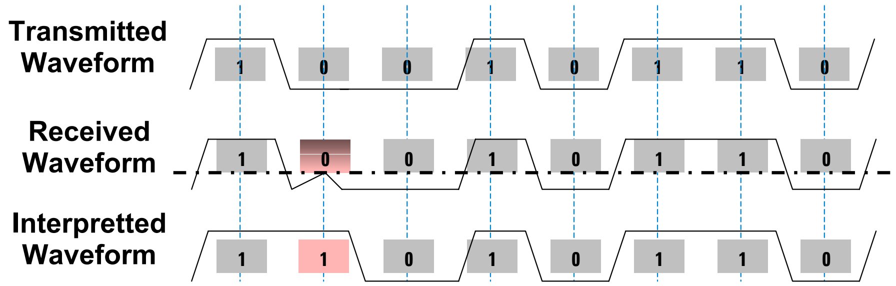
Unit Intervals

Radians (or Degrees)

picoSeconds

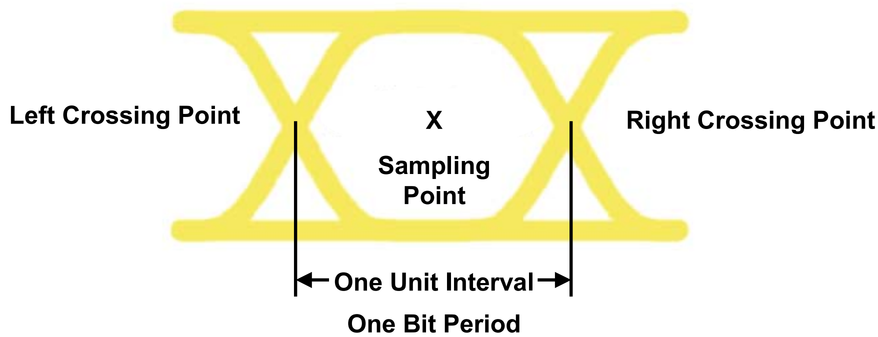
Why do we Care about Jitter?

- **It Causes Transmitted Bit Errors!**

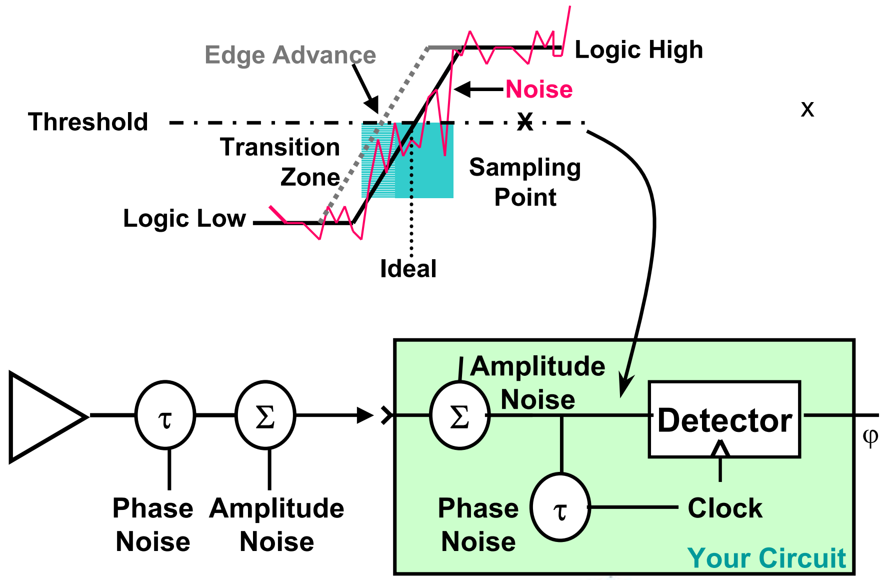


A Fundamental View of Jitter

- **The Eye Diagram**



Transition Model for Jitter



Jitter – What Causes It?

- Oscillator Topology
- PLL Design
- Crystal Performance
- Thermal Noise
- Shot Noise
- Dispersion

Noise Mechanisms

- Reference Spurious
- Radiated or Conducted Signals
- Crosstalk
- Duty Cycle Distortion mechanisms

System Mechanisms

- Inter Symbol Interference mechanisms
- Receiver Detector characteristics
- Clock/Data Recovery Design
- Impedance Mismatch
- PRBS Mechanisms

Data Dependent Mechanisms

Characteristics of the Causes of Jitter

- **Causes of Jitter are categorized Two Ways:**
  - **Those where the phase deviation achieves a Max and a Min value over an identifiable time interval..**

And….

  - **Those that don't!!**

$$P(\sin(2\pi f_d t + \varphi(t)))$$

$$P(\sin(2\pi f_d t + \varphi_B(t) + \varphi_{UB}(t)))$$

$\varphi_B(t)$ is composed of functions that have Bounded phase deviations because their max amplitudes don't change

$\varphi_{UB}(t)$ is composed of functions that have UnBounded phase deviations because their max amplitudes do change. The functions are characterized by their statistics

Lets Look at the Sources Again…

- Oscillator Topology
- PLL Design
- Crystal Performance
- Thermal Noise
- Shot Noise
- Dispersion

} Noise → UnBounded

- Reference Spurious
- Radiated or Conducted Signals
- Crosstalk
- Duty Cycle Distortion mechanisms

} System

- Inter Symbol Interference mechanisms
- Receiver Detector characteristics
- Clock/Data Recovery Design
- Impedance Mismatch
- PRBS Mechanisms

} Data

System + Data → Bounded

Expressing Jitter

- Usually represented as root-mean-square, J_{rms}, and peak-to-peak, J_{PP}

  Random Jitter (RJ) – results from the accumulation of random processes.
  - Assumed to Follow a Gaussian Distribution
    RJ contribution to J_{rms} is $J_{rms}^{RJ} = \sigma$
  - Since a Gaussian function is <u>unbounded</u>,
    RJ contribution to J_{PP} can be large $J_{PP}^{RJ} \to \infty$

  Deterministic Jitter (DJ) — results from systematic effects
  - E.g., duty-cycle-distortion (DCD), intersymbol interference (ISI), periodic jitter (PJ), PRBS effects, and crosstalk
  - DJ is <u>bounded</u>, J_{PP}^{DJ} is finite.

- Most useful to characterize jitter as a combination of J_{rms}^{RJ} and J_{PP}^{DJ} at a given Bit Error Ratio (BER)

