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An Overview of Signal Integrity

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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. It is common today to have serial data streams in storage area networks that exceed 2 Gb/s and it is expected that high-speed serial signals in backplanes will reach 6.25 Gb/s in 2003. Consequently, the minimum pulse width of these serial data streams have decreased to less than 500 ps, reducing the noise margin significantly. Insuring signal integrity at these data rates has become increasingly difficult for designers and engineers of systems and components. This paper will provide an overview of signal integrity and the associated measurement instruments that enable designers and engineers to fully characterize high-speed serial or parallel communication systems. This paper will focus on the information that can be obtained from eye diagrams and the importance of quantifying the various components of jitter in order to diagnose and eliminate design problems. Other topics in this paper include: how to measure jitter output and jitter tolerance for design characterization and compliance on systems and components, how to generate and verify various jitter components, why peak-to-peak and rms values alone are not good metrics for quantifying jitter. Actual test setups and methods for applications such as Fibre Channel, Gigabit Ethernet, Infiniband, PCI Express, XAUI, LVDS and clocks/oscillators will be discussed.

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.

1. Introduction

In high-speed device and system characterization, one ultimately wants to determine the Bit Error Rate of the device under test. Bit errors can be due to timing jitter and amplitude noise that is sufficiently large to cause a bit to be misinterpreted at the receiver. This paper is intended to provide designers and engineers with an overview of signal integrity, focusing on timing jitter and amplitude noise and their sources. A discussion of the different signal integrity measurement techniques used in today's laboratory and production environment and how they relate to characterizing and diagnosing devices will also be provided. In particular instrumentations such as Signal Integrity Analyzers (SIA), oscilloscopes, Bit Error Rate Testers (BERTs) and a variety of noise sources will be reviewed and how this equipment is used to characterize devices.

2. Timing Jitter

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 databusses and integrated circuits. Timing jitter is the deviation from the ideal timing of an event 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.

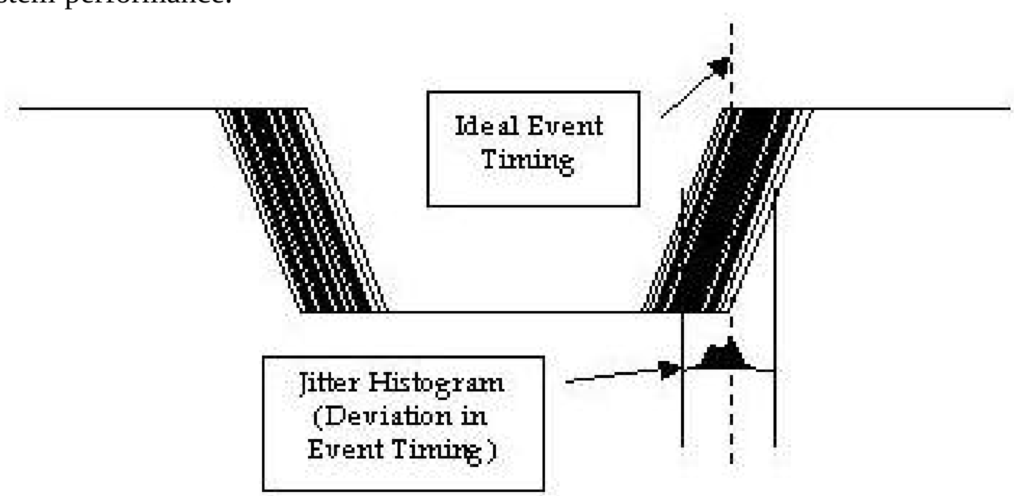


Figure 1. Timing jitter is the deviation from the ideal timing of an event. Jitter is composed of both deterministic and Gaussian (random) content. TJ is the convolution of all independent jitter component PDFs.

2.1 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].

