Jitter—Understanding it, Measuring It, Eliminating It
Part 1: Jitter Fundamentals

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Jitter is a key performance factor in high-speed data communications. This three-part series discusses methods for measuring jitter and presents techniques for its elimination

In data communications, once bit transfer rates exceed one gigabit-per-second, simply dealing with 1s and 0s is no longer sufficient. This situation is clearly the case with many of the new data transfer standards—InfiniBand, PCI Express, 10-Gigabit Ethernet, Fibre-Channel, HyperTransport, RapidIO, and the like. Now, designers must concern themselves with the true nature of a circuit carrying binary information, realizing that it is, in fact, an analog circuit. This means that many parametric issues have become more important than ever.

Among the parametric issues, jitter has risen to the top as one of the most significant and is therefore having a huge impact on the design, operation, and proof of many of today's products.

This series of three articles is intended for engineers who design data transfer systems and components operating at over one gigabit-per-second and so must be concerned with the effects of jitter on their system's bit error rate (BER). This first article covers the fundamental of jitter, the kinds of jitter, its causes, the characteristics of individual jitter components and some measurement vantage points.

Why Measure Jitter?

Jitter isn't measured simply to create statistics, it is measured because jitter can cause transmission errors. For if jitter results in a signal being on the "wrong side" of the transition threshold at the sampling point, the receiving circuit will interpret that bit differ-
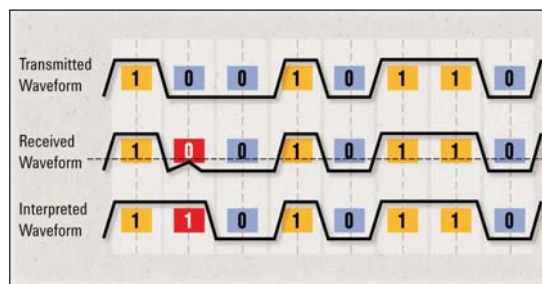

Figure 1 · Jitter can cause a receiver to misinterpret transmitted digital data.

ently than the transmitter intended, causing a bit error, as depicted in Figure 1.

Furthermore, as we will discuss in this and future articles, jitter measurements can aid in discerning the various kinds of jitter which, in turn, leads to their causes and to effectively diminishing their deleterious effect on circuit performance.

Jitter can be defined as "the deviation of the significant instances of a signal from their ideal location in time." To put it more simply, jitter is how early or late a signal transition is with reference to when it should transition. In a digital signal the significant instances are the transition (crossover) points. This applies whether the time reference is generated from the sampled data or is externally provided. These definitions allow for a number of ways of quantifying jitter, as noted next.

Quantifying Jitter

Cycle-To-Cycle Jitter—The time differences between successive periods of a signal.

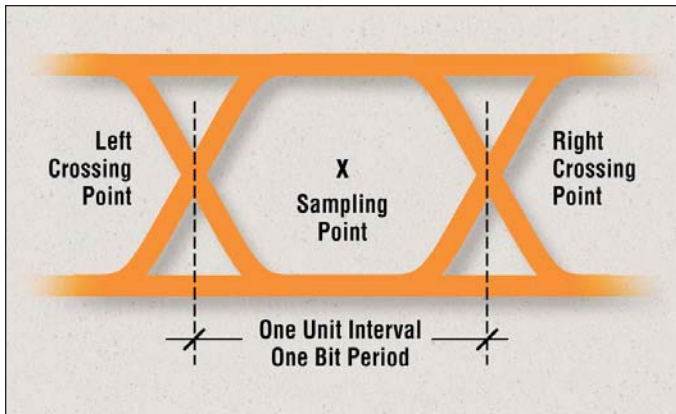*Period Jitter*—An RMS calculation of the difference of each period from a waveform average.

Figure 2 · An idealized eye diagram.

