DesignCon 2002

High-Performance System Design Conference

Comparison and Correlation of Signal Integrity Measurement Techniques

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Abstract

Data communication rates have increased tremendously over the past 5 years in order to accommodate the exponential growth in data transmission. One way to evaluate system or component performance is through an eye diagram using an oscilloscope. Another is by using a Bit Error Rate Tester (BERT), which provides statistical information about the data transmission quality. Characterization is generally done with both instruments but the process was tedious, difficult to set up and in many cases, inconclusive as a diagnostic utility. A third approach of measuring jitter uses a Time Interval Analyzer (TIA) that can determine the fundamental metric of eye opening as a function of BER as well as provide excellent diagnostic tools such as jitter deconvolution into its deterministic and random components. This paper will compare a variety of test conditions in order to correlate the results between these three approaches. This study will clarify where each measurement solution fits in the overall signal analysis picture.

Author Biography

Dr. Patrin is currently the Director of Product Marketing at Wavecrest. He has more than seven years engineering and marketing experience in scientific instrumentation and semiconductor capital equipment. Prior to joining Wavecrest, Dr. Patrin worked as a staff engineer and engineering manager for a semiconductor capital equipment company. He received a BS in physics from St. John's University in Collegeville, MN and a Ph.D. in Materials Science from the University of Minnesota in Minneapolis. He has published 15 papers in technical journals and has two patents and one pending.

Dr. Li is currently the Chief Technology Officer (CTO) of Wavecrest. He has many years experiences in SI related measurement instrumentation and analysis algorithms/tools. Prior joining Wavecrest, Dr. Li had worked in both industry and academic institutions. Dr. Li is experienced in measurement system architecture, hardware, software, performance, and accuracy. He also has experiences in modeling high energy astrophysical objects, and astrophysical data analysis tools. Dr. Li has a BS in physics from University of Science and Technology of China, a MSE in electrical engineering and a Ph.D. in physics from University of Alabama in Huntsville. He did his Post Dr. at University of California, Berkeley.

I. Introduction

This paper is intended to provide designers and engineers with an overview of jitter and its sources followed by a discussion on the different jitter measurement techniques used in today's laboratory and production environment. In particular jitter measurements from oscilloscopes, BERTs and TIAs will be performed with a variety of device input test conditions. Data will be shown outlining the strengths and weaknesses of each.

II. Jitter Overview

Traditionally, measuring jitter has been critical to determining the performance of high-speed digital communications systems. Recently, as internal and external data rates of computers and networks have increased to unprecedented levels, reducing jitter has become an even higher priority for ensuring high reliability in high-speed databuses and integrated circuits. Jitter is the deviation of a timing event of a signal from its ideal position as shown in figure 1. Jitter affects a system as a whole, and can be introduced by every circuit element used to generate, convey and receive signals. As a result, understanding the amount of jitter introduced by each element of a system is imperative for predicting overall system performance.

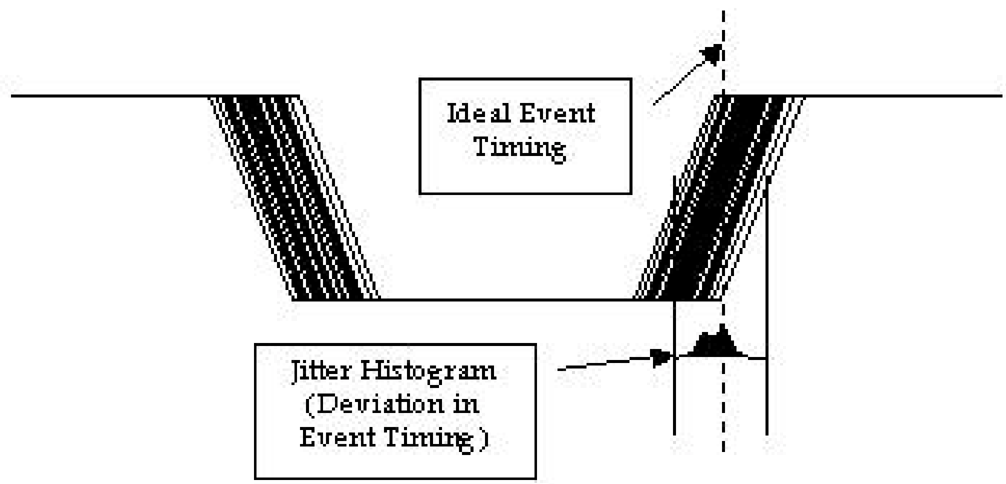


Figure 1. Timing jitter is the deviation from the ideal timing of an event. Jitter is composed of both deterministic and Gaussian (random) content. TJ is the convolution of all independent jitter component PDFs.

a. Random Jitter

Total jitter (TJ) is the convolution of all independent jitter component Probability Density Functions (PDF). A PDF describes the likelihood of a given measurement relative to all other possible measurements, and is typically represented by a normalized histogram. TJ includes contributions from all deterministic and random components, and is a pk-pk value specified for a given sample size or Bit Error Rate (BER). Figure 2 shows how TJ is broken down into it components. Random jitter (RJ), one of the main components of TJ, is characterized by a Gaussian distribution and assumed to be unbounded[1].