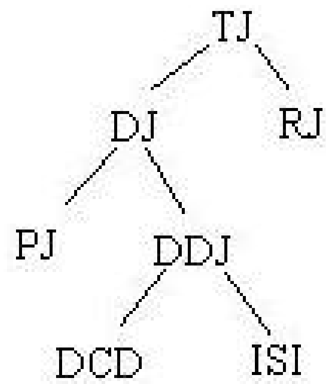
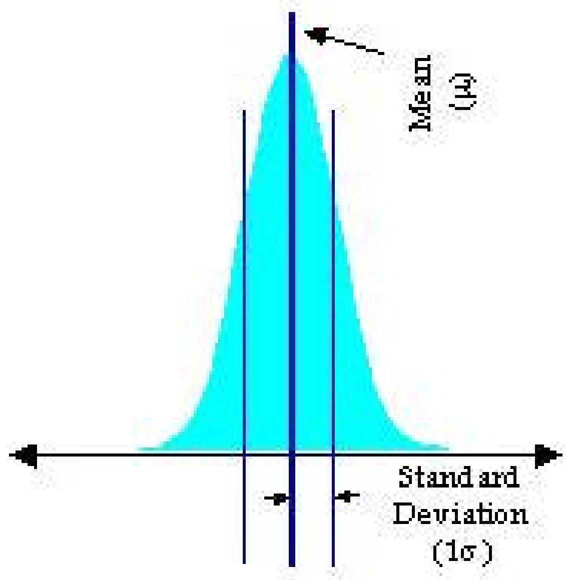


Figure 2. Total jitter (TJ) includes deterministic jitter (DJ) and random jitter (RJ). DJ can be further separated into periodic jitter (PJ), data dependent jitter (DDJ), duty cycle distortion (DCD) and intersymbol interference (ISI).

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.

2.2 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 left and right tails are used when calculating TJ. Figure 4 shows a Gaussian tail fit to the left side of the distribution. Chisquared 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.

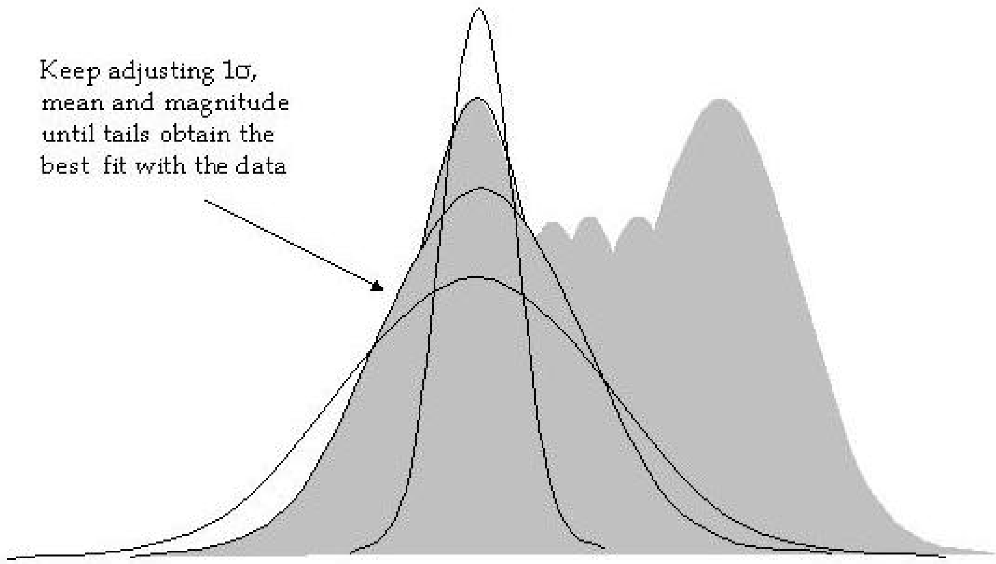


Figure 4. The TailFit algorithm enables the user to identify a Gaussian curve with a coincident tail region in order to quantify the random or Gaussian component of the distribution. Various curves are fitted against the distribution until an optimal match is found. Then, the 1σ of the matched curve 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.

2.3 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.