Figure 3 · An eye diagram with an irregular shape provides a wealth of information

Time Interval Error (TIE)—The difference in time between the actual threshold crossing and the expected transition point (or derived clock edge). The deviations in time use either the actual transmitter clock or a reconstruction of it from the sampled data set and take the form of instantaneous phase variations for each bit period of the waveform captured. Incidentally, this representation of jitter is of most interest for current standards.

How an Eye Diagram Portrays Jitter Intuitively

An eye diagram provides the most fundamental, intuitive view of jitter. It is a composite view of all the bit periods of a captured waveform superimposed upon each other. In other words, the waveform trajectory from the start of period 2 to the start of period 3 is overlaid on the trajectory from the start of period 1 to the start of period 2, and so on, for all bit periods.

Shown in Figure 2 is an idealized eye diagram, with very smooth and symmetrical transitions at the left and right crossing points. A large, wide-open "eye" in the center shows the ideal location (marked by an "x") for sampling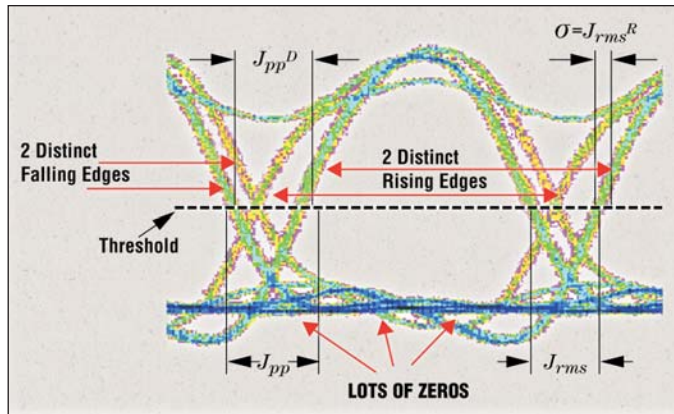 each bit. At this sample point the waveform should have settled to its high or low value and, if sampled here, is least likely to result in a bit error.

Sources of Jitter

Before examining the eye diagram with jitter effects, let's review the sources of jitter. Jitter on a signal will exhibit different characteristics depending on its causes. Thus, categorizing the sources of jitter is important. The primary phenomena that cause jitter are listed below:

1. System phenomena

These are effects on a signal that result from the characteristics of its being a digital system in an analog environment. Examples of these system-related sources include:

- Crosstalk from radiated or conducted signals
- Dispersion effects
- Impedance mismatch

2. Data-dependent phenomena

These are patterns or other characteristics of the data being transferred that affect the net jitter arriving in the receiver. Data-dependent jitter sources include:

- Intersymbol interference
- Duty-cycle distortion
- Pseudorandom, bit-sequence periodicity

3. Random noise phenomena

These are phenomena that randomly introduce noise in a system. These sources include:

- Thermal noise—kTB noise, which is associated with electron flow in conductors and increases with bandwidth, temperature, and noise resistance
- Shot noise—electron and hole noise in semiconductors in which the magnitude is governed by bias current and measurement bandwidth
- "Pink" noise—noise that is spectrally related to $1/f$

These phenomena occur in all semiconductors and components, and therefore are encountered in phase-locked-loop designs, oscillator topologies and designs, and crystal performance.

Further discussion of jitter sources can be found in the section "Jitter reduction requires a multi-faceted view" in Reference [1]. What's more, isolating and measuring these jitter sources will be discussed in the third article in this series.

4. Bounded and Unbounded Jitter

The sources of jitter are often categorized as "bounded" and "unbounded":

Bounded jitter sources reach maximum and minimum phase deviation values within an identifiable time interval. This type of jitter is also called deterministic, and results from systematic and data-dependent jitter-producing phenomena (the first and second groups identified above).

Unbounded jitter sources do not achieve a maximum or minimum phase deviation within any time interval, and jitter amplitude from these sources approaches infinity, at least theoretically. This type of jitter is also referred to as random and results from random noise sources identified in the third group above.

