DesignCon 2004

Characterizing Jitter Histograms for Clock and DataCom Applications

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Abstract

This TecForum will discuss the drawbacks of quantifying histograms with peak-to-peak measurements and recommend more thorough characterization methods that reflect true device performance thereby enabling engineers to accurately make pass-fail decisions. Included is a discussion of the common measurements that are used to analyze clock signals such as phase noise, period jitter and cycle-to-cycle jitter and when is it appropriate to use them. PCI Express will be used as an example for DataCom applications to describe current jitter methodologies. Additionally, a review and demonstration of measurement equipment used for clock and data analysis such as Signal Integrity Analyzers, Bit Error Ratio Testers, and oscilloscopes will be provided in order to determine how each instrument fits into the overall jitter analysis picture.

Author Biography

Dr. Patrin is currently the Director of Product Marketing and Engineering 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 three patents.

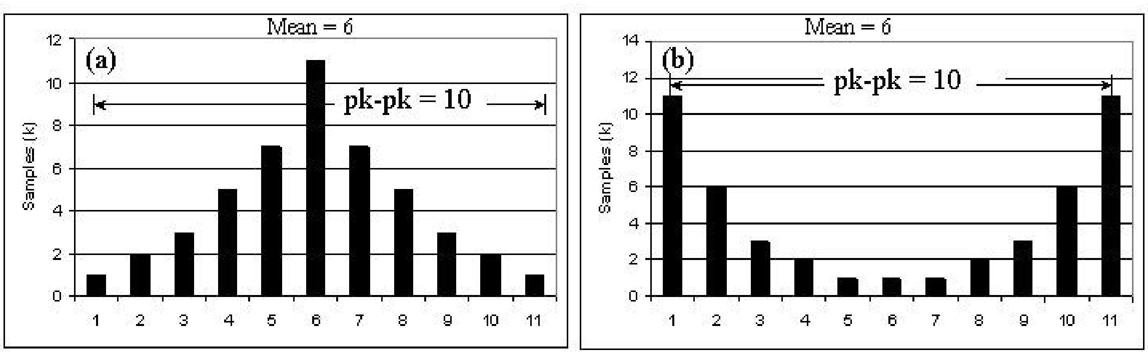
Dr. Mike Li is the Chief Technology Officer (CTO) with Wavecrest. Dr. Li pioneered jitter separation method (Tailfit) and DJ, RJ, and TJ concept and theory formation. Currently he is Co-Chairman for PCI Express jitter standard committee. Dr. Li has more than 10 years of high-speed related measurement instrumentation, testing, and analysis experience in applications including IC, microprocessor, clock and serial data communications for electrical and optical, and wireless communication. He 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 and worked there as a research scientist on high-energy astrophysics before he joined industry. Dr Li has published more than 40 papers in refereed technical journals, holds one patent and has four patents pending.

I. Introduction

Clocks, oscillators, Phase Lock Loops (PLLs) and Serial-Deserializers (SERDES) are a few of the most critical components in today's high-speed communication systems. Because these components are responsible for critical timing applications in systems, it is important to accurately characterize and quantify their jitter in order to determine system performance and reliability. Traditionally it was believed that the component performance and/or reliability could be determined with a simple peak-to-peak value from a jitter histogram. However peak-to-peak measurements can be misleading if sufficient information is not communicated. Furthermore, there are a number of measurements that are used to quantify jitter, including phase jitter, period jitter, and cycle-to-cycle jitter, and these measurements can produce dramatically different results. This article will discuss the drawbacks of quantifying histograms with pk-pk measurements and discuss which measurements are appropriate for quantifying device performance in both clock and datacom applications.

II. Gaussian Distributions

Intuitively, one would expect that two different devices with the same peak-to-peak jitter values (the jitter could be phase, period, or cycle-to-cycle) would have the same performance. However, that conclusion cannot be made without further analysis. For example, figures 1(a) and (b) show two different distributions with the same number of total hits, mean and pk-pk values. Clearly distribution (b) has more variability since there are fewer hits near the mean. The biggest drawback with quantifying a distribution with a pk-pk value is that it is based on only two points and ignores the rest of the distribution.[1] Most important, however, is quantifying a distribution based on only two peak points can result in poor measurement repeatability. Mathematically, there is an infinite number of distributions available for a given pk-pk value. In other words, jitter distribution cannot be uniquely determined if only pk-pk value is given.



Figures 1(a) and 1(b) show two bar charts with the same number of hits (48,000) and a pk-pk of 10 (11-1), but with dramatically different distributions.

One way to measure variability in a distribution is to calculate the standard deviation or σ (sigma). An important property of the standard deviation is that the calculation involves every point in the histogram and the σ stabilizes quickly as a function of sample size. Figure 2(a) illustrates that the σ is very stable as a function of samples in the histogram, however the pk-pk values increase with sample size. When quantifying the performance of a device it is important to use parameters that do not change as a function of a variable, such as sample size. In other words, a histogram with a particular pk-pk value has meaning only if it is given with sample size and test conditions. However, the accuracy of the pk-pk measurement is low. Figure 2(b) shows standard error for both pk-pk and standard deviation as a function of sample size. The standard error quantifies the uncertainty in a measurement. The standard error of the pk-pk measurement is larger than the σ for all sample sizes. Therefore, the standard deviation is more repeatable for describing a histogram because the value quickly stabilizes and has less error compared to pk-pk measurements.

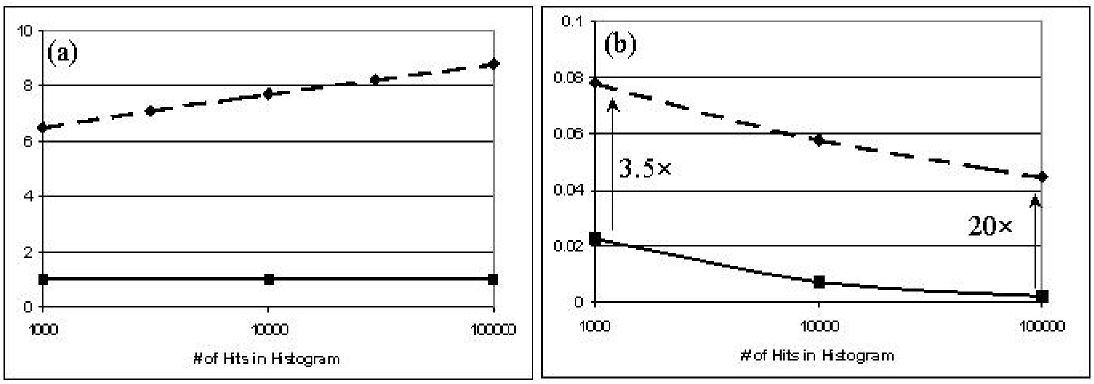


Figure 2(a) plots the σ (solid line) and pk-pk (dashed line) values as a function of sample size for a Gaussian variable. The figure shows that the pk-pk measurements increase with sample size, whereas the σ is nearly unchanged. Figure 2(b) shows the standard error for the σ (solid line) and pk-pk (dashed line) versus sample size. For all sample sizes the pk-pk measurements have a larger standard error compared to the σ. In addition, the accuracy of the pk-pk measurements relative to the σ gets worse with increasing sample size.