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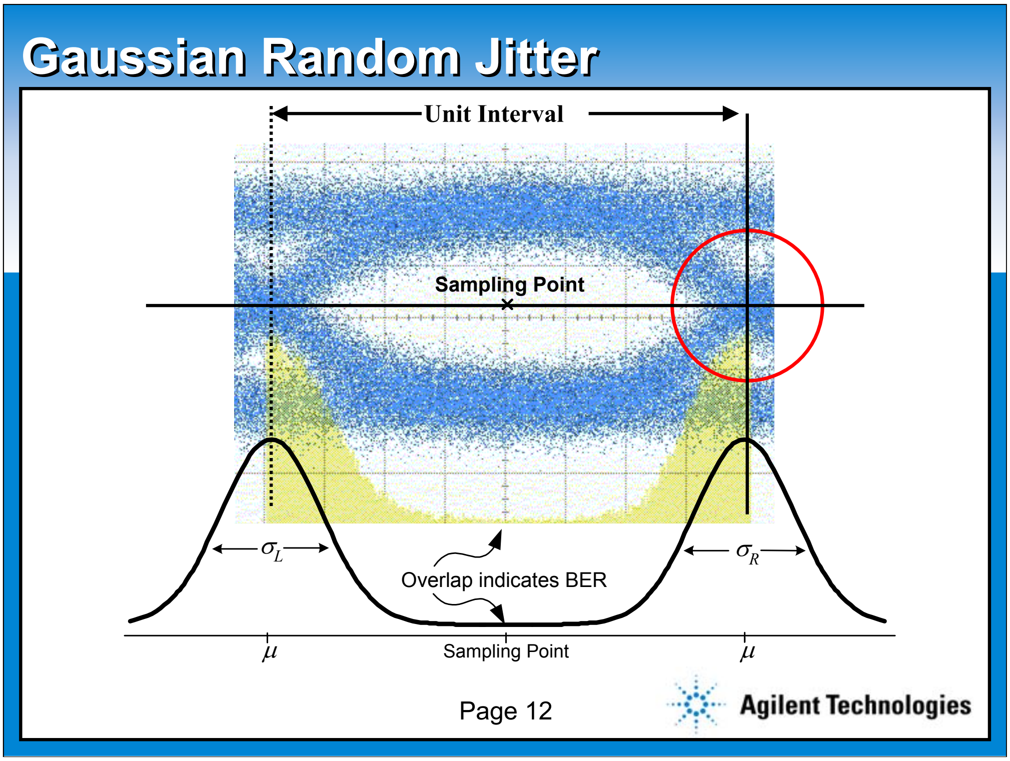
Test patterns induce data dependent jitter



There is random and there is gaussian random---

This is linear view of histogram and is hard to differentiate the effects at the bottom. In Log mode can see tail effects clearly. If sigmas aren't equal then we don't have true random---if these are significantly different we might be talking about deterministic type PRBS effects.

Peak-to-Peak Jitter Generation

Designing to a Jitter and BER Budget

- Since J_{PP}^{RJ} is unbounded, it can be *defined* by the BER that would result if there were *only* RJ. This is where the tails of the right and left distributions overlap (at the Sampling point):

For a BER = $10^{-12} \rightarrow J_{PP}^{RJ} = 14\times\sigma$ … *7 for each tail*

Then $J_{PP}^{RJ} \equiv n\times\sigma$ so that $J_{PP}^{RJ} = nxJ_{rms}^{RJ}$

- The Total Jitter (TJ), J^{TJ}, for a given BER is then

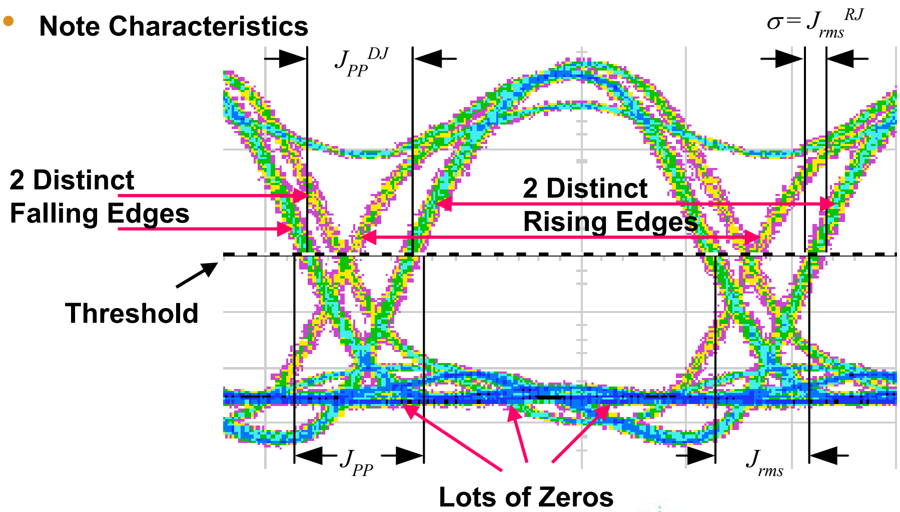
$$\begin{aligned} J^{TJ} &= n\times J_{rms}^{RJ} + J_{PP}^{DJ} \\ &= 14\times\sigma + J_{PP}^{DJ} \end{aligned}$$

which can be compared to a given jitter + BER budget

- J_{PP}, is useful for isolating rare error causing events.

Random and Deterministic Jitter

- Waveform Observation
- Pattern
- Note Characteristics



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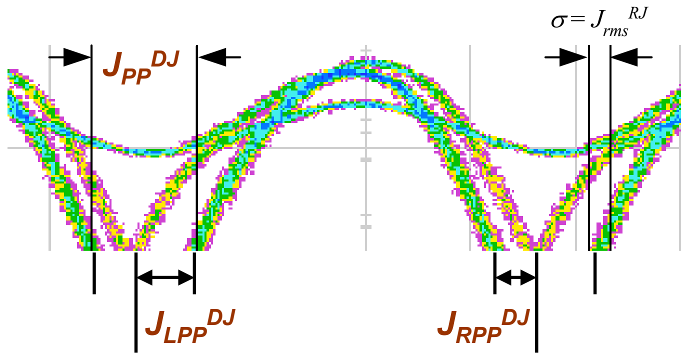
Random and Deterministic Jitter

- **Lets Look at Deterministic Component…**



$$J_{LPP}^{DJ} + J_{RPP}^{DJ} = J_{PP}^{DJ}$$

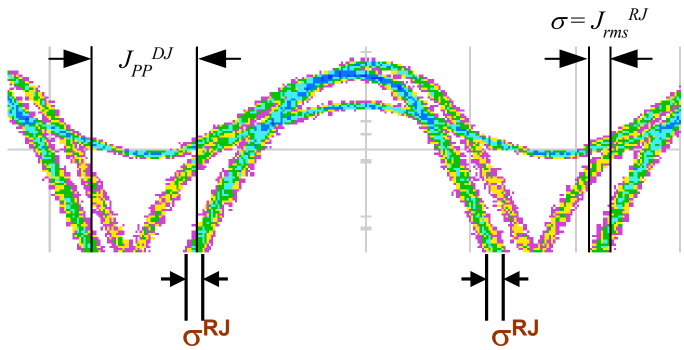
The Peak-to-Peak Deterministic value is the Delta between Worst case mean trajectories around a crossing point.

Make note that it is not the difference between the two rising edges but the worst case between a determined crossing point and a rising signal.