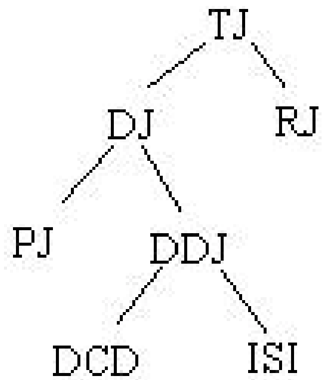
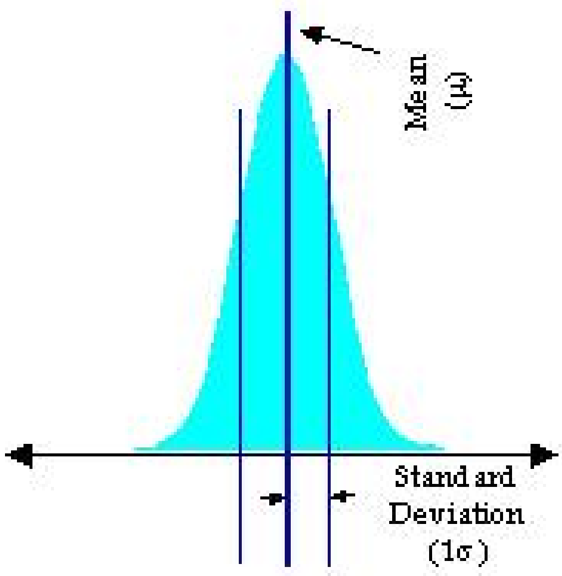


Figure 2. Total jitter (TJ) includes deterministic jitter (DJ) and random jitter (RJ). DJ can be further separated into periodic jitter (PJ), data dependent jitter (DDJ), duty cycle distortion (DCD) and intersymbol interference (ISI).

As a result, it generally affects long-term device stability. RJ is Gaussian in nature and the distribution is quantified by the standard deviation (σ) and mean (μ) as shown in Fig. 2. Because RJ can be modeled as a Gaussian distribution, it can be used to predict pk-pk jitter as a function of BER. This means that for a BER 1.3×10^{-3}, 6σ would provide a pk-pk range that includes all of the samples except 0.0013 of them.



BER	TJ Value
1.3×10^{-3}	6σ
3.17×10^{-5}	8σ
2.87×10^{-7}	10σ
9.87×10^{-9}	12σ
1.28×10^{-12}	14σ
1.0×10^{-12}	14.069σ

Figure 3. A Gaussian distribution with a mean (μ) and a standard deviation (σ). This figure represents a PDF for a Gaussian distribution. The table shows TJ values at various BER for a single Gaussian distribution.

b. Measuring RJ

Traditionally it is difficult to quantify RJ on complex histograms because the TJ PDF has a complicated shape and does not look like Figure 3. One method of quantifying RJ is by using the TailFit algorithm that is capable of separating RJ from actual measurement distributions by using the Gaussian nature of the tail regions of non-Gaussian histograms[2]. The algorithm first identifies a tail region of the histogram, then fits the data with a Gaussian histogram that best coincides with the tail region. The process repeats for each side of the histogram. The RJ values for the tails are averaged to represent the RJ for the distribution when calculating TJ. Figure 4 shows a Gaussian tail fit to the left side of the distribution. Chi-squared is used as a gauge to determine the quality of fit. It is an iterative process, and ends when the results converge. To limit the iterative process, an estimate of the initial fitting parameters is made by the algorithm using the tail portions of the distribution.

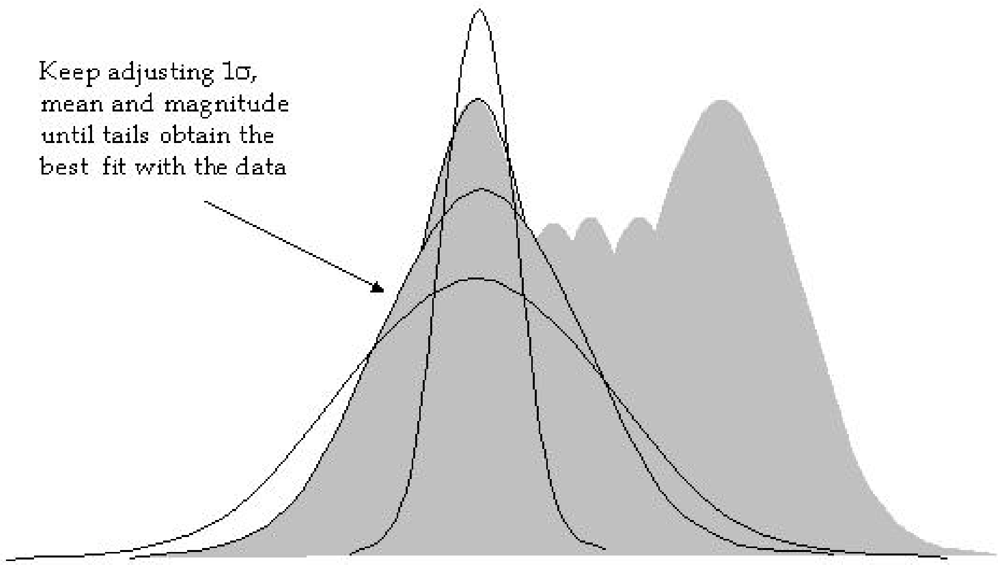


Figure 4. The TailFit algorithm enables the user to identify a Gaussian curve with a coincident tail region in order to quantify the random or Gaussian component of the distribution. Various curves are fitted against the distribution until an optimal match is found. Then, the 1σ of the matched curve is used as the RJ value for that particular tail. This is repeated for both sides of the distribution, and the two RJ values are averaged to get the overall RJ value.