For Gaussian distributions the standard deviation provides additional insight into the distribution's characteristics and can be used to predict pk-pk jitter as a function of probability level. The σ is often times referred to as the "width parameter." Large σ values imply a wide "bell shaped" distribution and a small σ value implies a narrow "bell shaped" distribution. Random jitter (RJ), seen in all clocks, oscillators and PLLs, is characterized by a Gaussian distribution and is assumed to be unbounded. Knowing the standard deviation of a Gaussian distribution is useful because it can be used to calculate the width of the histogram for a given probability level. In many data communication standards, it is common to express pk-pk jitter at a given BER.[2] For example, a BER of 1.3×10^{-3} would be a pk-pk range of $6 \times \sigma$. This means that the pk-pk range specified by $6 \times \sigma$ would contain all of the measurements except an amount represented by multiplying the total number of measurements by 0.0013. It is important to recognize that the pk-pk value at a given probability level can be obtained because the Probability Density Function (PDF) is known (a Gaussian distribution with a mean and standard deviation). This is dramatically different than knowing only the pk-pk value of a distribution.

III. Non Gaussian Distributions-Real life distributions

It is very common to observe jitter histograms of clocks, oscillators and PLL's that are not ideal Gaussian distributions containing a mixture of Gaussian and non Gaussian histograms. Quantifying a non Gaussian distribution with the σ and determining pk-pk jitter as a function of probability level is not valid and other methods must be employed. Figure 3(a) shows three different histograms with the same σ. Figure 3(b) shows BER or P(x) versus σ for the three histograms. Figure 3(a) illustrates that even though the three histograms have the same σ, they have dramatically different pk-pk ranges for a given BER. For example, if these were jitter histograms, the Gaussian distribution (blue) at 10^{-12} BER would have a pk-pk jitter of 14 × σ whereas distribution (green) would have a pk-pk jitter of 11.5 × σ with (red) being only 9.2 × σ. Both green and red histograms contain a mixture of deterministic and random components.[2] One method of separating the two components for any shaped histogram is accomplished by fitting Gaussian tails to the left and right side of the histogram, commonly called the TailFit™ method.[3] This method quantifies the random jitter (RJ) component and the difference between the means of the two Gaussian curves is the deterministic jitter (DJ). An example is shown in Figure 4 for a trimodal histogram where Gaussian tails are fit to the left and right most sides of the histogram. Quantifying RJ and DJ allows one to accurately calculate the pk-pk jitter as a function of BER. Furthermore, knowing the RJ and DJ components provides additional insight into system performance. The magnitude of these values relative to a specification will enable designers and engineers to use other diagnostic tools to locate the problem. For example, a large DJ component may suggest unwanted interference.

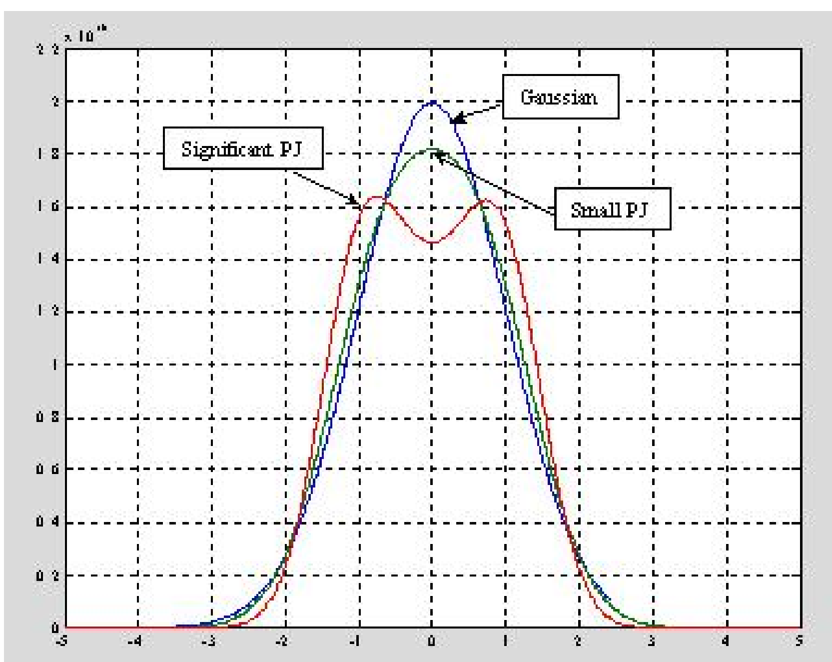
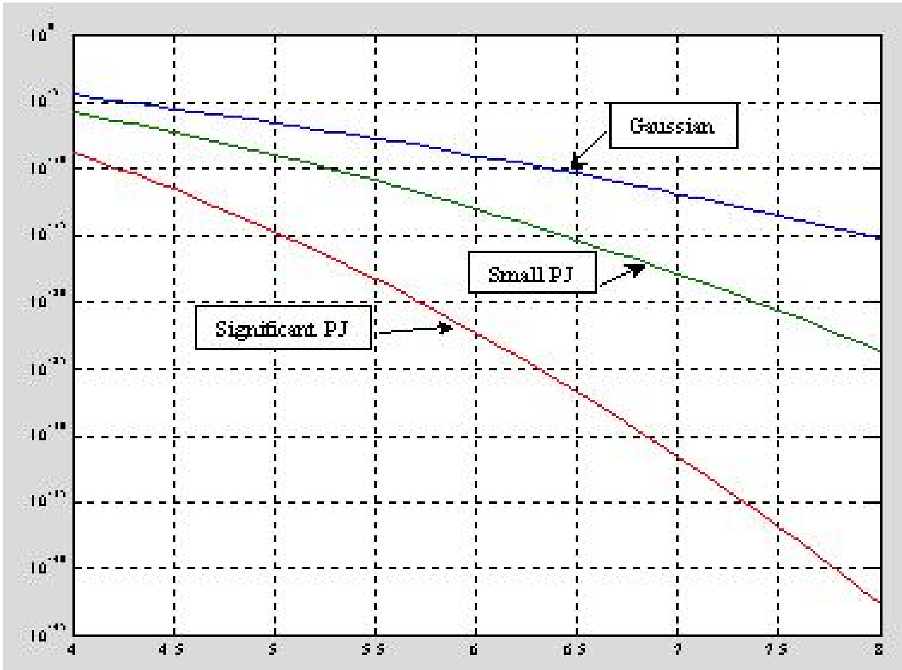


Figure 3(a). Three different histograms with the same standard deviation. Gaussian distribution. (blue) Gaussian distribution with a small amount of PJ (green) and Gaussian distribution with significant PJ (red).



3(b) Resultant curves showing BER as a function of standard deviation

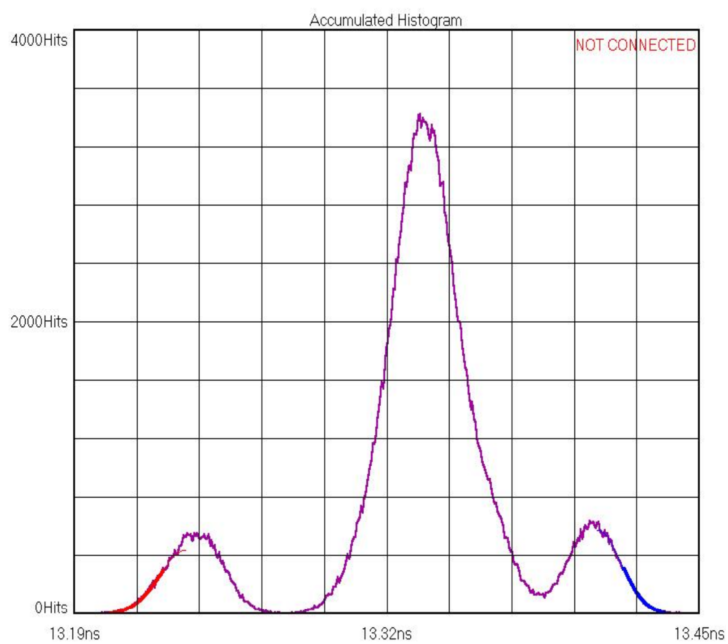


Figure 4. A jitter histogram of period measurements that contains both RJ and DJ. To accurately quantify random jitter and deterministic jitter tails have been fit with Gaussian distributions on the left (red) and right (blue).