Also for convenience I have used both crossing points---it applies to either

Random and Deterministic Jitter

- **Now lets Look at the Random Component…**

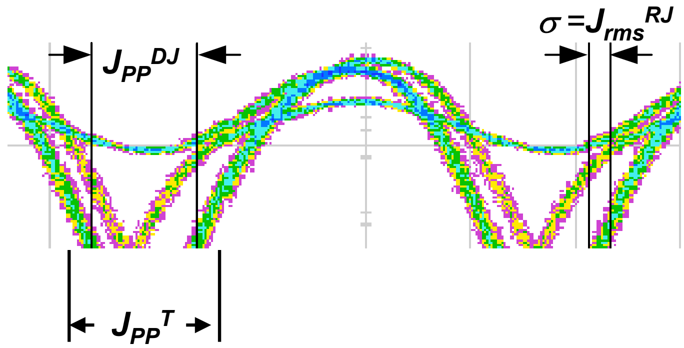


σ^{RJ} is a measure of the process that makes these traces wide

Note the Deterministic bias and need to add process spread

Random and Deterministic Jitter

- Now lets Summarize Jitter for the Circuit Measured…



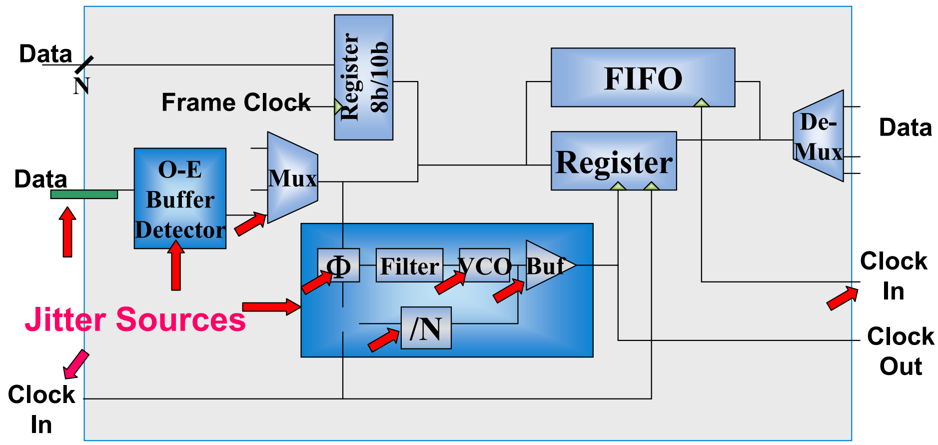
$$J_{PP}^{T} = n \text{ x } \sigma^{RJ} + J_{PP}^{DJ}$$

Caution is if long PRBS pattern then mis-estimation of sigma can occur. Can look random….

Jitter Introduction Summary

- Jitter is Time Shift or Phase Delay which allows for Time, Modulation, or Spectrum Analysis.
- Excessive Jitter Causes Bit Errors.
- The Sources of Jitter are many and they are classified as Unbounded or Bounded.
- Unbounded implies Random Processes and assumed Gaussian Distributions. The maximum value of such processes will increase over a growing observation period.
- Bounded processes are deterministic, or systematic, and will have a peak-to-peak value over a time interval.

General DUT Model



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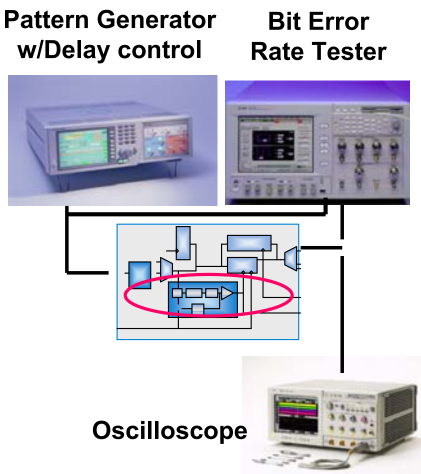
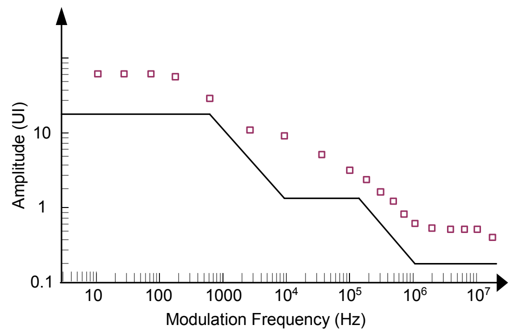
Important Jitter Views

- Jitter Tolerance
- Jitter Transfer
- Intrinsic Jitter Spectrum
- Eye Diagram
- Histograms
- Bathtub Plot
- FFT of Time Interval Error
- Separation of RJ/DJ

Jitter Tolerance (SONet/SDH)

- Ability to track large amounts of jitter before degrading the BER
  The amplitude of sinusoidal jitter applied to a device that results in an equivalent 1 dB reduction in sensitivity