c. Deterministic Jitter

Deterministic jitter (DJ) has a non-Gaussian PDF and is characterized by its bounded pk-pk amplitude as shown in Figure 5. There are several types of DJ, including periodic jitter (PJ), duty cycle distortion (DCD) and intersymbol interference (ISI). DCD and ISI are types of data dependent jitter (DDJ). (Other types of DDJ are still being investigated.) PJ, also referred to as sinusoidal jitter, has a signature that repeats at a fixed frequency. For example, PJ could be the result of unwanted modulation, such as electromagnetic interference (EMI). PJ is quantified as a pk-pk number, specified with a frequency and magnitude. DCD is the result of any difference in the mean time allocated for the logic states in an alternating bit sequence (e.g., 0, 1, 0, 1). Different rise and fall times and threshold variations of a device could cause DCD. DCD and ISI are functions of the data history that occur when the transition density changes. For example, Fibre Channel systems and devices are commonly tested with a Compliant Jitter Tolerance Pattern (CJTPAT) that stresses DCD and ISI by alternating long strings of zeros or ones with short strings of zeros or ones within the pattern. It is the DCD and ISI caused by the time difference that is required for the signal to arrive at the receiver threshold when starting from different places within the bit sequence (symbol). ISI occurs when the transmission medium propagates the frequency components of data (symbols) at different rates. One example of DCD and ISI is when jitter changes as a function of edge density.

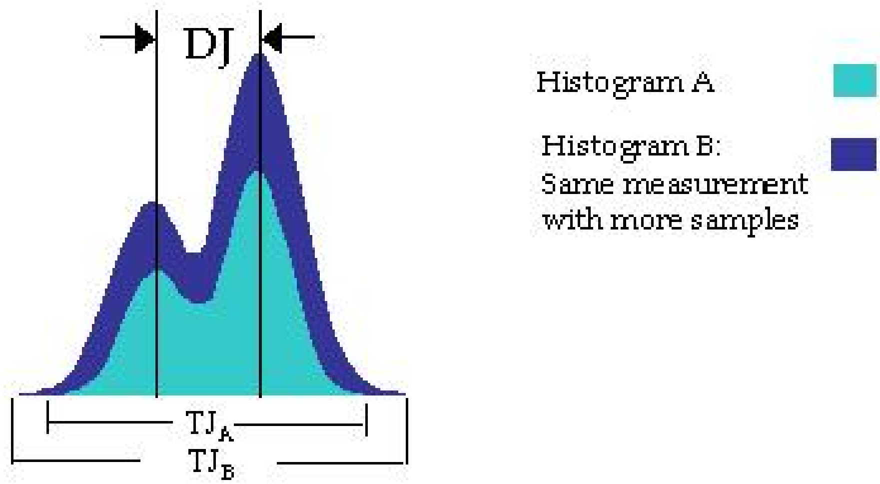


Figure 5. DJ is characterized by a bounded pk-pk value that does not increase with more samples. RJ is unbounded and its pk-pk value increases, resulting in larger TJ values with more samples.

d. Measuring DJ

Quantifying jitter components from measured data is the foundation of true signal integrity analysis. It involves statistics, DSP, algorithms and basic assumptions about the data histograms. In the time domain, jitter data are typically collected from one particular edge to another edge. For example, a period measurement is taken between a rising edge and the next rising edge. The histogram of period measurements contains a mixture of DJ and RJ processes. Traditionally, the TJ histograms included DJ and RJ components, and were quantified by a pk-pk value and a 1σ. However, given the Gaussian nature of the random component, it is incorrect to quantify a jitter histogram with a pk-pk number without specifying the number of samples. Therefore, for a given jitter histogram containing RJ, the pk-pk value will increase with more samples. Furthermore, in the presence of DJ, the 1σ of the total distribution does not depict the Gaussian component RJ. The TJ histogram represents the TJ PDF. However, if the DJ and RJ processes are independent, then the total PDF is the convolution of the RJ PDF and DJ PDF. If DJ was absent from the jitter histogram, then the distribution would be Gaussian as shown in Figure 3. Adding DJ to the histogram effectively broadens the distribution while maintaining Gaussian tails. Adding DJ to the distribution effectively separates the mean of the right and left Gaussian distribution. The difference between the two means, μ_L and μ_R, is the DJ (see Fig. 6). The tail portions of the histogram represent the RJ component of the TJ histogram. A single Gaussian can be used to model these phenomena.

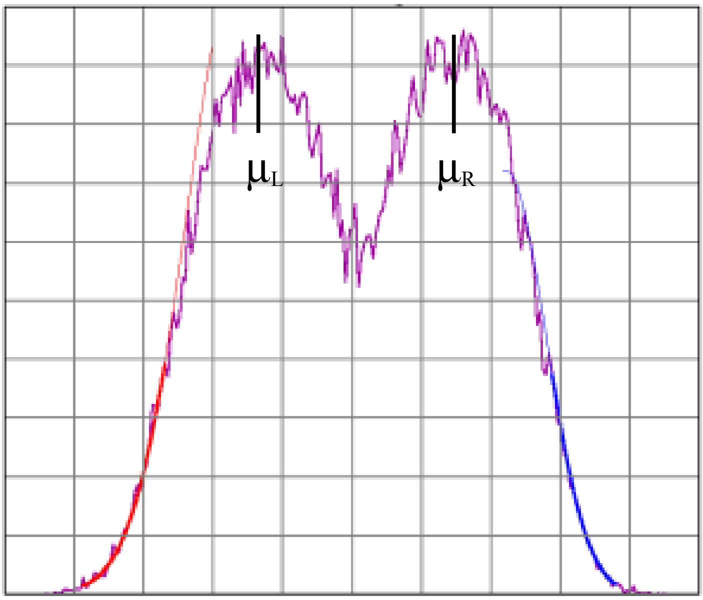


Figure 6. A bimodal distribution that contains both RJ and DJ components, achieved by adding a single DJ component to an otherwise Gaussian distribution. DJ is the difference between the two means.

e. Sources of Jitter

Understanding the underlying cause of jitter is crucial to signal integrity analysis. Determining the source of jitter allows you to characterize and eliminate the potential problem. Here, we examine the most frequent causes of DJ and RJ. Some common sources of DJ include EMI, crosstalk and reflections.