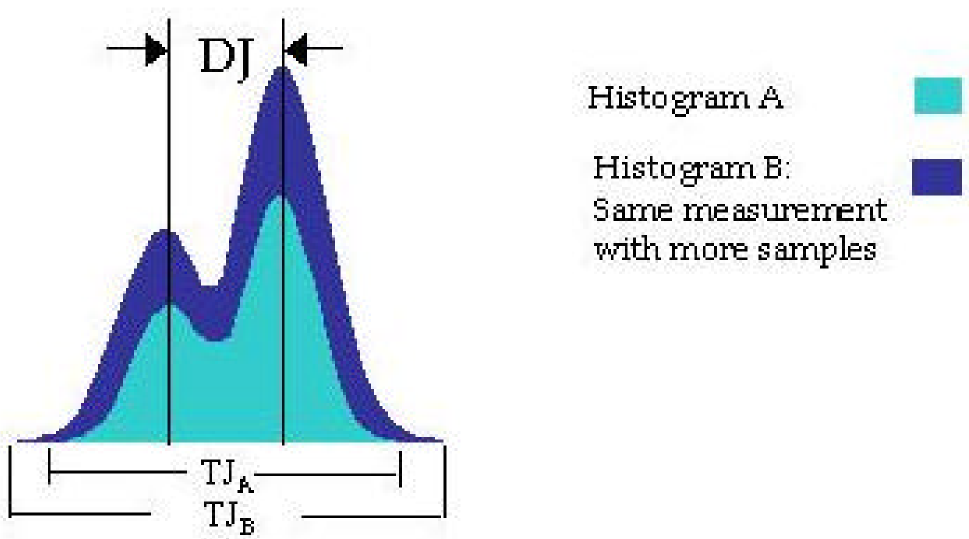


Figure 5. DJ is characterized by a bounded pk-pk value that does not increase with more samples. RJ is unbounded and its pk-pk value increases, resulting in larger TJ values with more samples.

2.4 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 s. 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 standard deviation 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.

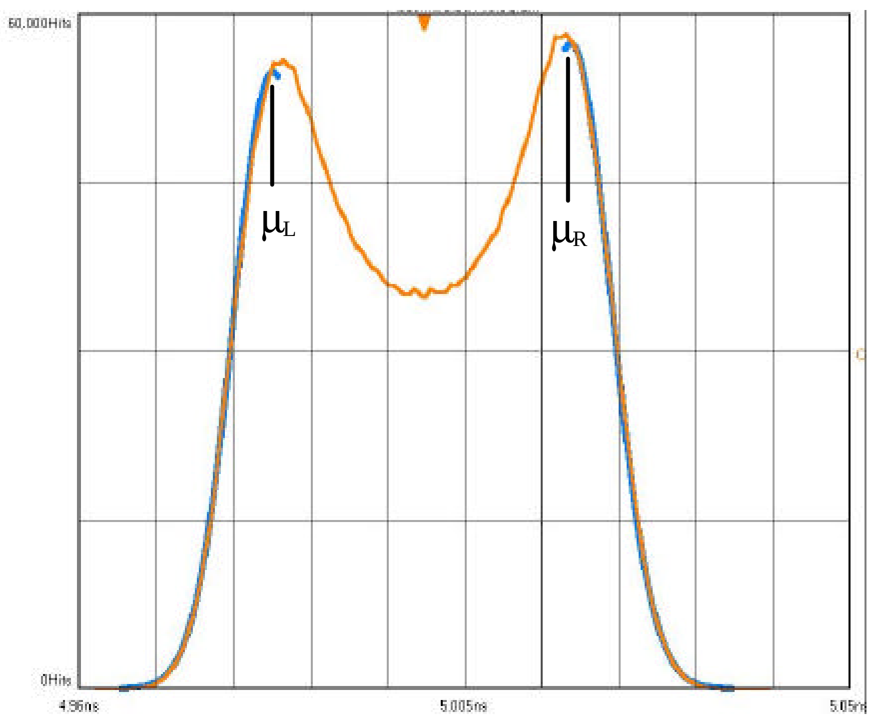


Figure 6. A bimodal distribution that contains both RJ and DJ components, achieved by adding a single DJ component to an otherwise Gaussian distribution. DJ is the difference between the two means.

2.5 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 $1/f^{a}$ where a 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.

3. Amplitude Noise

Just as timing jitter can induce errors in a system, amplitude noise can also cause errors. In binary data communication systems the data is either transmitted as a 1 or a 0 and if the amplitude noise is sufficiently large at the receiver it is possible to misinterpret a 1 as a 0 and vice versa. Amplitude noise is present in all data signals and is due to random and deterministic sources.