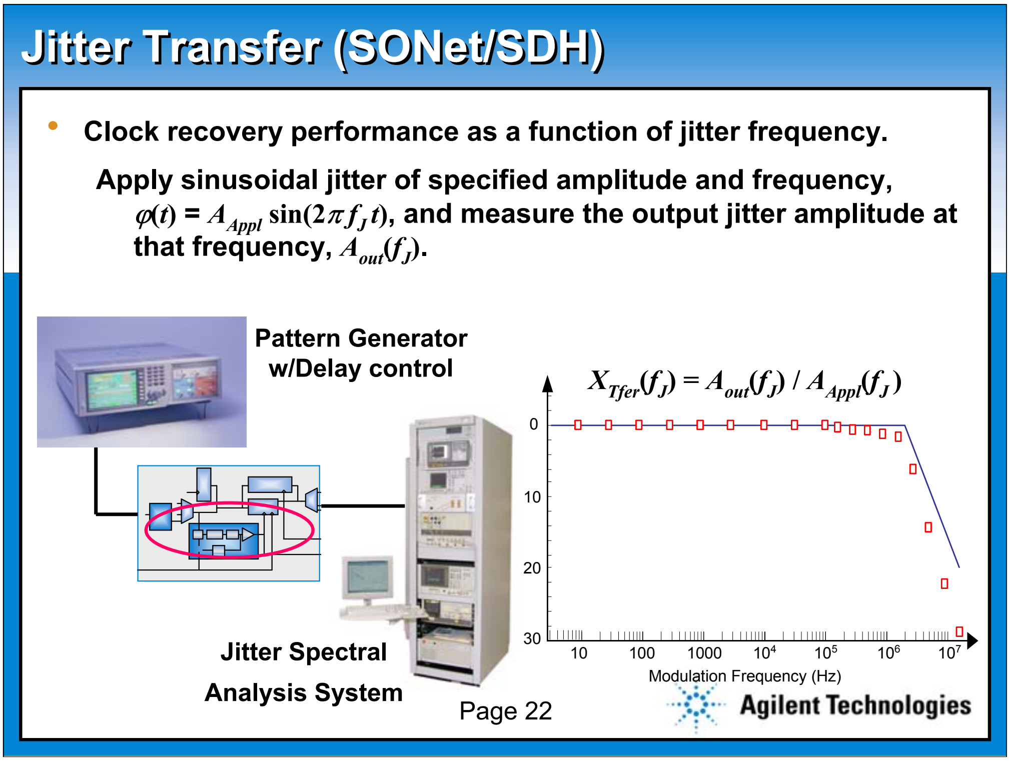
Measure BER without applied jitter

Attenuate until onset of errors or a given BER

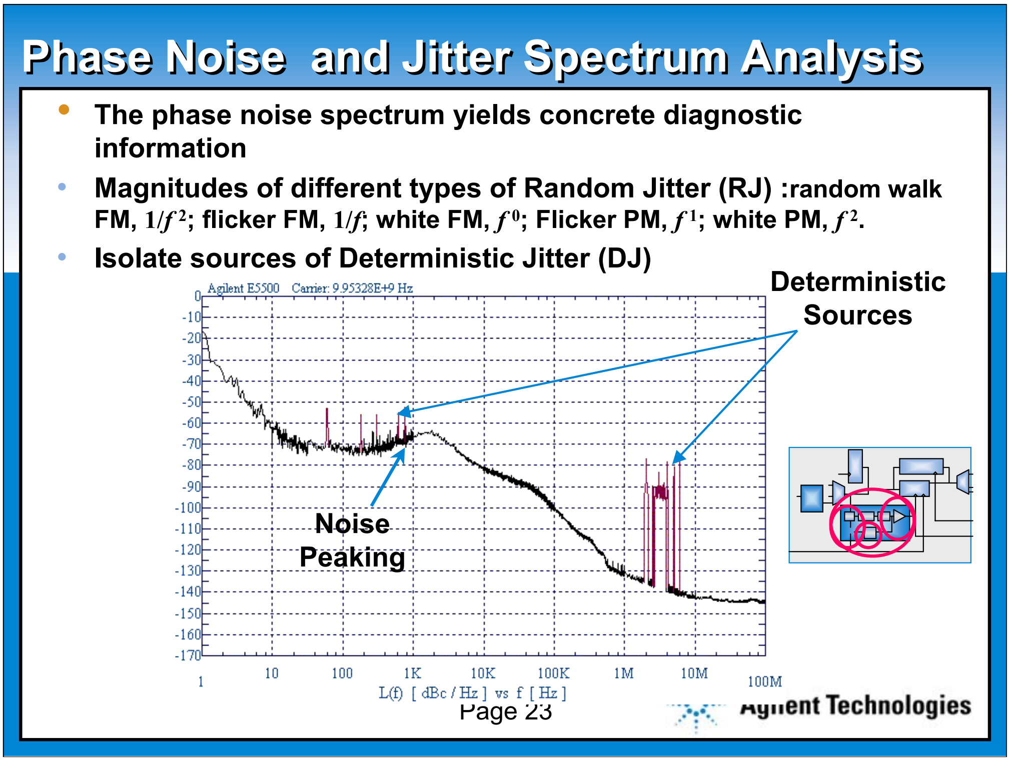
Reduce attenuation by 1 dB

Transmit unattenuated signal with applied sinusoidal jitter, $\varphi(t) = A_{Appl} \sin(2\pi f_J t)$.

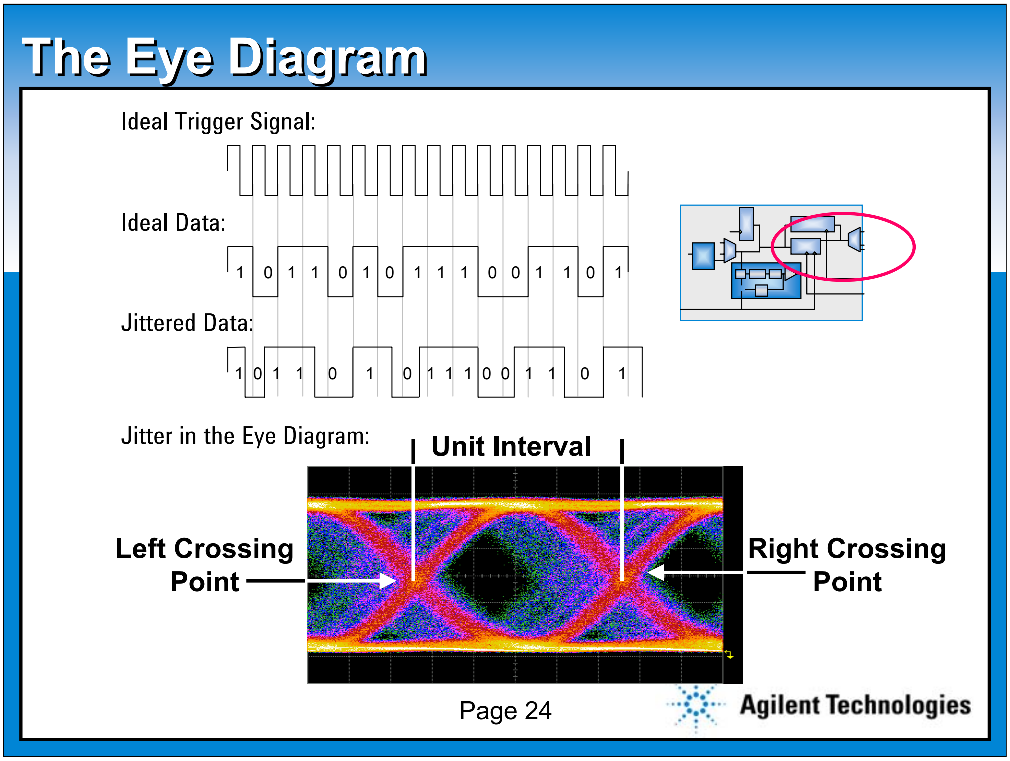
Increase A_{Appl} **until onset of errors or a given BER**



System to handle the spectral content of jitter



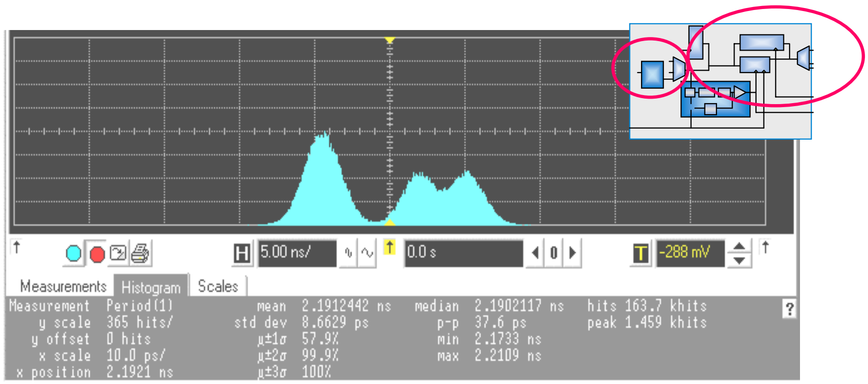
- **Jitter Generation**
  - **Band limited rms and peak-to-peak without RJ/DJ separation**
  - **Wide Bandwidth Peak-to-Peak with RJ/DJ separation**
  - **This measurement must be done at many different offsets as the shape of the noise changes**
  - **Most accurate way to measure phase non-idealities within the measurement bandwidth available**



Particularly good at showing Intersymbol Interference—which is caused by having a low pass structure on the transmission line or alternatively a high pass structure from capacitively coupling signals. In the first case the lpf prevents final value of a transmission to be reached in the appropriate amount of time (bit period) and in the other dc bias of the signal changes with data because of droop which affects effective threshold point.

Histograms

- **Two Classes of Histograms:**
  1. **Diagnostic or Waveform Parametric (Duty Cycle, Rise Time, Fall Time, etc)**



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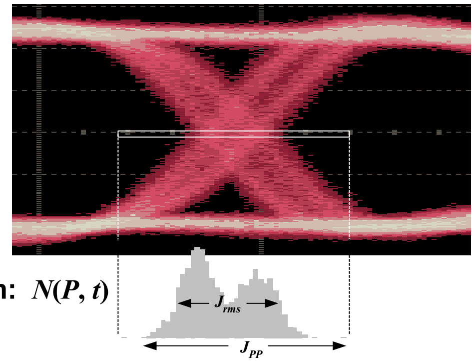
Time domain measurements of large amounts of jitter is pretty easy… the smaller amount of jitter the more errors you will see

Histograms

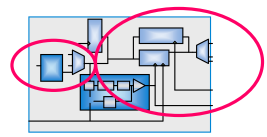
2. Time Interval Error

(Referenced to Recovered Clock). The intensity (or color) of each pixel indicates the number of instances, N, that a pulse was sampled with that power, P, at that time, t



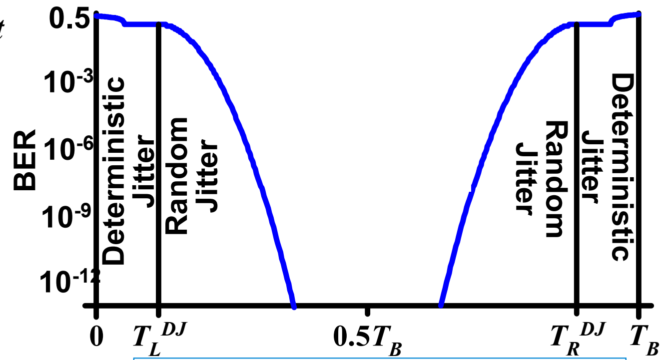
A two dimensional histogram: $N(P, t)$

- Jitter generation is measured by projecting a pixel-wide slice of the crossing point onto the time axis, $N_{crossing\ point}(t)$, and calculating
  J_{PP} = distance in time between extreme points of $N_{crossing\ point}(t)$
  J_{rms} = the standard deviation of the histogram
- This measurement is not band limited