This section reviewed a variety of ways to quantify jitter histograms whether it is phase, period, cycle-to-cycle or clock-to-data measurements in datacom applications. It was shown that a pk-pk number does not adequately quantify a histogram because it is inaccurate and its magnitude depends on sample size. Standard deviation provides a good metric of describing Gaussian distributions because it quickly converges to a stable value with increased sample. The magnitude of the standard deviation also provides a relative measure of a distributions width and pk-pk jitter can be determined as a function of probability level or BER. For non Gaussian or "real life" histograms, it was shown that the random and deterministic components of histograms need to be quantified in order to correctly calculate jitter and relate it to system performance. The benefits and drawbacks for each measurement parameter are summarized below in Table 1.

Parameter	Benefits	Drawbacks
pk-pk measurement of a histogram	• Provides a number	• Measurement must be stated with sample size and setup conditions. • Measurement not repeatable
Standard deviation (σ)	• Measurement parameter is repeatable relative to pk-pk measurements • Can be used to calculate pk-pk jitter as a function of BER or probability level (only when distribution is Gaussian)	• Useful only for Gaussian distributions
Quantifying random and deterministic components	• Can be used to calculate total jitter as a function of BER or probability level for any shape of histogram. • The magnitude of the components provides diagnostic information	

Table 1 showing the benefits and drawbacks for each measurement parameter.

IV. Phase, Period and Cycle-to-Cycle Jitter

The preceding discussion reviewed the importance of correctly quantifying a jitter histogram. When analyzing clocks, oscillators, and PLLs it is common to measure phase, period and/or cycle-to-cycle jitter in order to determine device performance. The next section describes the relationship between the three types of jitter and the effect of sinusoidal error on the results.

For the following section assume that the test instrumentation measures the threshold crossings of a waveform and stores them in an array. Figure 5 shows the timestamps of the threshold crossings of a waveform with a sinusoidal error term added to the ideal threshold spacing of 400 ps, the unit interval for PCI Express and Infiniband.

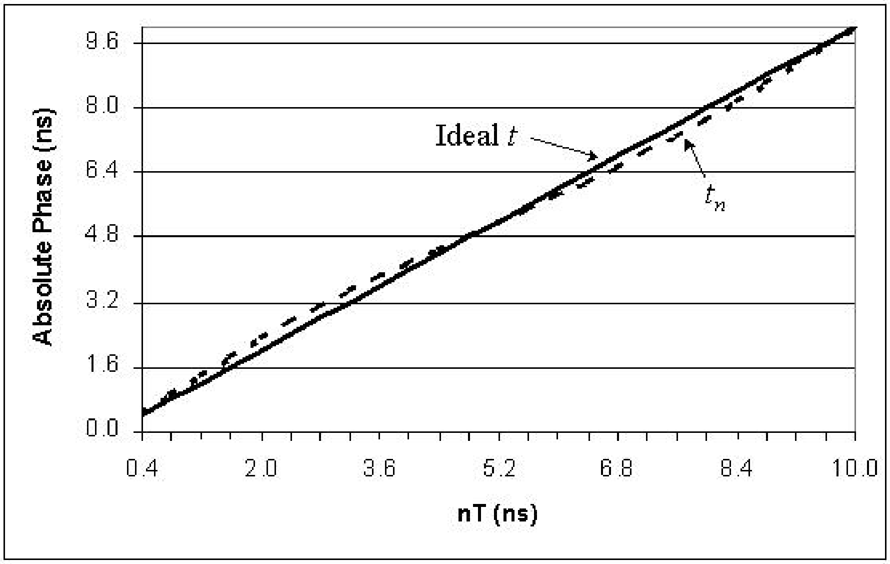


Figure 5 showing timestamps of an ideal waveform (solid) and one with a sinusoidal error term added (dashed).

Phase jitter is defined as the difference between the measured time and the ideal period as shown in equation 1. The jitter magnitude is proportional to the relative phase magnitude. The time error accumulates for increasing bit periods. Phase jitter is also known as phase noise or accumulated jitter.

$$\Phi_n = t_n - nT, \qquad n = 1,2,3\ldots.. \qquad (1)$$

where T is the ideal bit period. An example of sinusoidal phase jitter at 100 MHz having a magnitude of 300 ps on a signal with an ideal bit period of 400 ps is shown in Figure 6.

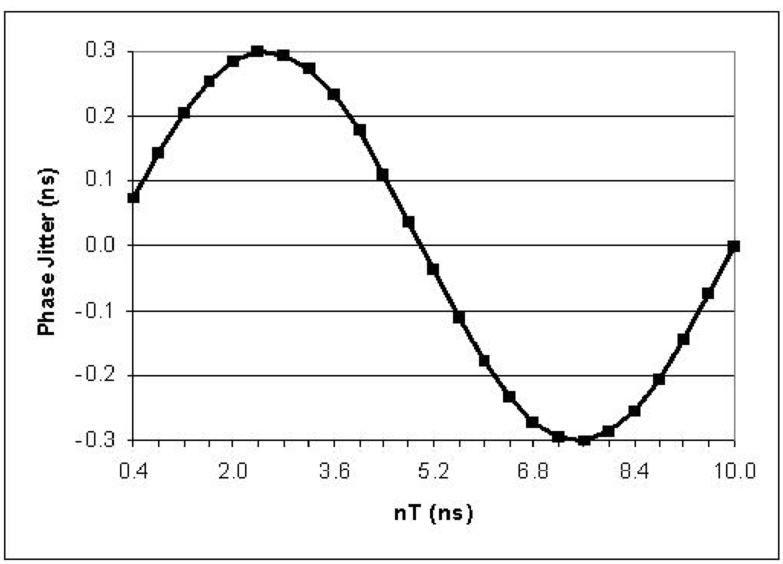


Figure 6 showing Phase Jitter versus increasing bit period for a waveform with sinusoidal jitter.

Period jitter (Φ'_n) is the difference between the measured period and the ideal period as shown in Equation 2. Period jitter is also the first difference of the phase jitter.

$$\Phi'_n = (t_n - t_{n-1}) - \mathrm{T} \qquad n = 1,2,3\ldots. \qquad (2)$$

Figure 7 shows the period jitter for the waveform with added sinusoidal error from Figure 5.

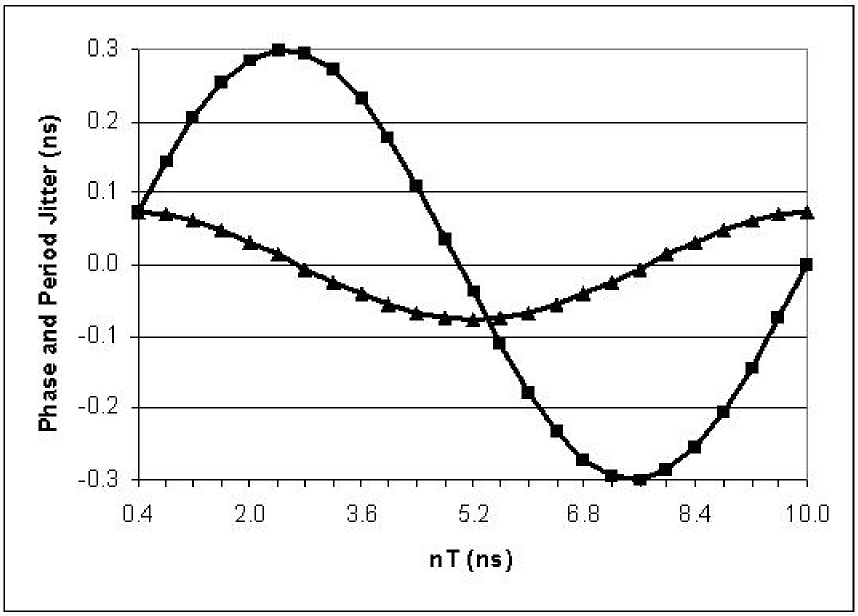


Figure 7 showing phase jitter (■) and period jitter (▲) with a sinusoidal error term added to a signal with and ideal bit period of 400 ps.