3.1 Random Noise

Random amplitude noise is assumed to have a Gaussian distribution and unbounded [4]. Figure 7 depicts how random amplitude noise can cause errors in data. The figure shows random voltage

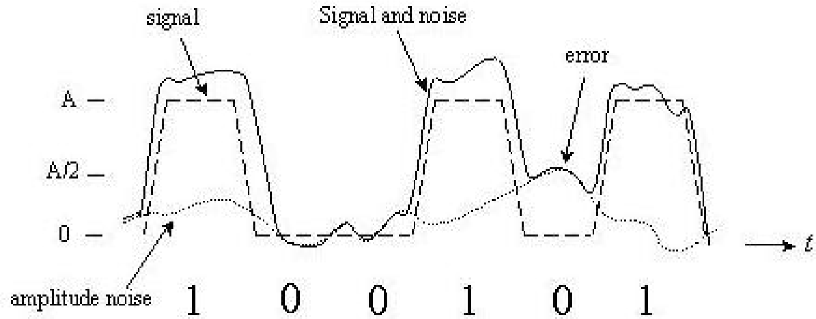


Figure 7 showing the effect of amplitude noise on a signal. The noise (dotted line) is summed onto the data signal (dashed line). The amplitude noise at the 5th bit is sufficiently large to cause an error so that the 0 is interpreted as a 1.

fluctuations summed on a data signal (notice that the amplitude noise causes amplitude fluctuations and timing jitter). In this simple example the 5th bit is misinterpreted as a 1 instead of a 0 because the random amplitude noise is large enough that the 0 level is above the V/2 threshold level. The amplitude noise in Figure 7 was drawn to show the effect on the data signal and was not meant to represent typical noise in a circuit. For a data signal without any deterministic noise sources, the random amplitude noise can be depicted as two voltage levels having a Gaussian distribution as shown in figure 8. Because the distribution is Gaussian

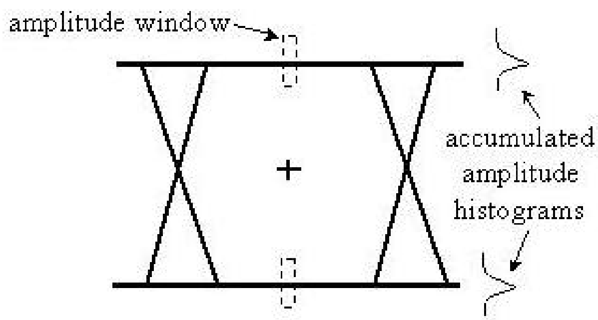


Figure 8 showing random amplitude noise on a data signal. The accumulated amplitude histograms have a Gaussian distribution for both 0 and 1 levels. The "+" at the center of the eye diagram is the ideal sampling point of the receiver and is assumed to be at the center of the unit interval.

in nature, it is possible to estimate the probability that the distribution of the 1 level will be below the ideal sampling point and the probability that a 0 will be above the ideal sampling point. It can be shown that the probability of an error for an equal likelihood of 1's and 0's is[4]:

$$P_e = \tfrac{1}{2}\,\mathrm{erfc}(A/\sqrt{2}*\sigma) \qquad (1)$$

where erfc is the complementary error function, A is the amplitude and σ is the standard deviation. The equation shows that the error probability depends only on the ratio of the amplitude, A, and the standard deviation of the amplitude noise (a similar analysis can also be done for timing jitter [1]). The ratio is commonly referred to as the signal-to-rms noise ratio. For a BER of 10^{-12} the signal-to-rms ratio is ~14. For a 200 mV signal this would require the amplitude noise to be less than 14 mV rms to achieve a BER less than 10^{-12}. Common sources of random amplitude noise are thermal noise, shot noise, flicker noise and in optical systems noise due to lasers.