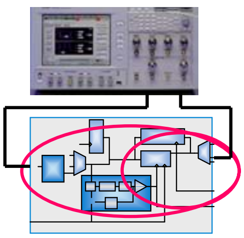


The Bathtub Plot

1. Bit Error Rate versus Sampling Point Location
2. Step the sampling point from the center to the crossing points.
3. Measure BER vs. t



Bit Error Rate Tester

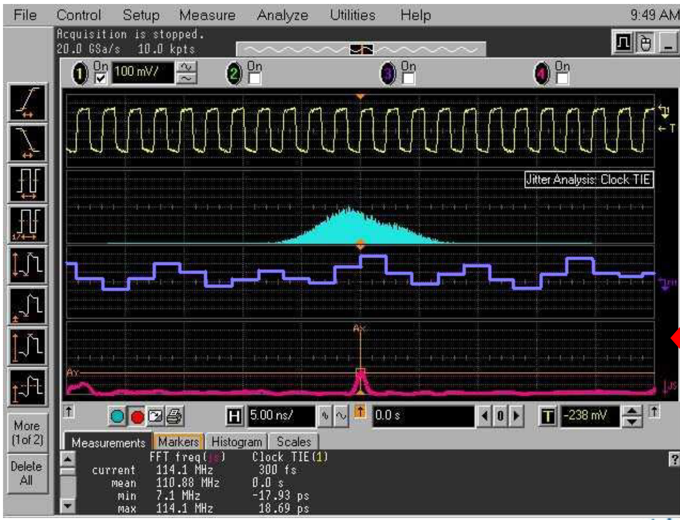


$$T_L^{DJ} < t < T_R^{DJ}$$

$$\mathrm{BER}_{RJ}(t) = N_L \,\mathrm{erfc}\left(\frac{t - T_L^{DJ}}{\sqrt{2}\sigma_L}\right) + N_R \,\mathrm{erfc}\left(\frac{t - T_R^{DJ}}{\sqrt{2}\sigma_R}\right)$$

Jitter Spectrum (FFT of Time Interval Error)

- Great Diagnostic Tool

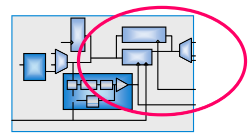


Data

Histogram

T.I.E. vs. Time

FFT of T.I.E.



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456 MHz clock signal. With 114 MHz /4 subharmonic that causes transition errors. Low frequency hump appears random---when you put it in infinite persistence mode the hill grows over time… Very suspicious because it is not white in nature…

FFT of waveform parametrics is possible as well.

Analogous to phase noise measurements---low level of resolution limits the fft.

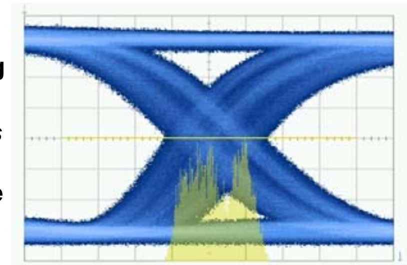
Measuring things with Sonet compliance vs stuff outside SONet. Sonet differentiates between wander and jitter… phase noise looks at each zero crossing---comparing with a low jitter clock. This gives good view of large contributors

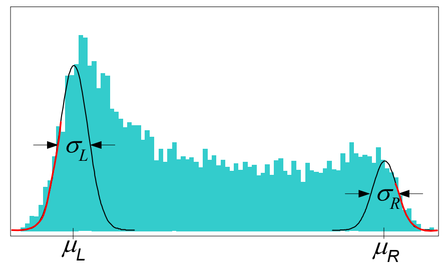
Separating RJ and DJ

1. Project the histogram of the crossing point
2. Fit Gaussian distributions to the *tails* of the distribution outside the DJ dominated region, where eye-closure is due to RJ.

$$A \exp\left[-\frac{(t-\mu)^2}{2\sigma^2}\right]$$

3. Obtain the means: μ_L & μ_R and the widths: σ_L & σ_R.
4. Separate RJ and DJ: $J_{PP}^{DJ} = \mu_L - \mu_R$ and $J_{rms}^{RJ} = ½ (\sigma_L + \sigma_R)$
5. σ_L and σ_R are assumed different!





Major assumption is skirt is gaussian. If crossing is long PRBS data pattern then assumption doesn't hold. It looks gaussian, however the linear represntation is deceiving. Assumption holds if Gaussian is significant portion of total.

The same sigma should be on either side if gaussian random data is truly present

Separating RJ and DJ From BER(t)

- **The Gaussian tail is hiding in the "complementary error function":**

BER = fraction of times the edge fluctuates across the sampling point

= sum of the probability density function on the wrong side of the sampling point

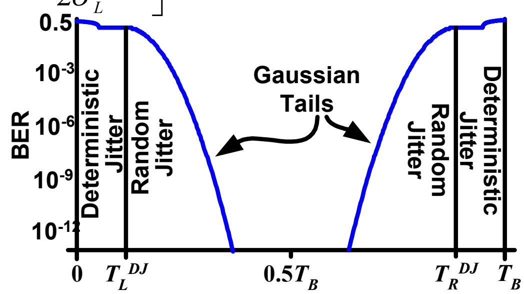
$$\mathrm{BER}_{RJ}^{L}(t) = \frac{1}{\sigma_L}\sqrt{\frac{2}{\pi}} N_L \int_t^{\infty} \exp\left[-\frac{(t' - T_L^{DJ})^2}{2\sigma_L^2}\right] dt'$$