Cycle-to-cycle jitter is defined as the difference between consecutive bit periods as shown in Equation 3. Cycle-to-cycle jitter is also the first difference of period jitter.

$$\Phi''_n = (t_n - t_{n-1}) - (t_{n-1} - t_{n-2}), \quad n = 1,2,3\ldots. \qquad (3)$$

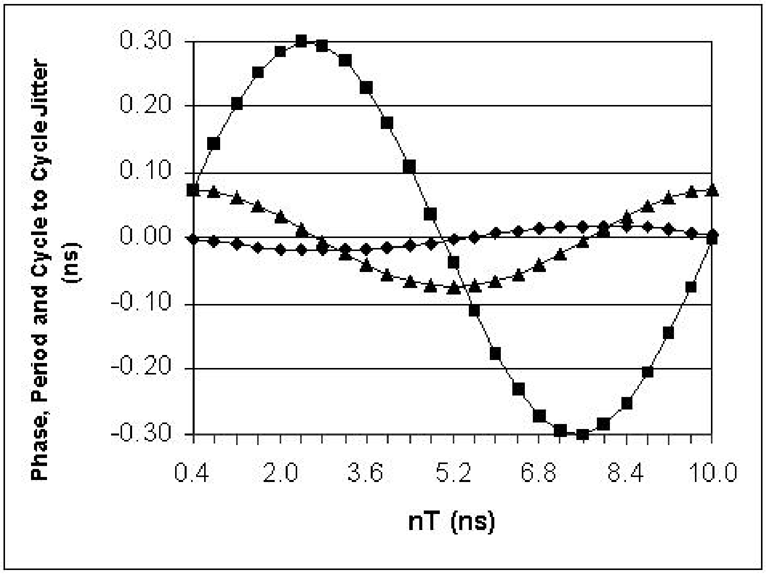


Figure 8 showing phase jitter (■), period jitter (▲) and cycle-to-cycle jitter (◊)with a sinusoidal error term added to a signal with and ideal bit period of 400 ps.

Figure 8 shows the cycle-to-cycle jitter for the waveform with added sinusoidal error from Figure 5. Figure 8 shows the relationship between three types of jitter; phase, period and cycle-to-cycle jitter. The example shows that the magnitude of the sinusoidal error decreases from phase to period to cycle-to-cycle jitter measurements. Figure 8 indicates that the three different jitter measurements have different frequency responses. Figure 9 shows the frequency response of the various types of jitter. The plot shows that for low frequencies cycle-to-cycle jitter has a second order rolloff of 40 dB/decade and period jitter has a rolloff of 20 dB/decade. Therefore it is important to understand the application and then use the appropriate measurement. For Phase Lock Loops (PLL) it would be appropriate to measure the phase jitter because PLLs develop an output that is proportional to the phase error of the reference and output signal. It is common to diagnose periodic modulation or crosstalk sources in systems and devices and for those applications it would be appropriate to measure phase or period jitter.

Figure 10 shows the measurement results from a 1 GHz clock signal with a 50 MHz sinusoidal modulation using a Signal Integrity Analyzer. The results show how the measurement impacts the magnitude of the jitter modulation. The phase jitter (accumulated jitter) results show the magnitude of the 50 MHz modulation is 98 ps pk-pk. The period jitter histogram shows the deterministic component has a magnitude of 29 ps pk-pk with the cycle-to-cycle distribution nearly Gaussian.

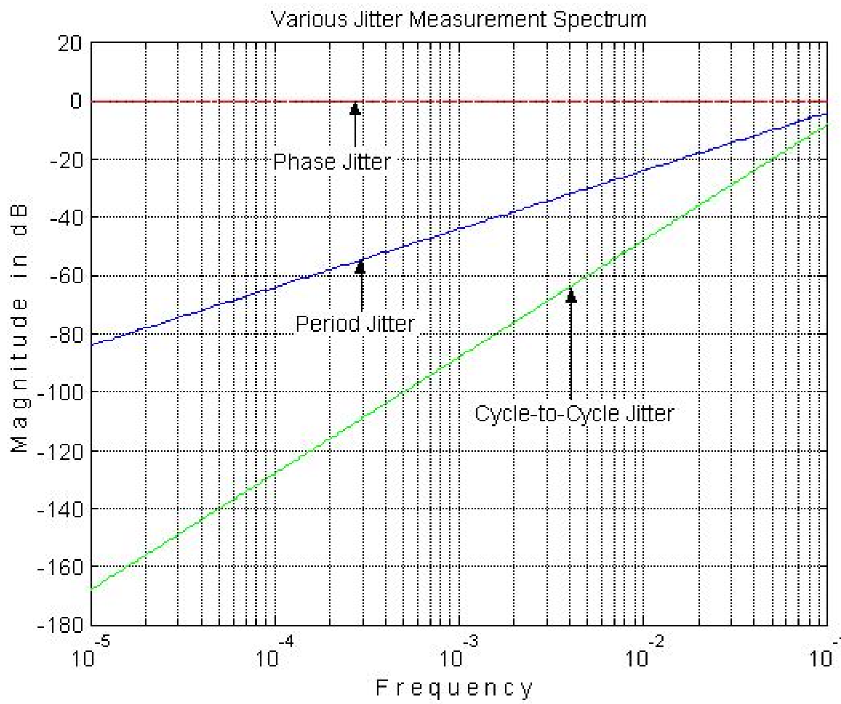
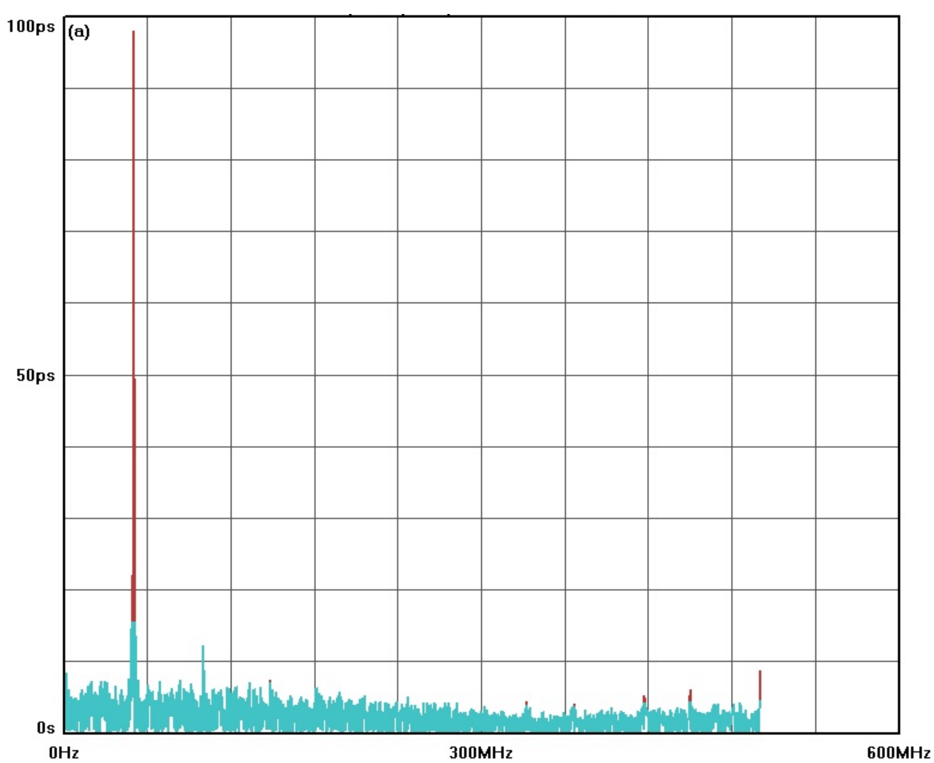