EMI is the result of unwanted radiated or conducted emissions from a local device or system. Switching-type power supplies are common sources of EMI. These devices can radiate strong, high-frequency electric and magnetic fields, and they can conduct a large amount of electrical noise into a system if they lack adequate shielding and output filtering. EMI can couple or induce noise currents in a signal conductor and corrupt the signal by altering its bias. Because the interfering signal is deterministic, the resulting jitter is also deterministic. EMI may also corrupt a ground reference plane or a supply voltage plane by introducing transient noise currents. Noise currents can sporadically alter the effective input thresholds of signal receivers. Given that logic signals require a finite time to change states, a sporadic change in receiver threshold results in signal jitter.

Crosstalk occurs when the magnetic or electric fields of a signal on a conductor are inadvertently coupled to an adjacent signal-carrying conductor. The coupled signal components algebraically add to the desired signal, and can slightly alter its bias depending on the amount of coupling and the frequency content of the interfering signal. The altered bias translates into jitter as the signal transitions the receiver's threshold.

Reflections in a data signal channel create DJ due to the signal interfering with itself. Signal reflections occur when impedance mismatches are present in the channel. With copper technology, optimum signal power transfer occurs when the transmitter and receiver have the same characteristic impedance as the medium. If an impedance mismatch is present at the receiver, a portion of the energy is reflected back through the medium to the transmitter. Reflections typically come from uncontrolled stubbing and incorrect terminations. Reflected energy, or energy not available to the receiver, reduces the signal-to-noise ratio at the receiver and increases jitter. If the transmitter is also mismatched, the transmitter absorbs a portion of the reflected signal energy while the remainder is reflected toward the receiver (again). Eventually, the delayed signal energy arrives at the receiver, out of phase with the original signal. The portion that is absorbed is algebraically summed with first-time arriving signal energy, resulting in DJ (specifically, ISI) from the receiver's perspective.

Common sources of RJ include shot noise, flicker noise and thermal noise. Shot noise is broadband "white" noise generated when electrons and holes move in a semiconductor. Shot noise amplitude is a function of average current flow. The current fluctuations about the average value give rise to noise. This will depend on the process. For example, in a semiconductor it is the randomness with the number of electrons and holes or the number that diffuse. In a signal channel, shot noise contributes to RJ.

Flicker noise has a spectral distribution that is proportional to $1/f^{\alpha}$ where α is generally close to unity. Because flicker noise is proportional to 1/f, its contribution is most dominant at lower frequencies. The origin of flicker noise is a surface effect due to fluctuations in the carrier density as electrons are randomly captured and emitted from oxide interface traps.

Thermal noise can be represented by broadband "white" noise, and has flat spectral density. It is generated by the transfer of energy between "free" electrons and ions in a conductor. The amount of energy transfer and, therefore, the amount of noise, are related to temperature. Thermal noise is unrelated to signal current flow, but it is a contributor to RJ in systems with low signal-to-noise ratios. Electron scattering due to a nonperfect lattice structure causes RJ. The deviations of the lattice structure are due to crystal vibrations. Ions do not remain at their ideal crystal location because of thermal energy. The deviation of the lattice structure from its ideal position can induce electron scattering. The amplitude of the ionic perturbation decreases with temperature and at sufficiently low temperatures impurity and defect scattering dominates. However, reducing the temperature will not completely eliminate RJ because of intrinsic defects, such as impurities, missing atoms, or discontinuities in the lattice structure caused by an interface. In these cases, the defect or impurity causes a localized scattering center, giving rise to RJ.

III. Instrumentation for Measuring Jitter

The preceding sections outlined jitter and some of its common sources. There are many types of instruments that are capable of measuring jitter and these are oscilloscopes, BERTs and TIAs. However, the data acquisition methods that these instruments use are very different and the diagnostic capabilities of the data varies greatly. Therefore a brief overview of each method that was used in this correlation paper will be described.

a. Oscilloscopes

For high speed signals, digital sampling oscilloscopes are generally used to characterize the signal integrity of clock and data signals. These oscilloscope can have a very high bandwidth, typically ~30-50 GHz. For repetitive sampling oscilloscopes the input signal is randomly sampled at various time intervals to obtain the voltage level. The waveform is built up after repetitive samples of the signal. This type of oscilloscope requires a trigger signal to control the timing of the sampling process. Digital sampling oscilloscopes measure voltage and timing accurately and can create "eye diagrams" for tolerance testing. The measured data can then be compared to an eye mask or specification of eye opening. Figure 7 shows a typical measurement from an oscilloscope with a histogram taken at the midpoint of the data crossing point. In this example the pk-pk value of the histogram is 62.2 ps. The oscilloscope provides a valuable tool for viewing time and voltage, determining voltage levels, overshoot, ringing, rise and fall times but due to its slow acquisition speed it is not practical to determine jitter for serial data communication standards such as Fibre Channel because of the requirement to test to

10^{-12} BER. Additionally, the oscilloscope solutions currently available cannot determine the RJ or DJ components of jitter. The data acquision rate in Figure 7 was ~120 points/sec for a voltage range of 1.5 mV at the data crossing point. The time required to acquire data for at 10^{-12} BER would be in the hundreds of years, unreasonable for any lab characterization.