$$= N_L \operatorname{erfc}\left(\frac{t - T_L^{DJ}}{\sqrt{2}\sigma_L}\right)$$

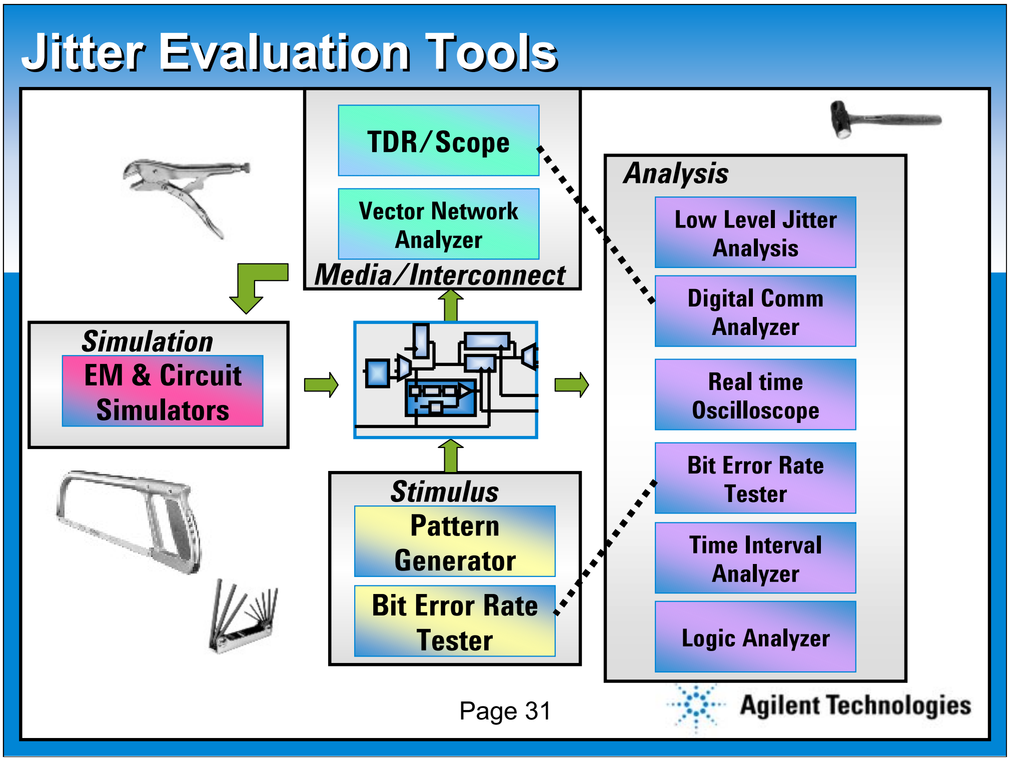
The Gaussian mean and width

$$J_{PP}^{DJ} = T_L^{DJ} + (T_B - T_R^{DJ})$$

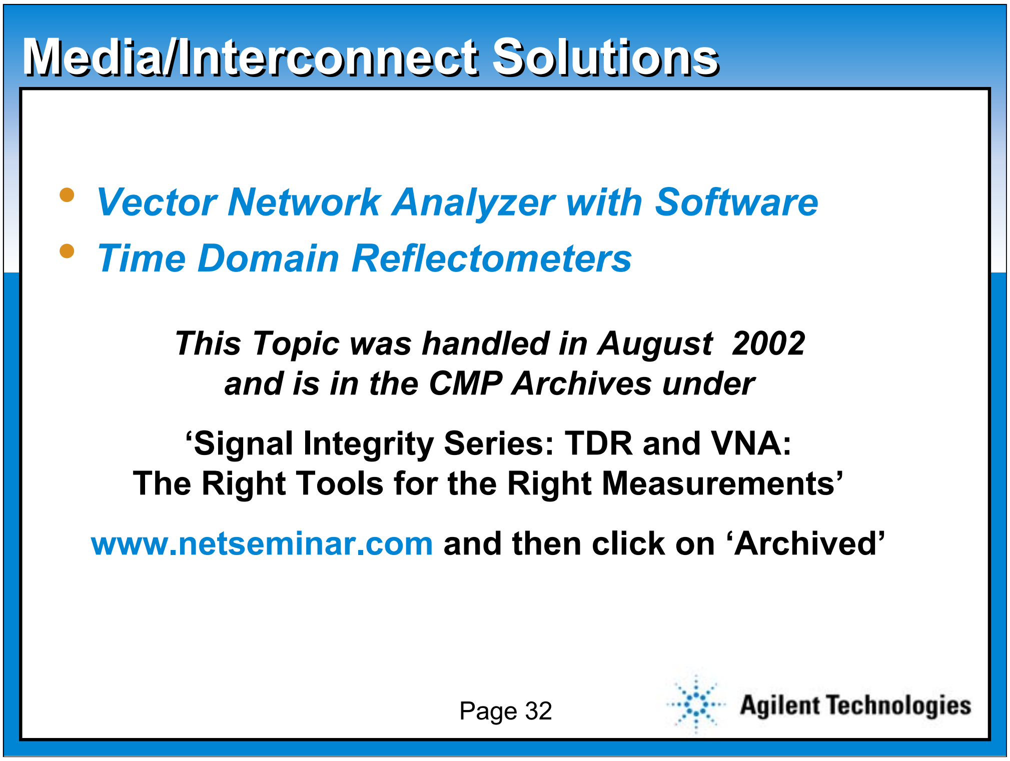
$$J_{RMS}^{RJ} = \tfrac{1}{2}(\sigma_L + \sigma_R)$$



Then use $J^{TJ} = 14.1 \times J_{rms}{}^{RJ} + J_{PP}{}^{DJ}$ for $\mathrm{BER} = 10^{-12}$ a la GigE



Low Level Jitter is Phase Noise



Also known as the physical layer—passive or media/transmission line

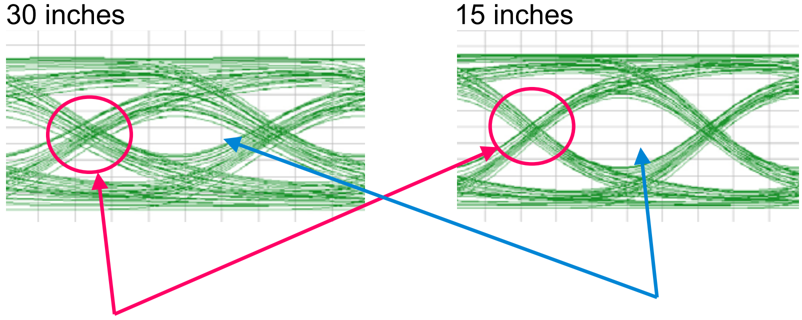
Conclusions from seminar

Media/Interconnect Solutions

Vector Network Analyzer Measurement System
Differential Eye Diagram (from Agilent N1951A)

Xaui Backplane differences because of transmission line length

30 inches 15 inches



Note cleaned up transition point

Note degree of eye closure

Simulation Solutions

- **EM Solvers to Model Structures**
- **Circuit Simulators**

Candidates for Circuit Simulation Analysis

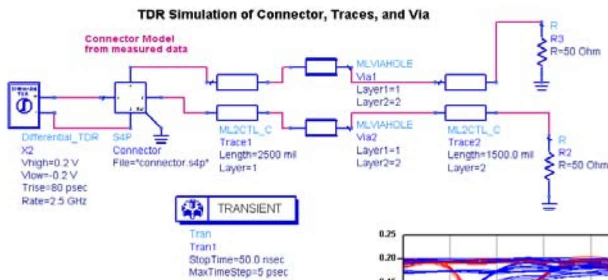
- **VCO Analysis**
- **PLL Analysis**
- **Interconnect/Transmission Line Analysis**
- **Amplifier Analysis**

This Topic was handled in February 2002 and is in the Archives under

‘Challenges of Differential Bus Design’

Simulation Tools

Agilent ADS Simulation Toolset

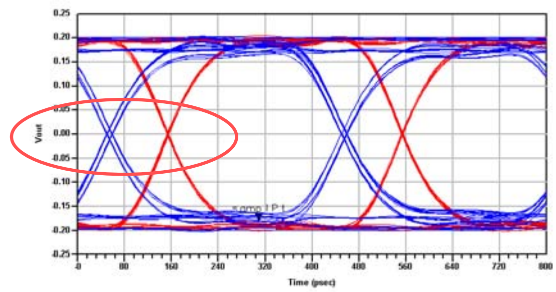


- •Noise Spectral Density
- •Jitter Analysis
- •Crosstalk
- •Eye Measurements
- •Histograms