Figure 9 showing the frequency response of three types of jitter. The x-axis has been normalized to 1 Hz, therefore multiply the x-axis by the frequency of the application. For PCI Express the x-axis would be multiplied by 2.5 GHz. Note the rolloff for cycle-to-cycle jitter at low frequencies is 40 dB/decade and 20 dB/decade for period jitter.



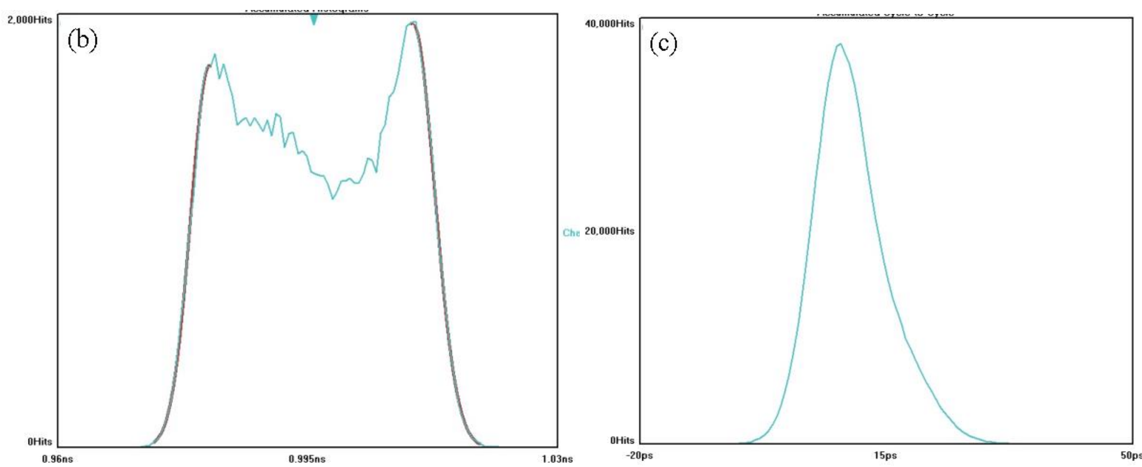


Figure 10(a) showing measurement results from a 1 GHz clock signal with a 50 MHz modulation using an SIA 3000. Top view showing a spectral view of accumulated jitter with a 50 MHz component having a magnitude of 98 ps pk-pk. Another view of 10(a) can be shown with the plot normalized to one cycle and the resultant magnitude of the 50 MHz component is 15 ps pk (30 ps pk-pk). Figure 10(b) left, showing histogram of period measurements having a Deterministic Component of 29 ps pk-pk. Figure 10(c) right, showing histogram of cycle-to-cycle measurements having nearly a Gaussian distribution and a pk-pk deterministic component of near zero.

For serial communication systems it is common to have a clock recovery device using PLLs. The PLL will have a frequency response and when the receiver uses the recovered clock to time/retime the data, the jitter seen by the receiver will follow the PLL frequency response.[4] Because the jitter output of the PLL will have a high pass jitter transfer function the receiver can tolerate more low frequency jitter than high frequency jitter. The frequency in which the PLL begin to track is commonly referred to as the corner frequency, f_c, or the 3 dB frequency of the transfer function. For Fibre Channel and Gigabit Ethernet the corner frequency is defined as Data Rate/1667. Therefore, for a data rate of 2.5 Gb/s the corner frequency is 1.5 MHz.

Figure 5 showed the effect of a sinusoidal error term that was added to an ideal waveform. If the output simulated a clock recovery system with a PLL and the modulation frequency was below the corner frequency, then the magnitude of the phase jitter would be reduced and this is illustrated in Figure 11. The magnitude of the sinusoidal jitter will be dependent on the corner frequency and the roll off below f_c.

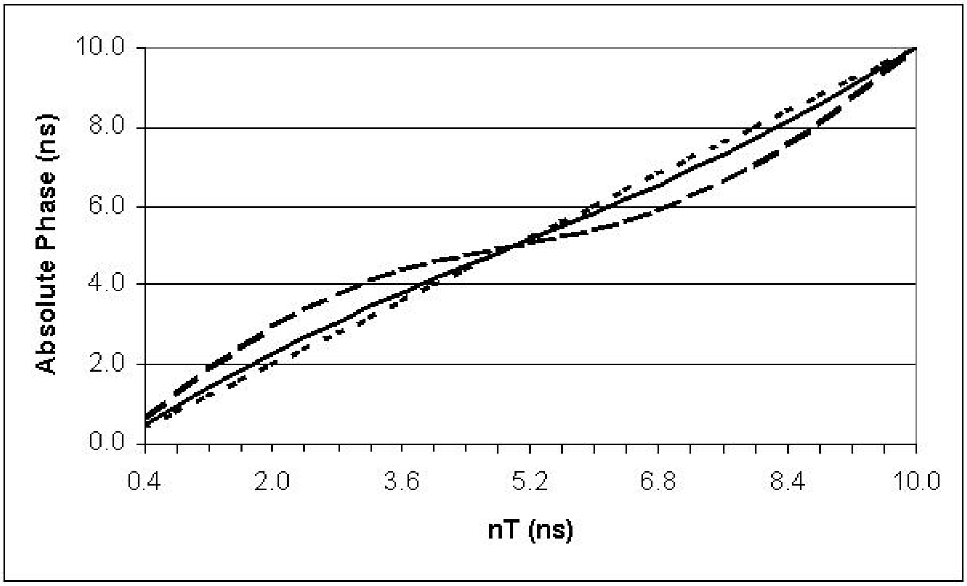


Figure 11 showing timestamps of an ideal waveform (solid) and one with a 100 MHz sinusoidal error term with 1 ns magnitude added (long dash) and the resultant phase jitter from a device that reduces the amount of jitter (short dash). The short dashed line might resemble the effect of a clock recovery system in a serial data communication device.

The results shown in Figure 11 illustrate the need for the test instrumentation to correctly emulate the application when measuring jitter. For example, as discussed earlier many standards specify the corner frequency. If a clock or recovered clock is used to make the measurement (for example when making an eye diagram measurement) it is imperative that the clock have the characteristics of the application. For a Fibre Channel application this would require using a clock in the measurement that has a corner frequency of the Data Rate/1667. Figure 12 illustrates the effect of using a recovered clock with a corner frequency of Data Rate/1250 and a noncompliant clock when making a clock-to-data measurement at 2.5 Gb/s with a 200 kHz periodic modulation added to the data signal. The measurement was performed with a Wavecrest SIA 3000. The results show that the Deterministic Jitter using the recovered clock 13 ps and with a non compliant clock was 140 ps. Eye diagrams for each case are also provided. This example illustrates the importance of the clock recovery frequency response because the system with the higher corner frequency is more tolerant of periodic modulations.