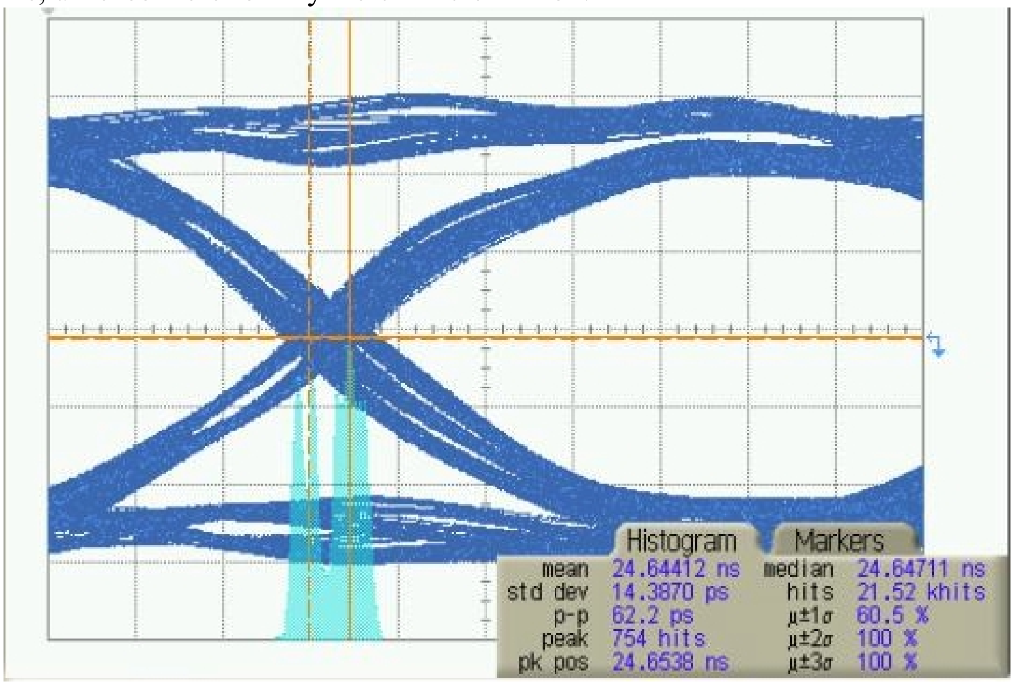


Figure 7. Output from an oscilloscope showing the data crossing points and the resultant histogram acquired at the crossing point. In this example the pk-pk value is 62.2 ps for a histogram with 21,520 hits was acquired over a ~3 minute time period.

b. BERTs

Bit Error Rate measurements are commonly performed on high-speed systems as a means of characterizing system performance. BER is defined as the number of bits in error divided by the number of bits received. BERTs are comprised of two components, a pattern generator and an error detector. A BERT operates by transmitting a pattern to the device under test and the error detector analyzes and records the differences between the transmitted and received pattern. Many high-speed serial protocols require testing to 1×10^{-12} BER to insure interoperability and system reliability. In order to obtain the amount of eye closure as a function of BER, the BERT must vary the data edge placement with respect to the clock edge in order to obtain a BER, this is commonly called the BERT scan technique. The plot that is generated is commonly referred to as a bathtub curve and a typical curve is shown in Figure 8. BERTs provide a valuable total jitter diagnostic tool because of its ability to accurately measure the eye opening as a function of BER. The drawback is that the long time required to complete a bathtub curve for a BER of 10^{-12}. The data obtained from a BERT cannot separate TJ into RJ and DJ unless drastic oversimplifications of the DJ PDF are made. Typical device test times for a BER of 10^{-12} is on the order of 2-8 hours.

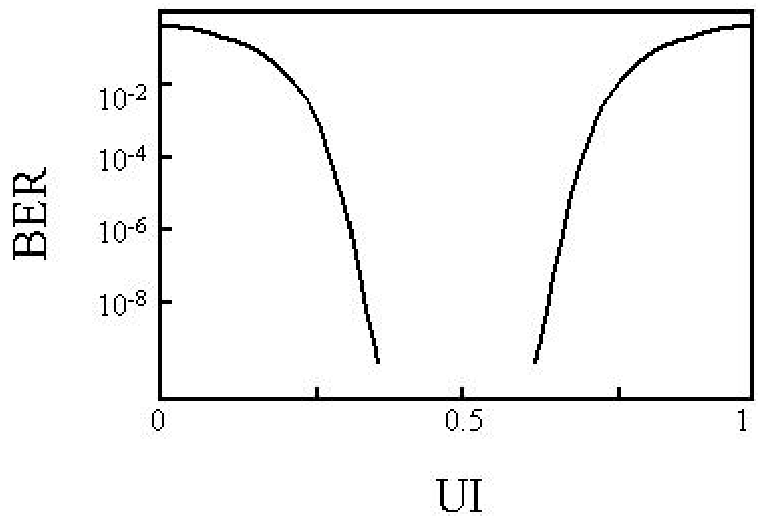


Figure 8. A bathtub curve showing BER as a function of eye closure.

c. TIA

TIA's measure accurate and repeatable single shot edge-to-edge time intervals on a non-continuous and random basis. The statistics of these measurements provides information on total jitter, deterministic jitter, random jitter, propagation delay and skew. Two different data acquisition methods were performed in this paper. The first method measures the jitter between a data edge relative to a clock edge. A histogram of rising and falling edges is obtained. The Tailfit algorithm is used to determine the RJ component and the difference between the two mean positions of the Gaussian distribution is the DJ value. A typical data set is shown in Figure 9.