Note the difference at transition point…

Red=Optimized T-Line

Blue=non-optimized



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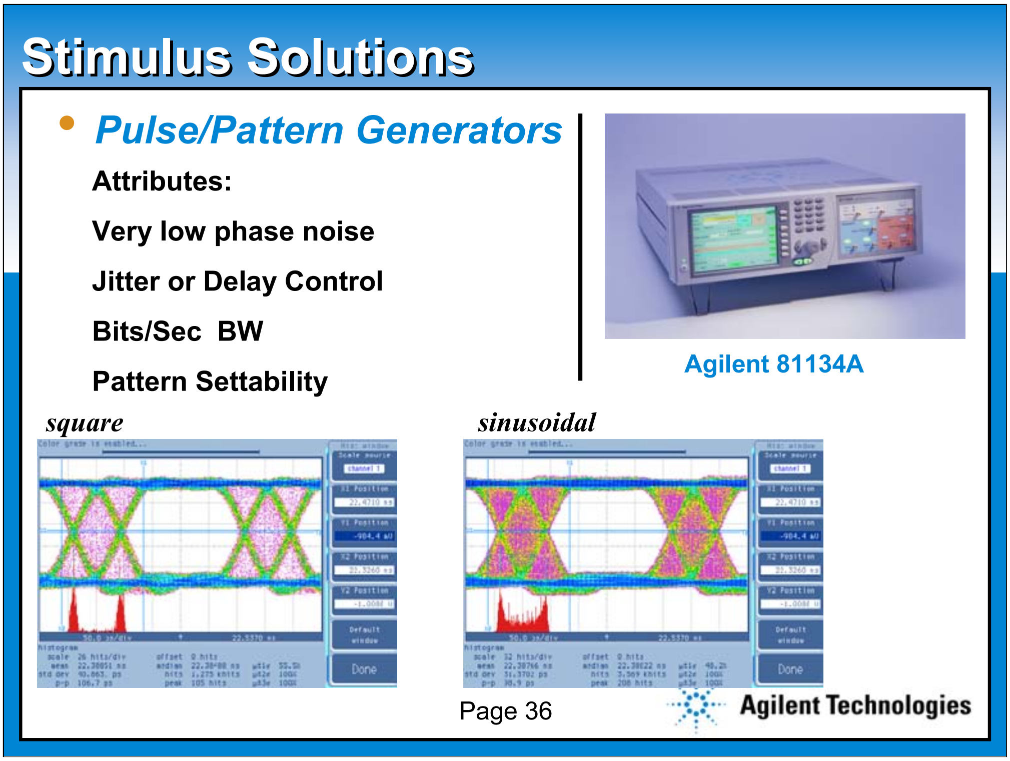


(Mention BERT in script)

Benefits of Pattern Jitter—arb data, simulate data, and jitter

Jitter Analysis Solutions

- *Low Level Jitter Analysis and/or Phase Noise*
  - **Total Jitter in Integrated Spectrum**
  - **Clock signals only or on a Data Signal with a Golden PLL**
  - **Understanding of Noise Floor Shape, Phased Locked Loops, VCOs and Crystal Oscillators**
  - **Reveals Spurious Mechanisms that are not Data Dependent**
  - **Provide Frequency Domain information for design optimization of total jitter.**
  - **Extremely Low Noise Floor (μUI)**

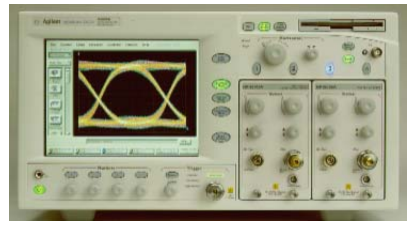
Agilent E5500 Series

Agilent JS-1000

Would be real cool to have a xtal, vco plots and finally a Phased Lock Loop Result

Jitter Analysis Solutions

- *Digital Communications Analyzer*
  - Is the only Scope solution above 3.2 Gb/S
  - Under Sampling Method
  - Precision Time Base
  - Inexpensive
  - Flexible … with TDR option
  - Requires narrow band CR or clock access for trigger



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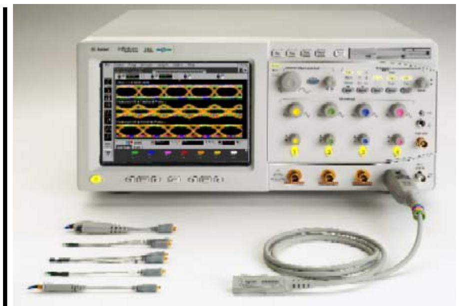
- (know relationship between Gb/s and GHz)
- Rj/dj sep (?)(histogram)… 60GHz optical 85GHz electrical BW
- timebase accuracy

Point out that the points are true for the class of instrumentation in general and that our solution is on the side

Jitter Analysis Solutions

- *Real Time Sampling Oscilloscope*
  - 6 GHz BW allows viewing signals to 3.2 Gb/S
  - Over Sampling Method is >10x faster than DCA, but still slow on a per edge basis
  - Any Active Signals can be analyzed, in circuit with high bandwidth probes
  - <1.5 pS Pk-to-Pk Jitter
  - Captures contiguous cycles
  - Jitter Analysis Software to recover clocks, perform RJ/DJ Separation
  - Versatile and Intuitive Measurements with analysis of waveform parameters such as Rise Time, Duty Cycle, etc.
  - Eye Diagram, Histograms, FFT, Standard Oscilloscope Views



Agilent 54854/55 and InfiniiMax High BW Probes

Jitter Analysis Solutions

- *Bit Error Rate Testers*
  - Stimulus/Response and Response Only Testing
  - The ultimate measure of channel quality
  - Counts every Edge or transition in waveform so is the fastest measurement on a per transition basis
  - Has threshold adjust which allows point eye diagram evaluation, eye contours
  - Serial Only, Serial to Parallel, and Parallel to Parallel Configurations
  - Solutions to 45Gb/s
  - Software for Bathtub curve, Bathtub Extrapolation, RJ/DJ Separation
  - Bit Errors time stamped for burst and length Bit Error failure analysis

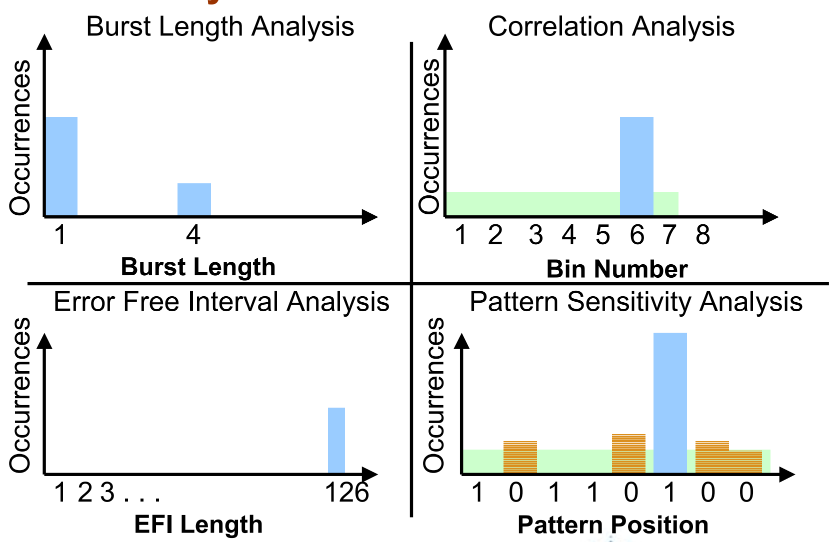
Agilent 86130 BitAlyzer

Agilent 71612 BERT

Agilent 81250 ParBERT

Jitter Analysis Solutions

Bit Error Analysis



Jitter Analysis Solutions

- *Time Interval Analyzer*
  - **Counts time between two events in a repeating pattern**
  - **Scalable Architectures in solutions allow for simultaneous measurements**
  - **Measurement Speed and efficiency is function of pattern and repetitions required**
  - **SW for Jitter Analysis and other waveform assessments**
  - **RJ/DJ Separation through Tail fitting Histogram**
  - **Qualified Edge Sampling. Reset time after each measurement event so cycles are missed**
  - **Linearity in interpolators can be an issue**

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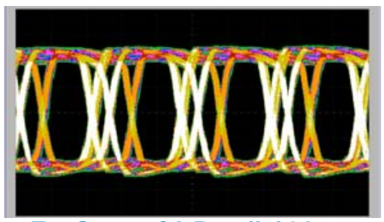
Tail fitting sensitivity to non gaussian tails.