3.2 Deterministic Noise

The above discussion adequately quantifies the probability of error when the amplitude noise is only Gaussian in nature. In real devices and systems, deterministic noise sources are also present. Typical deterministic noise sources include crosstalk, reflections, EMI, periodics and bandwidth limitations as

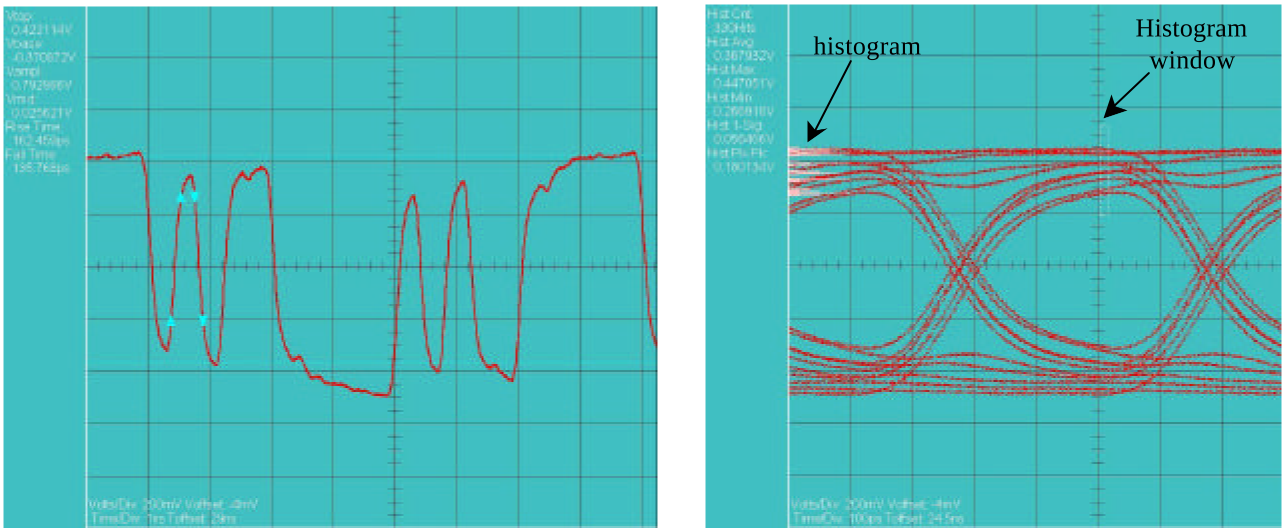


Figure 9 showing a K28.5 data pattern at 2.5 Gb/s transmitted through 16" trace of a backplane. An eye diagram with a histogram acquired at the unit interval midpoint showing the effect of ISI on the amplitude.

described earlier. Figure 9 shows a K28.5 pattern and eye diagram of a 2.5 Gb/s data signal transmitted through a backplane. The dominant amplitude noise in this case is due to ISI. The pattern shows that the high frequency bits have lower amplitude than the portions of the pattern with five 0's or five 1's. A voltage histogram at the center of the eye is a convolution of random and deterministic amplitude noise sources. The histogram is no longer Gaussian and as a consequence equation (1) cannot be used to estimate the error probability. Advanced techniques need to be employed to correctly estimate the pk-pk amplitude noise for a given probability level [2].

4. Instrumentation for Measuring Signal Integrity

The preceding sections reviewed timing jitter and amplitude noise and some of their common sources. There are many types of instruments used for signal integrity analysis and these are SIA's, oscilloscopes, and BERT's. 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 and equipment that is used in jitter tolerance measurements will be described.

4.1 Oscilloscopes: Sampling and Digital Storage

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 ~30-65 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. The trigger can either be a pattern or bitclock. Digital 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 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. Additionally, the oscilloscope solutions currently available cannot determine the RJ or DJ components of jitter. 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.

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 used to improve the hardware resolution limitations. To date the highest bandwidth digital storage oscilloscopes are 6 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 that enable TJ estimation for a given BER, but the methodologies have not yet described and the results have not been correlated to industry standards.

4.2 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 10. 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.