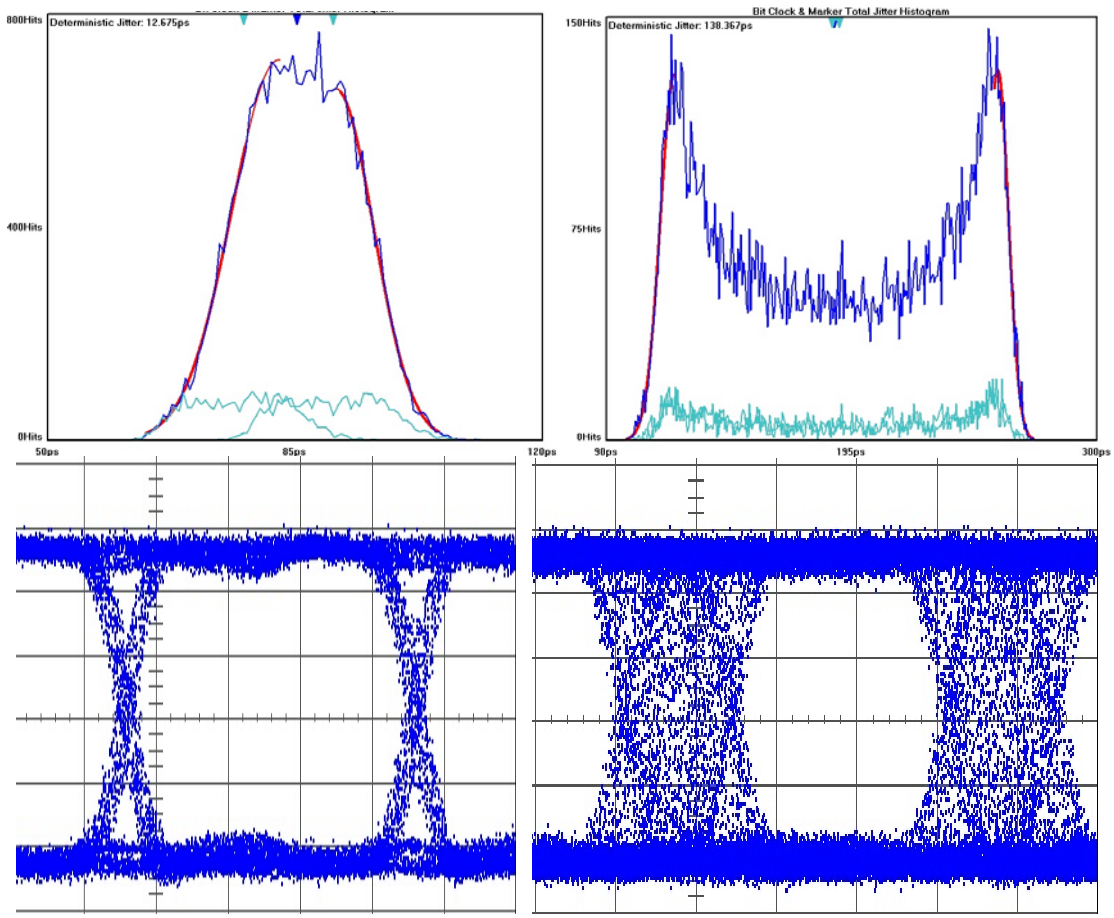


Figure 12 showing the resultant jitter histogram using a recovered clock with a corner frequency of Data Rate/1250 (top left) in a clock-to-data measurement compared to a clock-to-data measurement using a clock with a very low corner frequency (top right). The data signal was 2.5 Gb/s and the modulation frequency was 200 kHz and is common to both cases. The eye diagram at the bottom left was obtained using the recovered clock and the eye diagram at the bottom right was obtained with a noncompliant clock.

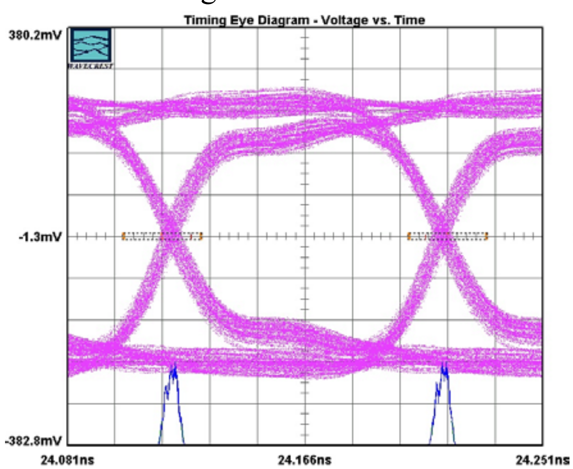
V. Instrumentation for Measuring Signal Integrity

The preceding section reviewed some of the common signal integrity measurements and the importance of measurement statistics. This section reviews some of the common test instrumentation that is used to perform signal integrity measurements. There are many types of instruments used for signal integrity analysis and these are Signal Integrity Analyzers (SIA), oscilloscopes, and Bit Error Ratio Testers (BERT). 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 instrument will be described.

a. Oscilloscopes: Equivalent Time Sampling and Digital Storage

For high-speed signals equivalent time sampling oscilloscopes are generally used to characterize the signal integrity of clock and data signals. These oscilloscopes can have a very high bandwidth, up to 70 GHz today. These oscilloscopes have a very low

Intersymbol Interference noise floor (typically ~1 ps at 10 Gb/s) with a low random jitter noisefloor (down to 200 fs) making them ideal instruments for 10 Gb/s and above applications. For equivalent time 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. The trigger can either be a pattern marker or bitclock. Equivalent time sampling oscilloscopes measure voltage and timing accurately and can create “eye diagrams” for compliance testing. The measured data can then be compared to an eye mask or specification and to measure voltage levels, rise and fall times. The equivalent time sampling 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. Typical data acquision rates with a small voltage window (few mV) at the data crossing level are on the order ~100-1000 points/sec. The time to acquire data for an error probability of 10^{-12} BER would be in the hundreds of years, unreasonable for any lab characterization. Recently software has become available for equivalent time sampling oscilloscopes that greatly expands the instruments capabilities and enables compliance measurements. The software package quantifies random and deterministic jitter and noise, Total Jitter and Noise to 10^{-16} BER, and quantifies Data Dependent Jitter (DDJ). The software package can be used on both Tektronix (CSA and TDS 8000) and Agilent (DCA 86100) oscilloscopes for applications above 8 Gb/s. A few of the results are shown in Figures 13 and 14 for a 10.3 Gb/s data signal.



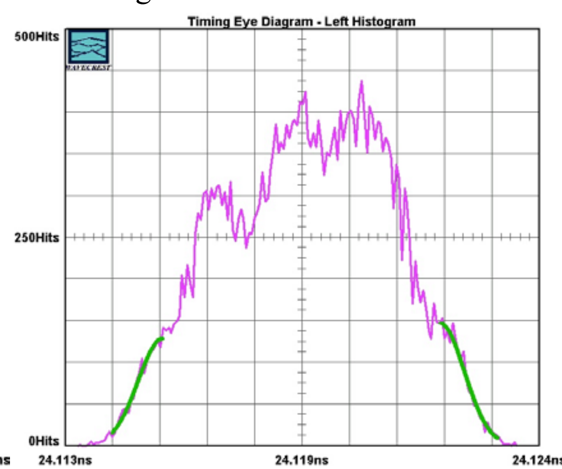


Figure 13 (left) timing jitter analysis showing an eye diagram of a 10.3 Gb/s signal and the resultant histogram from the crossing point at the left portion of the eye diagram. The Random Jitter is 0.45 ps, the Deterministic Jitter is 6.5 ps with the Total Jitter at 10^{-12} BER of 16 ps.