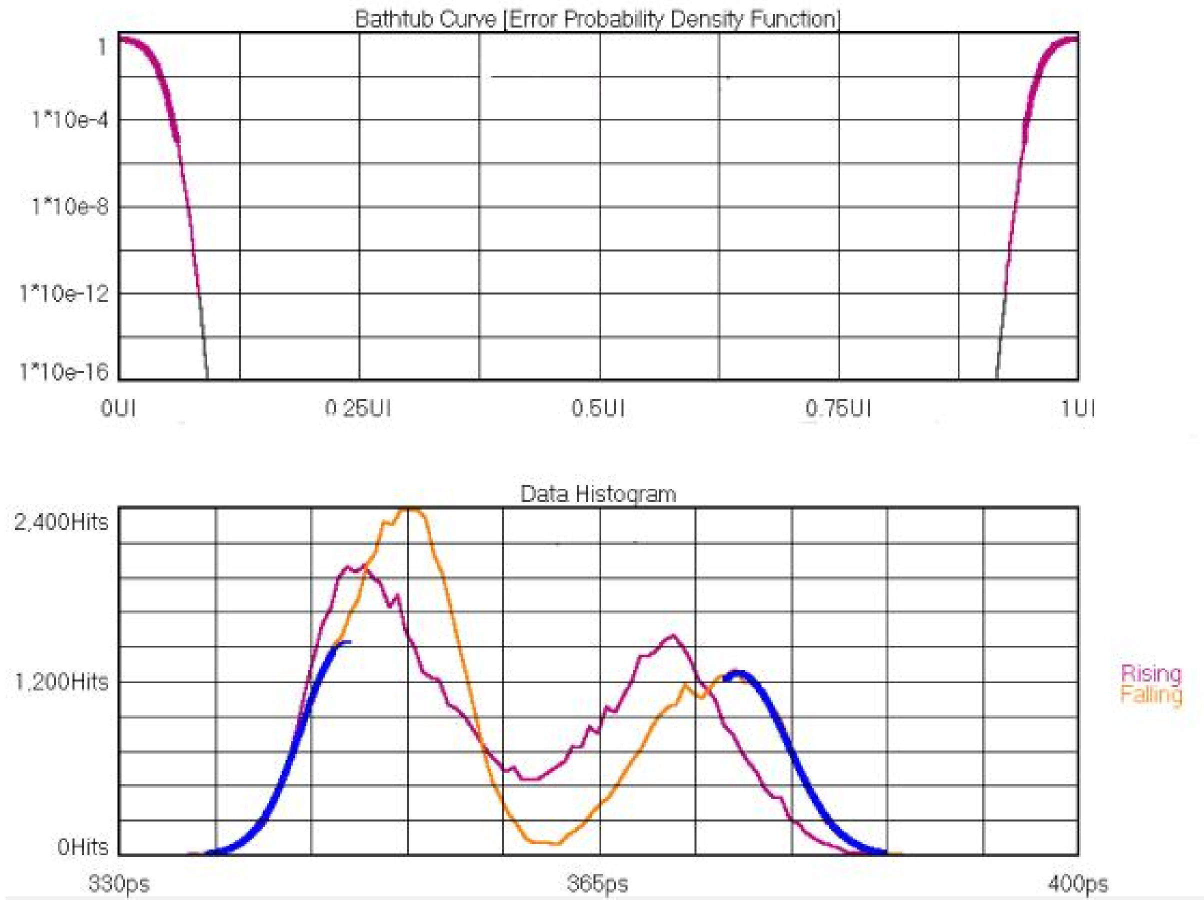


Figure 9. Typical data acquired with a TIA using clock-to-data method. Bottom figure shows histograms for rising and falling data edges. This view enables the user to determine the jitter contribution from the polarity of edges. The right and left most portion of the histograms are fitted with Gaussian tails in order to determine the 1σ for RJ, the difference between the means of the Gaussian distributions is the DJ value. The top figure shows the bathtub curve.

The second method measures TJ, RJ, DJ, DCD&ISI and PJ on a repeating data pattern with a pattern marker[3]. In this method a pattern marker provides an arm or trigger in order to perform measurements from the same reference point in the pattern. First, the expected pattern is compared against the measured pattern and rotated, if necessary, until the expected pattern matches the measured pattern. Next, DCD&ISI is measured from the difference between the expected edge location and the mean of the histogram from each pattern edge. The DCD&ISI measurement is calculated based on the peak-to-peak spread of this array. Periodic and random jitter components are determined by taking the variance of timing measurements from the histogram at each unit interval also known as the autocorrelation function. A FFT of the autocorrelation function is used to determine the periodic components. The Fourier transform of the autocorrelation function is commonly referred to as the power spectral density (PSD). The RJ component is determined by subtracting the spectral spikes, summing the background then taking the square root to provide a 1-sigma value. Alternatively RJ can be calculated by fitting Gaussian tails to both sides of each histogram from each edge in the pattern. Figure 10 shows a typical data set using a repeating pattern and a pattern marker.