Jitter Analysis Solutions

- ***Logic Analyzer***
  - Unexpected for Jitter Analysis!
  - Trigger architecture can allow for parallel analysis of up to 100s of parallel lines.
  - Troubleshooting and Diagnostic Tool
  - <1.5 Gb/s 10pS resolution

Agilent 16702B Logic Analyzer



EyeScan of 3 Parallel Lines

Agilent 16754/760 Module

Agilent Technologies

Eye measurements built into high performance logic analysis up to 1500 Mbits/sec

Measure eyes on up to 339 single ended or differential signals at once with 10 ps / 3 mV resolution

View one, a few, or hundreds of signals in one display

Identify problem signals instantly using built in tools and display modes

Find infrequent violations quickly (in minutes, not hours or days)

Gain confidence by obtaining eye patterns quickly over many operating conditions:

Temperature, Supply voltages, Operating Modes **w/Ribbonized Coax**

Agilent Jitter Solutions

Measurement	54850 RT Scope	86100 DCA	86130 BERT	71612 BERT	81250 ParBERT	16702 Logic An.	JS-1000 Perf. Jit.	81134 PulseGen
Eye Diagram/Mask	Best fit	Good fit	Fair fit	Fair fit	Fair fit	Fair fit		Good fit
Bathtub Curve			Best fit	Best fit	Best fit			
Extrapolated Bathtub	Good fit		Best fit	Best fit	Best fit			
TIE Histogram	Best fit	Good fit			Fair fit		Best fit	
Parameter Histogram	Best fit							
Parameters vs Time	Best fit	Good fit						Good fit
Jitter Spectrum	Good fit						Best fit	
RJ/DJ Separation	Best fit		Best fit	Best fit	Best fit		Best fit	Good fit
DDJ Views	Best fit		Best fit	Best fit	Good fit			Good fit
Low Level Jitter							Best fit	

Best fit Good fit Fair fit

Agilent Technologies

This table documents what Agilent solutions are available for jitter measurements. The solutions are distinguished between components, subsystems, and systems, with some subsegmentation between R&D and Manufacturing. Another segmentation is whether your data speed is below 3.2 Gb/s, which ends up being the limit of the 6 GHz 54850 Oscilloscope.

Some solutions require a software option to make the jitter measurements.

For sub 3.2 Gb/s measurements, the 54850 Oscilloscope is the most versatile solution while the 86100B DCA may be more appropriate in Mfg due to its lower cost (basically this is a cost vs. speed tradeoff). The 86130A BitAlyzer is the BERT of choice, while the 82150 ParBERT is more appropriate in systems due to its modular, parallel design. And finally, the 81134A Pulse Generator is a high-performance stimulus.

For >3.2 Gb/s measurements, your choices are fewer due to the bandwidth requirements. The DCA is the scope while the 81250 ParBERT offers up to 45 Gb/s capability.

The following slides provide a quick overview of each of these products.

Agilent Jitter Solutions for Digital Circuits

Data Rate	Components R&D*	Components Mfg	SubSystems R&D*	SubSystems Mfg	Systems R&D*	Systems Mfg
<3.2 Gb/s	54850 Scope#	86100B DCA	54850 Scope#	86100B DCA	54850 Scope#	86100B DCA
	86130A BitAlyzer#		86130A BitAlyzer#		81250 ParBERT#	
	81134A Pulse Gen		81134A Pulse Gen			
	JS-1000		JS-1000			
>3.2 Gb/s	86100B DCA		86100B DCA		86100B DCA	
	71612C BERT#		71612C BERT#			
	81250 ParBERT#		81250 ParBERT#		81250 ParBERT#	
Media	N1951A PLTS	86100B TDR	N1951A PLTS	86100B TDR	N1951A PLTS	86100B TDR

With Jitter S/W option

* Includes Compliance Test

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Summary

- Digital Design is now becoming an Analog/RF affair.
- Bit Error Rate is the Golden metric for digital data transfer.
- Jitter is comprised of two components which demand characterization: Random and Deterministic.
- There are many ways to View Jitter. The Eye Diagram is the most fundamental.
- Different Jitter Analysis Tools are required for the full spectrum of Jitter problem solving:
  - From simulation and prototype evaluation to production testing.
  - Target Design type, speed or bit rate, signal availability.

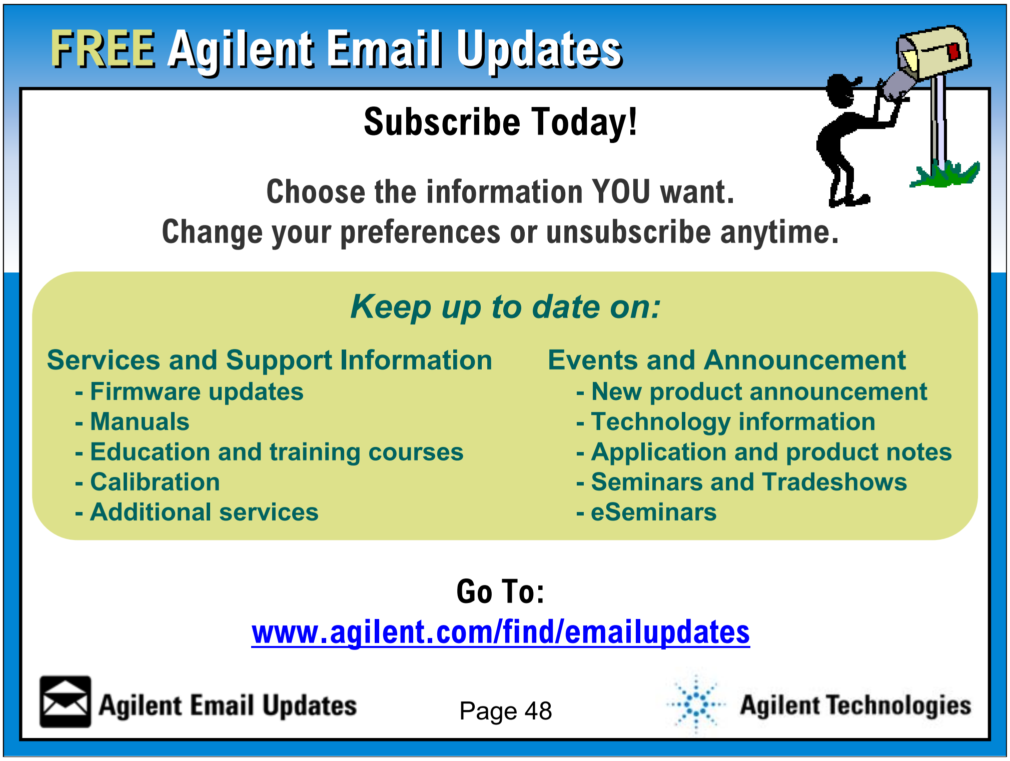
•Deterministic Jitter is Systematic and will cause a given amount of Peak to Peak Jitter and will not increase with observation time. Random Jitter is Gaussian or Noise-like and has arbitrarily high peak to rms value: the Peak to Peak Jitter will increase as observation time increases.

•Some pinpoint specific causes — i.e. Bit Error Analysis and Phase Noise.

•Design or Product Solutions needed will depend on the type of circuit block under analysis, presences of serial vs. parallel structures, BW or bit rate, Life Cycle phase, Active Live vs. passive.

•A Bit Error Rate Tester can make this

The engineers are trained to help guide you through the selection for your best return.



In a moment we will begin with the Q&A but 1st, for those of you who have enjoyed today's broadcast, Agilent Technologies is offering a new service that allows you to receive customized Email Updates. Each month you'll receive information on:

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Now on to the feedback form then to Q&A……..