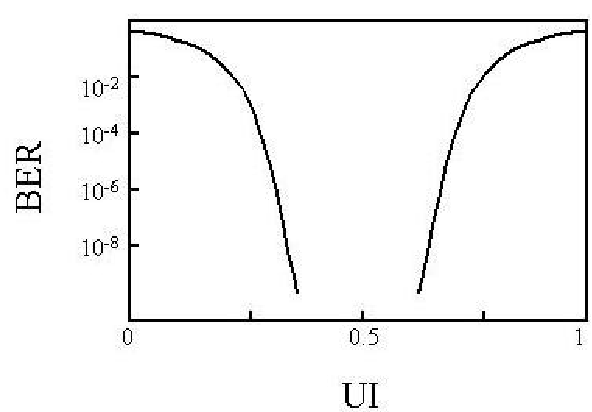


Figure 10. A bathtub curve showing BER as a function of eye closure. The Total Jitter increases as a function of decreasing BER.

4.3 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 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 11.

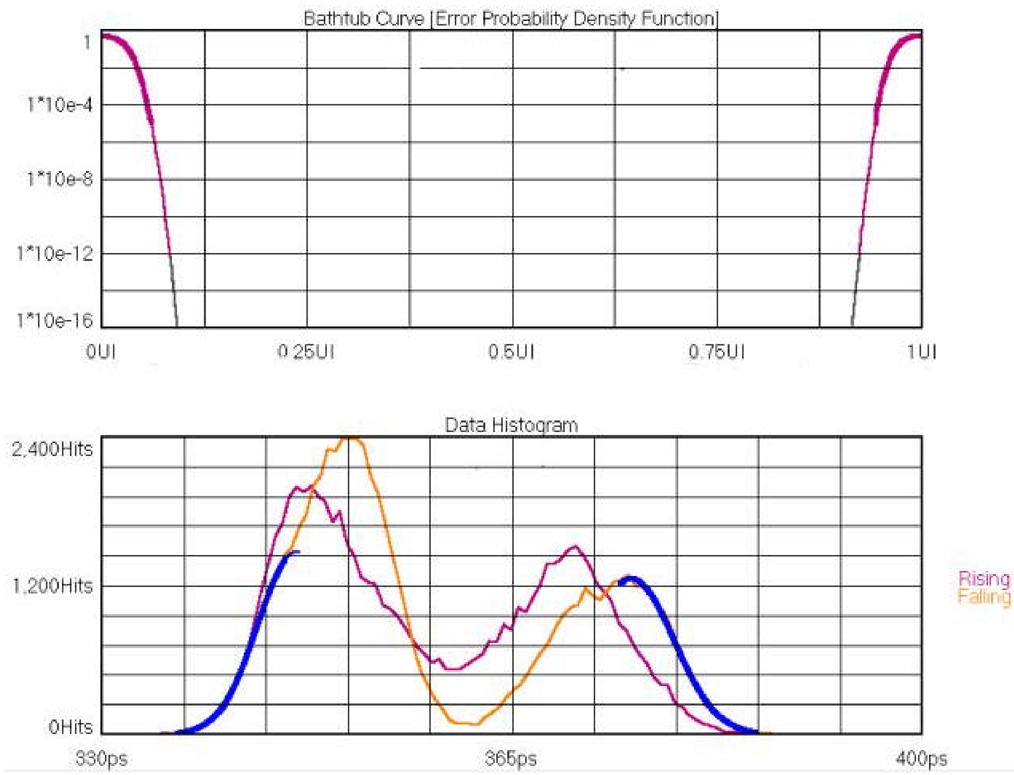


Figure 11. Typical data acquired with an SIA using clock-to-data method. Bottom figure shows histograms for rising and falling data edges. This view enables the user to determine the jitter contribution from the polarity of edges. The right and left most portion of the histograms are fitted with Gaussian 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 [3]. 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 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 12 shows a typical data set using a repeating pattern and a pattern marker.