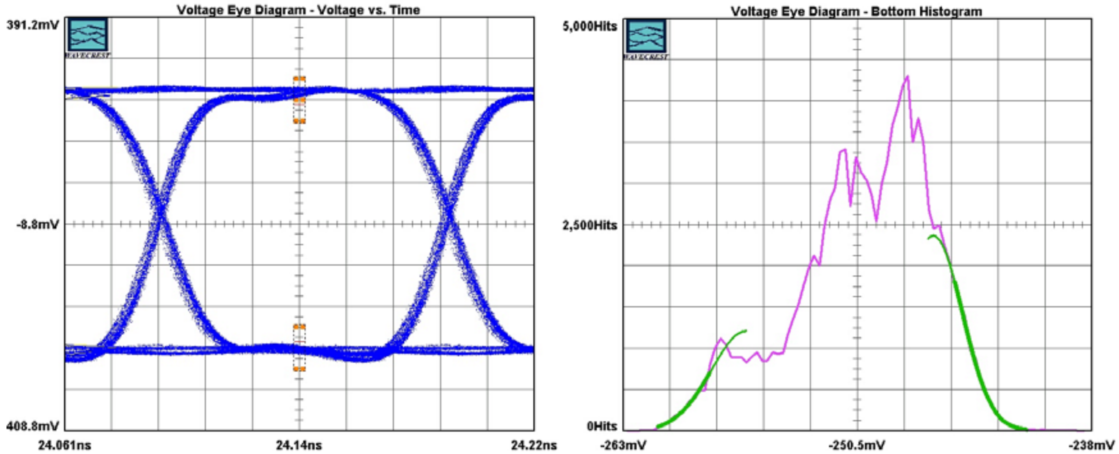


Figure 14 (left) amplitude noise analysis showing an eye diagram from a 10.3 Gb/s signal and the resultant histogram obtained from the bottom portion of the eye diagram. The Deterministic Noise is 12 mV with the Random Noise of 2 mV and the Total Noise at 10^{-12} BER of 38 mV.

Digital storage (real time) oscilloscopes acquire entire waveforms over a time interval. The length of the time record is dependent on the oscilloscope memory. The rate of the data acquisition is typically 20 GSa/sec or less. This equates to data points spaced every 50 ps or larger. Interpolation methods are necessary to improve the hardware resolution limitations. To date the highest bandwidth digital storage oscilloscopes are 7 GHz. The digital storage oscilloscope provides a valuable tool for viewing eye diagrams, determining voltage levels, overshoot, ringing, rise and fall times. Jitter packages are available for these oscilloscopes from multiple vendors that enable TJ estimation for a given BER, but the methodologies have not yet described and the results have not been correlated to industry standard test instruments such as BERTs.

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 standard require testing to 1×10^{-12} BER to insure interoperability and system reliability. In order to obtain TJ 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 15. BERTs provide a valuable total jitter diagnostic tool because of its ability to accurately measure the TJ as a function of BER. The drawback is that the long time required to complete a bathtub curve for a BER of 10^{-12}. Typical device test times for a BER of 10^{-12} is on the order of 2-8 hours. The data obtained from a BERT cannot separate TJ into RJ and DJ unless drastic oversimplifications are made about the DJ PDF.

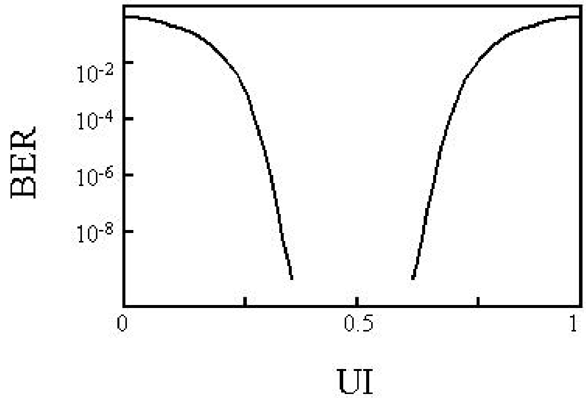


Figure 15. A bathtub curve showing BER as a function of eye closure. The Total Jitter increases as a function of decreasing BER.

c. Signal Integrity Analyzers (SIA)

SIA's are instruments that combine the capabilities of oscilloscopes, BERTs and Time Interval Analyzer (TIA) into one box. The TIA capability allows one to measure accurate and repeatable single shot edge-to-edge time intervals on a non-continuous and random basis. Time measurements are acquired at a particular voltage level (for example, the midpoint) on a random schedule to insure a solid and unbiased statistical basis. The statistics of these measurements provides information on total jitter, deterministic jitter, random jitter, propagation delay and skew. Data signals can also be analyzed in one of two methods. 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 16.

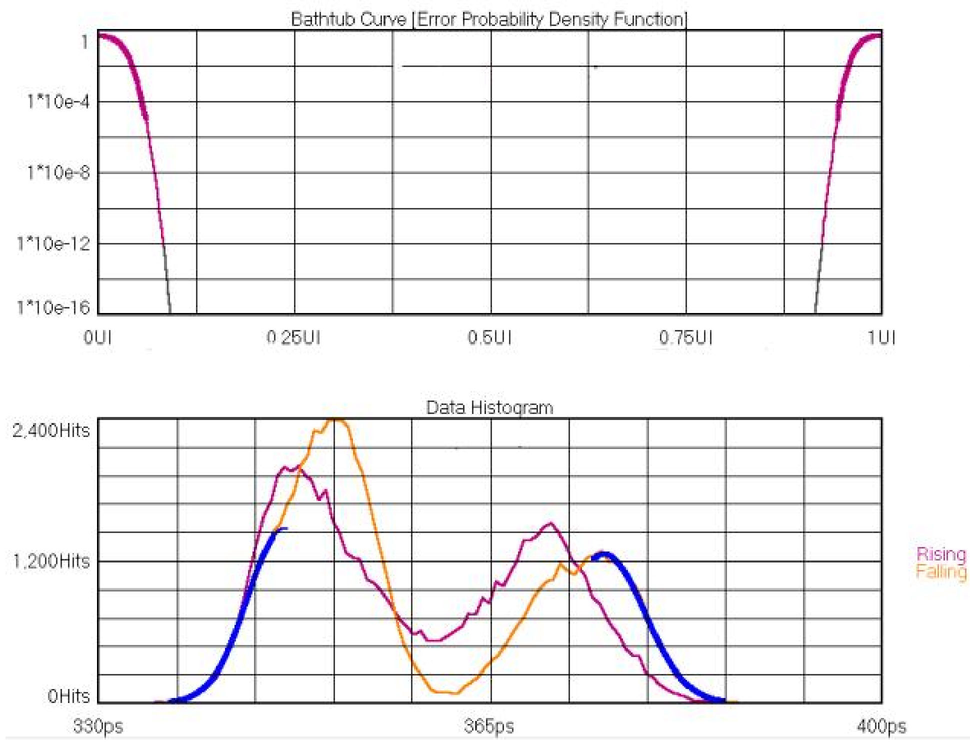


Figure 16. Typical data acquired with an SIA using clock-to-data method. Bottom figure shows histograms for rising and falling data edges. This view enables the user to determine the jitter contribution from the polarity of edges. The right and left most portion of the histograms are fitted with Gaussian tails in order to determine the σ 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[5]. In this method a pattern marker provides an arm or enable 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 data transition unit interval also known as the autocorrelation function. A FFT of the autocorrelation function is used to determine the periodic component and random 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 or periodic jitter, 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 17 shows a typical data set using a repeating pattern and a pattern marker.