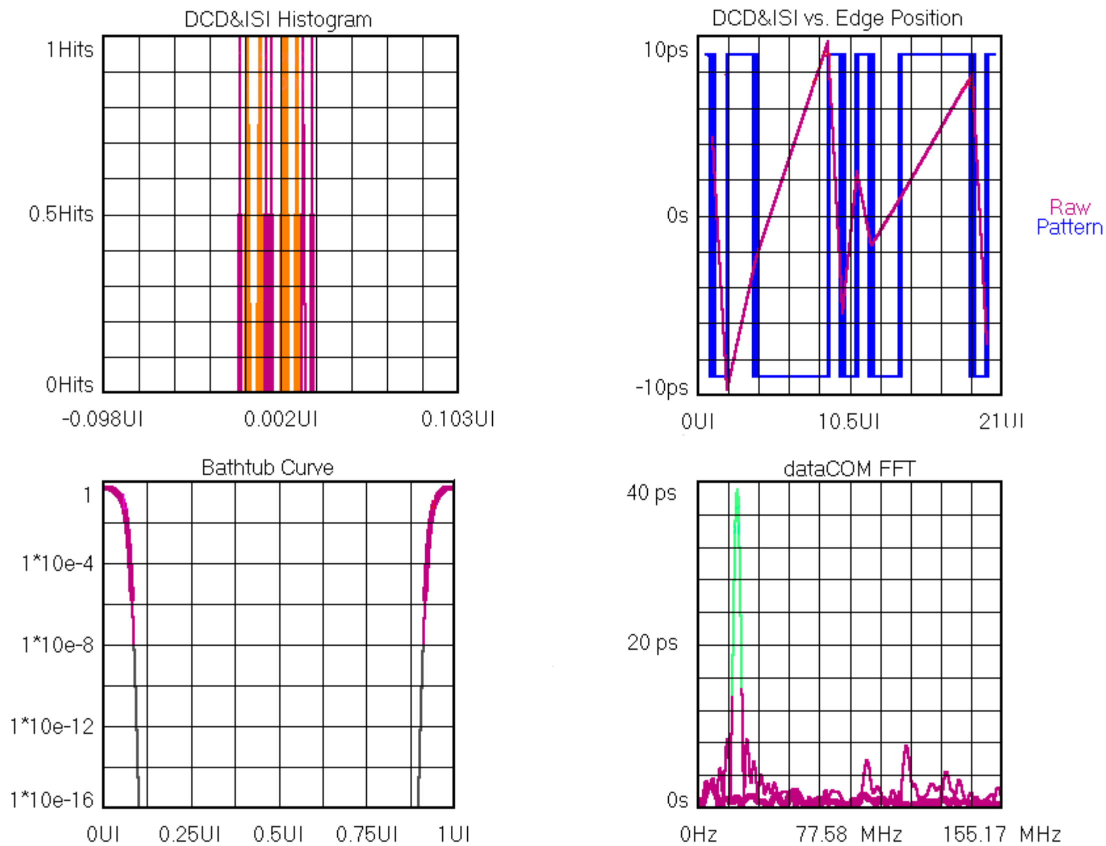


Figure 10. Typical data set using a repeating pattern and pattern marker with a TIA. Clockwise, the DCD&ISI histogram from a K28.5 pattern showing the pk-pk contribution. The DCD&ISI contribution at each edge location in the pattern. The wide range of time deviations (dark purple line) indicates possible bandwidth limitations. The FFT of the autocorrelation function from 637 kHz to 155 MHz showing a spectral component at 20 MHz contributing 38 ps of periodic jitter. The FFT is a useful diagnostic tool for isolating crosstalk or EMI sources. The DCD&ISI and FFT plot illustrate the DJ components of TJ. The bathtub curve showing eye opening as a function of BER.

The advantage of the TIA is that measurements can be performed with a setup having data and a bit clock or with a setup having a repeating pattern and pattern marker. In either case the TIA can separate TJ into its deterministic and random components. Additionally the TJ values are provided down to a BER of 10^{-16}. Figures 9 and 10 show representative data sets from the two methods illustrating the diagnostic capabilities of the TIA method. Test times are the same independent of BER because the TIA method determines the DJ and RJ PDF and convolves them together and integrates the TJ PDF to generate a bathtub curve. Typical test times are 1-10 seconds for BER $<10^{-16}$.

IV. Results with different Jitter components

a. Setup

The setup for the experiments included a Wavecrest SIA 3000 Time Interval Analyzer, a HP 70842B Error Detector and HP 70841B Pattern Generator, Tektronix CSA 803 Oscilloscope and Agilent Infinium 86100A Oscilloscope. The RJ noise source was a Noisecom UFX 7110 and the PJ source was a Marconi 2041. ISI was added to the signal by a line trace with stubs. The experimental setup is shown in Figure 11.