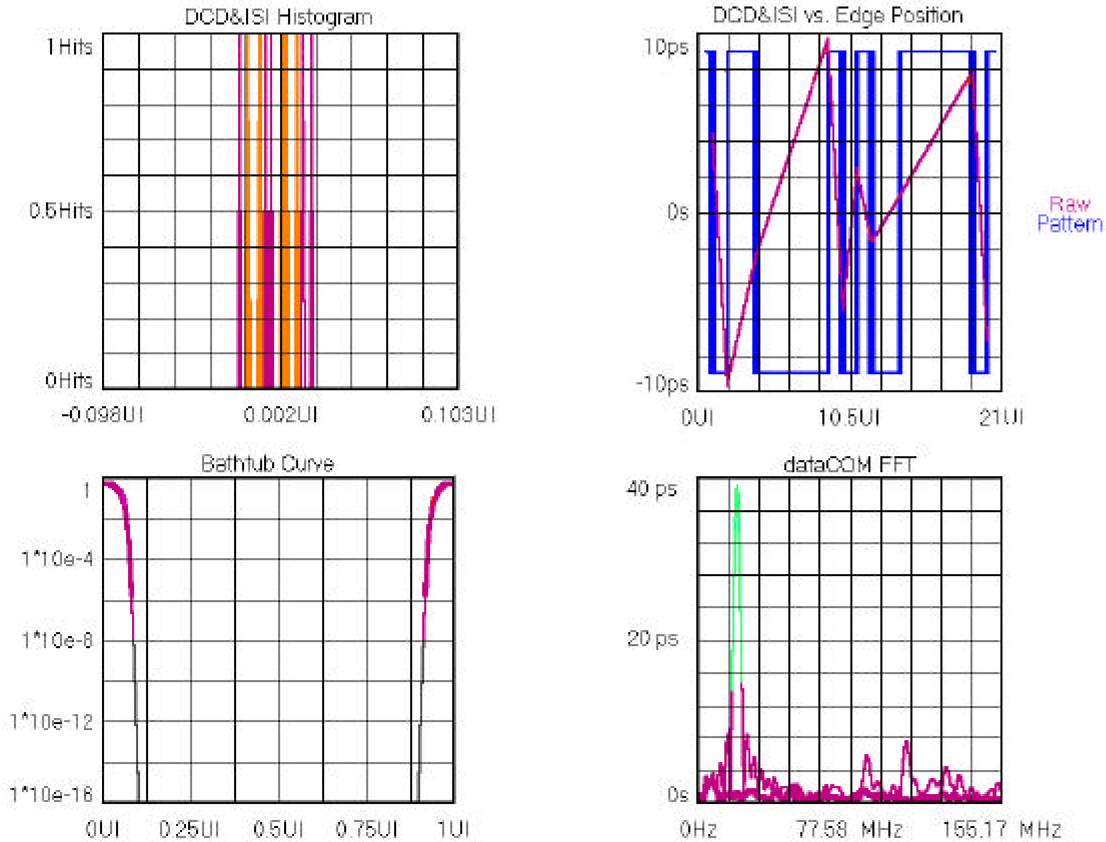


Figure 12. Typical data set using a repeating pattern and pattern marker with an SIA. Clockwise from top left, the DCD&ISI histogram from a K28.5 pattern showing the pk-pk contribution. The DCD&ISI contribution at each edge location in the pattern. The wide range of time deviations (dark purple line) 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}. Figures 11 and 12 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 13), mask testing, measure voltage levels, rise and fall times and other waveform characteristics. The typical bandwidth of the sampling oscilloscope is >6 GHz. The functionality of this type of oscilloscope was described in section 4.1 above.

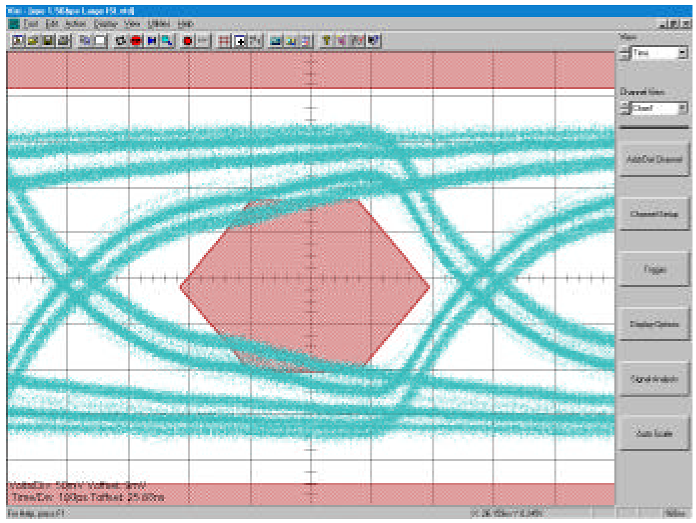


Figure 13 showing an eye mask test obtained from the sampling oscilloscope of the SIA-3000.