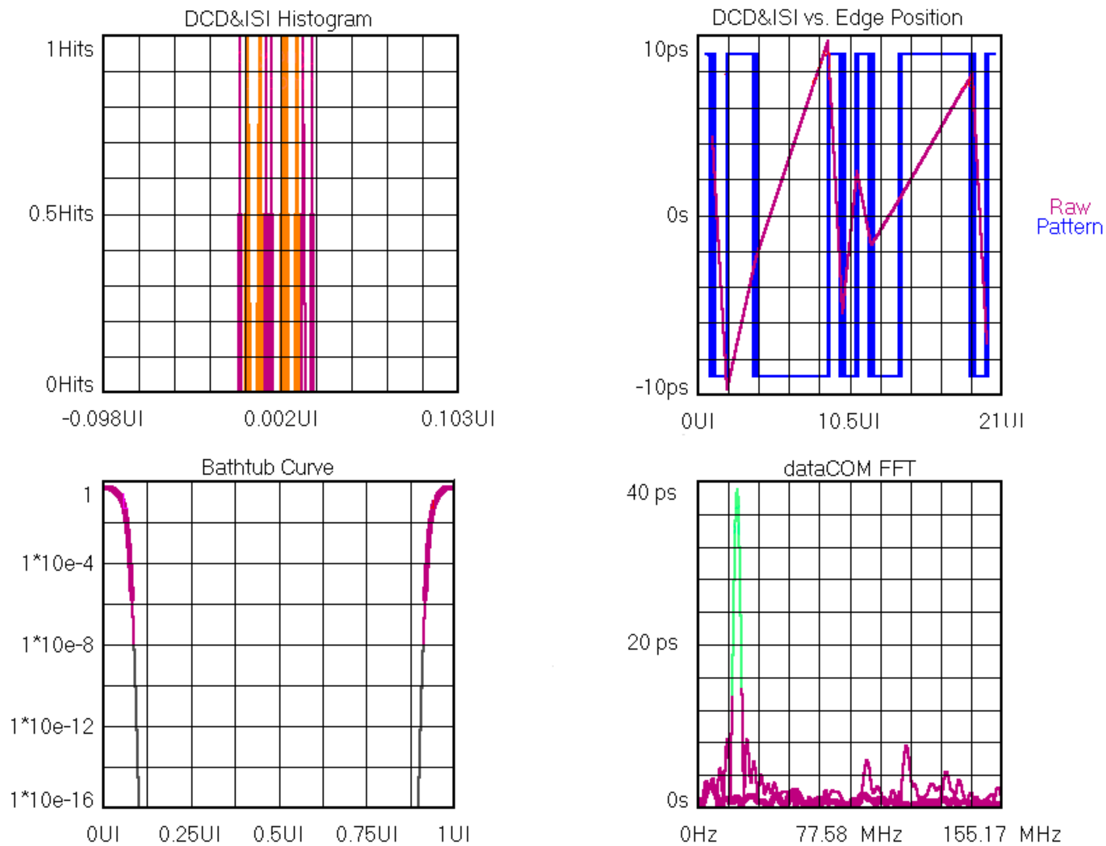


Figure 17. Typical data set using a repeating pattern and pattern marker with an SIA. Clockwise from top left, the DCD&ISI histogram from a K28.5 pattern showing the pk-pk contribution. The DCD&ISI contribution at each edge location in the pattern. The wide range of time deviations (dark purple line) 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 TJ increasing as a function of lower BER.

The advantage of the SIA 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 SIA can separate TJ into its deterministic and random components. Additionally the TJ values are provided down to a BER of 10^{-16} allowing compliance measurements for many datacom standards. Figures 16 and 17 show representative data sets from the two methods illustrating the diagnostic capabilities of the SIA method. Test times are the same independent of BER because the SIA 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 $\leq 10^{-16}$.

Another capability of the SIA is the ability to detect bit failures on repeating patterns. The SIA has a bit error counter that records and calculates the BER. The region where the bit failure occurred can be reviewed to determine if a particular portion of the pattern is contributing to the bit errors or if the errors are due to some other source. Although this functionality only captures “hard” errors, it does provide quantitative information on low probability errors.

SIA's also have the capability to analyze the shape of the waveform using the oscilloscope functionality. SIA's have an integrated sampling oscilloscope on the analysis channel in addition to the time measurement circuitry. Further analysis can be done such as eye diagrams (see Figure 18), mask testing, measure voltage levels, rise and fall times and other waveform characteristics. The bandwidth of the sampling oscilloscope is >6 GHz.

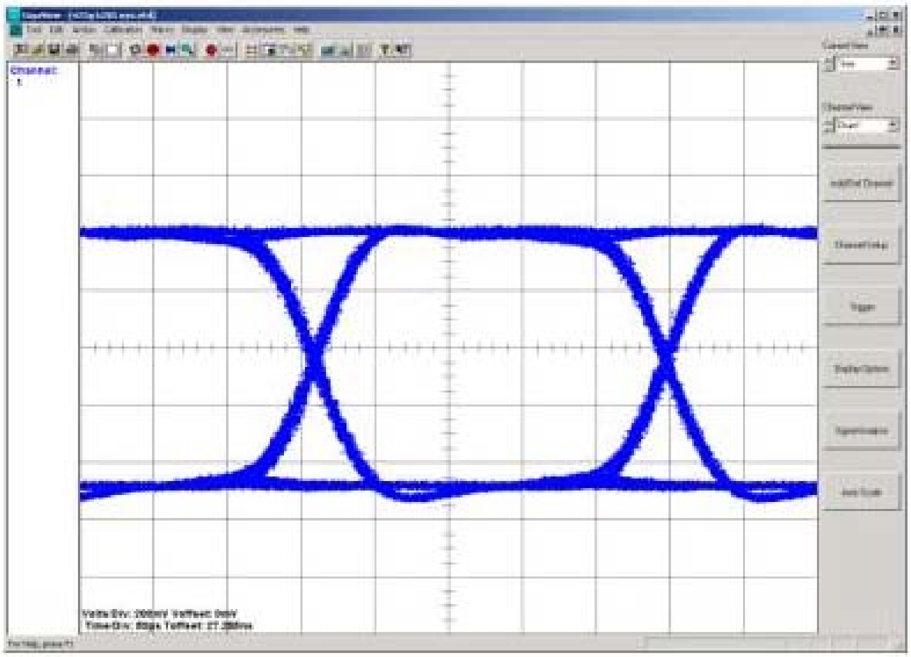


Figure 18 showing an eye diagram of a 4.25 Gb/s data signal obtained from the sampling oscilloscope of the SIA-3000.

VI. Conclusion

This paper illustrated the importance of the measurement statistics when quantifying the device performance. Determining random and deterministic jitter and quantifying total jitter at a BER provides a more accurate means of quantifying device performance compared to traditional techniques using only pk-pk or standard deviation. In addition, quantifying the random and deterministic components provides diagnostic information that may be useful in debug and characterization tests. An overview of phase, period and cycle-to-cycle jitter was provided to illustrate the relationship between the three types of jitter and the measurements frequency response. Oscilloscopes, BERT's and Signal Integrity Analyzers were described in order to show where each instrument is used in signal integrity analysis.

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