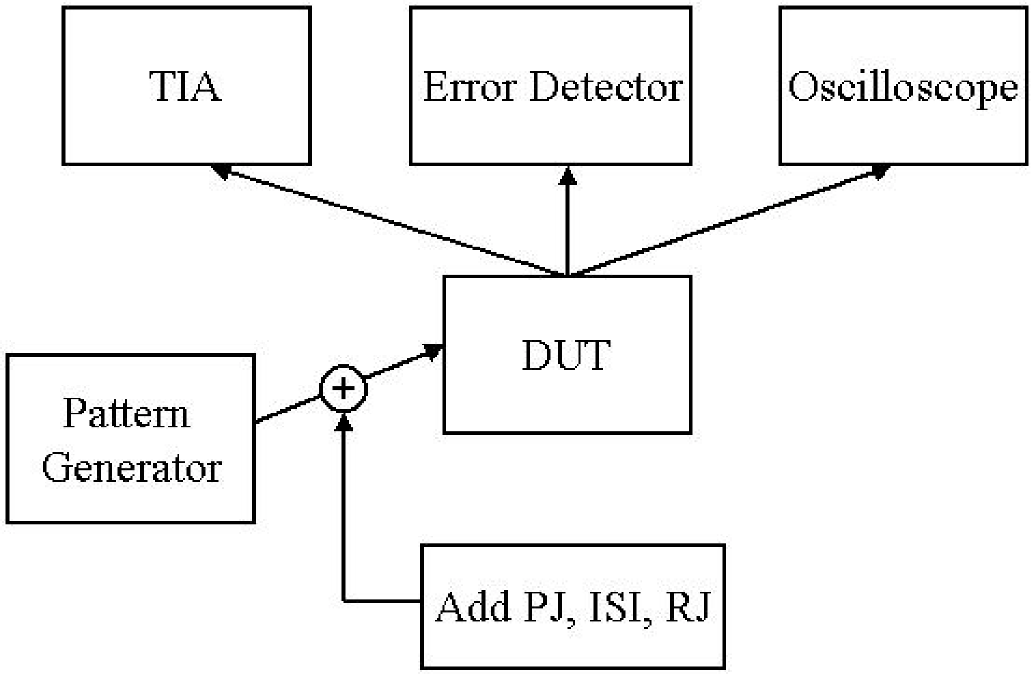


Figure 11. The experimental setup consisted of a pattern generator that transmitted a pattern to the Device Under Test (DUT). PJ, ISI and RJ could be added to the transmitted signal. The pattern was then input to the DUT and then output to the Error Detector, Oscilloscope or TIA for jitter analysis.

b. Results

Results are shown below for a variety of test conditions. Due to the length of time required to acquire data for a BER of 10^{-12} using the BERT measurement technique, tests are compared for BER of 10^{-8}.

Comparison of measurement techniques with ISI added to the data. TJ pk-pk values for a BER of 10^{-8}

	BERT	TIA with clock to data	TIA with a repeating pattern	Oscilloscope
1.0625 Gb/s K28.5 Pattern	66 ps	58.5 ps	62.7 ps	
1.0625 Gb/s CRPAT Pattern	55 ps	58 ps	62 ps	
2.125 Gb/s K28.5 Pattern	52 ps	54 ps	57 ps	62.2 ps
2.125 Gb/s CRPAT Pattern	54 ps	54 ps	57 ps	

Comparison of measurement techniques with RJ added to the data. TJ pk-pk values for a BER of 10^{-8}

	BERT	TIA with clock to data	TIA with a repeating pattern
2.125 Gb/s CRPAT Pattern with RJ	81 ps	79 ps	85 ps

Comparison of measurement techniques with 20 MHz frequency component added to the data. TJ pk-pk values for a BER of 10^{-8}

	BERT	TIA with clock to data	TIA with a repeating pattern
2.125 Gb/s CRPAT Pattern with PJ	69 ps	72 ps	82

Time required to perform measurement

	BERT	TIA	Oscilloscope
10^{-8} BER at 2.125 Gb/s	100 seconds	2 seconds for repeating pattern method 8 seconds for clock-to-data method	10.5 days
10^{-12} BER at 2.125 Gb/s	~30,000 seconds	2 seconds for repeating pattern method 8 seconds for clock-to-data method	>250 years

c. Discussion

The results for a variety of test conditions show that the BERT and the TIA agree over a wide variety of input conditions. With large amounts of ISI the BERT, TIA and oscilloscope agreed within about 5 ps. When RJ was added to the signal the TIA and BERT varied within a range of 6 ps for a TJ value of ~82 ps. The oscilloscope was not used for this measurement because of the long time required for a pk-pk value of a histogram to capture RJ events. With a 20 MHz sinusoidal component added to the signal the BERT and the TIA clock-to-data method were within 3 ps. The TIA method using a repeating pattern and pattern marker was larger than the other two because the method assumes the largest magnitude of PJ in the DJ calculation because the phase information of the periodic is not known. However, this TIA method has its advantages because it determines the frequency and worse case magnitude of the modulation whereas the BERT and the TIA clock-to-data method does not. The final table shows a wide range of typical measurement test times. The oscilloscope acquisition speed is very slow (~120 points/sec in this experiment) thereby making this technique impractical for most serial communication standards that require testing to 10^{-12} BER. The BERT can generate a bathtub curve to 10^{-8} BER in approximately 100 seconds but for a BER of 10^{-12}, the measurement technique becomes very long. The TIA captures the true RJ and DJ PDF in the measurement process and convolves them together and integrates out to the appropriate BER without the need for additional data. Therefore, the TIA test times are the same as a function of BER in the examples above.

V. Conclusion

This paper provided a review of the various components of jitter and its sources. It was shown that a simple histogram at the data crossing points or a bathtub curve does not completely answer all the signal integrity questions because the data provides little to no diagnostic information. The TIA provides additional diagnostic capabilities because of its ability to deconvolve TJ into DJ, PJ, DCD&ISI and RJ and providing a spectral view of PJ and RJ. The TIA has additional advantages in that the data acquisition method is approximately 10-1000 times faster than conventional techniques. The BERT is a valuable test and measurement instrument in that the data is straightforward to interpret and provides an accurate BER plot. Correlating the oscilloscope to the other measurement techniques will always be difficult because of the inherently slow acquisition times. However, the oscilloscope does provide useful 2D time versus voltage plot of the data signal and can accurately quantify rise and fall times, voltage levels, overshoot and ringing. Finally, the correlation study conducted with a wide range of input jitter conditions showed that the BERT and the TIA compared favorably with the addition of ISI, PJ and RJ. Ultimately it is up to the designer and engineer to determine which jitter technique(s) are most suitable for their signal integrity needs.

Acknowledgements

I would like to thank Timothy J. Naumoff for writing the software programs to control the test equipment and for his effort in acquiring data used in this paper. I would also like to thank Michael deBie for his input on test conditions and editorial comments and Sean Attapattu for help in acquiring data used in this paper.

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