5. Instruments for Jitter Tolerance Measurements

Tolerance tests are performed to test the ability of the CDR circuit to recover the incoming data stream correctly in the presence of jitter. Typical standards that require jitter tolerance testing are Fibre Channel, Infiniband, XAUI, and Gigabit Ethernet. Random, periodic and ISI are added to the data

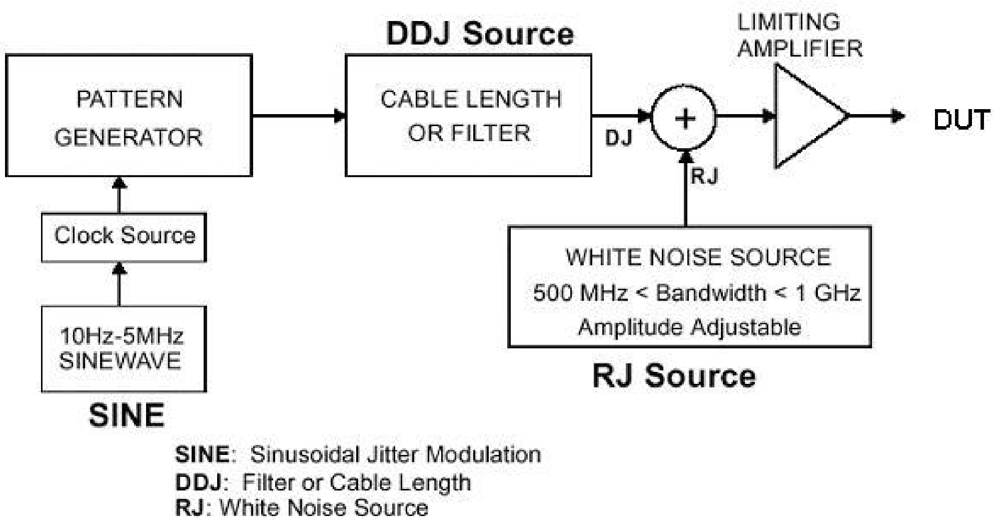


Figure 14 showing a typical jitter tolerance setup [1].

stream in various percentages to simulate worst-case jitter at the receiver. A typical jitter tolerance setup is shown below in Figure 14. A periodic modulation is added to the clock of the pattern generator. Typically the periodic modulation will have a magnitude of 0.1 UI. ISI is added to the data path using addition cable lengths or filters. Random jitter is power summed onto the data signal. Typical random jitter sources such as the Noisecom UFX 7110 can be used. The data is then sent through a limiting amplifier to reduce the effects of amplitude and slew rate. Other pattern generators now have an input that provides an easy means for adding modulation sources (see for example the Agilent 81134A). In this case the RJ and PJ sources are added directly to the pattern generator and ISI added to the output of the pattern generator. This setup eliminates the need for a limiting amplifier. An SIA is a useful instrument for jitter tolerance measurements because it can quantify random jitter, DCD&ISI and the magnitude and frequency of periodic jitter.

6. Conclusion

This paper provided an overview of signal integrity. Topics that were reviewed included timing jitter and amplitude noise. Some common deterministic noise sources include EMI, crosstalk and reflections and with random noise sources mainly due to thermal effects. It was shown that both timing jitter and amplitude noise contribute to the underlying BER of devices and that both parameters need to be quantified in order to determine device performance. Oscilloscopes, BERT's and Signal Integrity Analyzers were described in order to show where each instrument is used in signal integrity analysis. A brief description of instruments used and a typical setup for jitter tolerance measurements was described.

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[3] J. Wilstrup, "A method of serial data jitter analysis using one-shot time interval measurements", ITC Proceeding, 1998.
[4] For an excellent discussion of amplitude noise see; M. Schwartz, "Information Transmission, Modulation, and Noise", McGraw-Hill Inc. 1990.