The total jitter on a signal, speci-fied by the phase error function $\varphi_j(t)$, is the sum of the deterministic and random jitter components affecting the signal:

$$\varphi_j(t) = \varphi_j(t)^D + \varphi_j(t)^R$$

where $\varphi_j(t)^D$, the deterministic jitter component, quantified as a peak-to-peak value, $J_{pp}{}^D$, is determined by adding the maximum phase (or time) advance and phase (or time) delay produced by the deterministic (bounded) jitter sources.

$\varphi_j(t)^R$, the random jitter component, quantified as a standard deviation value, $J_{rms}{}^R$, is the aggregate of all the random noise sources affecting the signal. Random jitter is assumed to follow a Gaussian distribution and is defined by the mean and sigma of that Gaussian distribution. To determine the jitter produced by the random noise sources, the Gaussian function representing this random jitter must be determined and its sigma evaluated.

How to calculate total jitter is explained in the section "Calculating total jitter" in Reference [1].

Why an Eye Diagram Contains a Wealth of Information

Shown in Figure 3 is an eye diagram of a waveform that is even less ideal. But the characteristics of its irregular shape enables the viewer to learn much about it—without having to resort to far more complex measurements.

The bottom appears to have a smaller amplitude variation than the top, so the signal seems to carry more 0s than 1s. There are four different trajectories in the bottom, so at least four 0s in a row are possible. Whereas on top there appears to be no more than two trajectories, indicating the waveform contains at most only two 1s in a row. The waveform has two different rising and falling edges, denoting the presence of deterministic jitter. The rising edges have a greater spread than the falling edges,
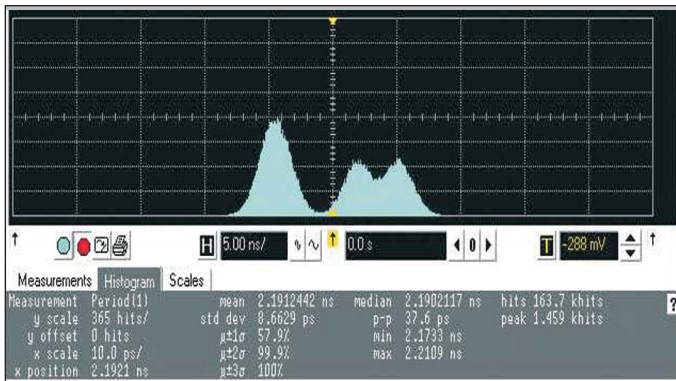
Figure 4 · Histogram of period jitter.

Figure 5 · Bathtub plot.

and some of the crossover points intersect below the threshold level, denoting duty-cycle distortion, with 0s having a longer cycle or on-time than 1s.

Additional discussion of this eye diagram is given in "A case study: jitter evaluation on an eye diagram" in Reference [1].

Now that jitter has been briefly described and explained, let's examine some additional ways to measure and view jitter. Each of these various jitter measurement vantage points can each provide insight into the nature of the jitter affecting a system or device. Then by mentally 'integrating' the different viewpoints you can acquire a more complete picture of the jitter, that will assist you in identifying the jitter sources and in choosing ways to reduce or eliminate it.

The Histogram

A histogram is a plot of the range of values exhibited by a chosen parameter—often time or magnitude —along the *x*-axis versus the frequency of occurrence on the *y*-axis. The histogram provides a level of insight that the eye diagram cannot, and so is very useful in understanding a circuit and for diagnosing problems. In addition, histograms, particularly TIE histograms, are essential data sets for jitter-separation routines required by various digital bus standards.

For troubleshooting, waveform parameters such as rise time, fall time, period, and duty cycle can be histogrammed. These histograms clearly illustrate conditions such as multi-modal performance distributions, which can then be correlated to circuit conditions such as transmitted patterns.

Shown in Figure 4 is a histogram of period jitter. The left hump appears to have a normal Gaussian shape but the right side has two peaks. Further analysis discloses that this signal, a clock reference, has a second and fourth harmonic that are a source of jitter.

An invaluable application of the histogram is to display the frequency of occurrence of the TIE values for all
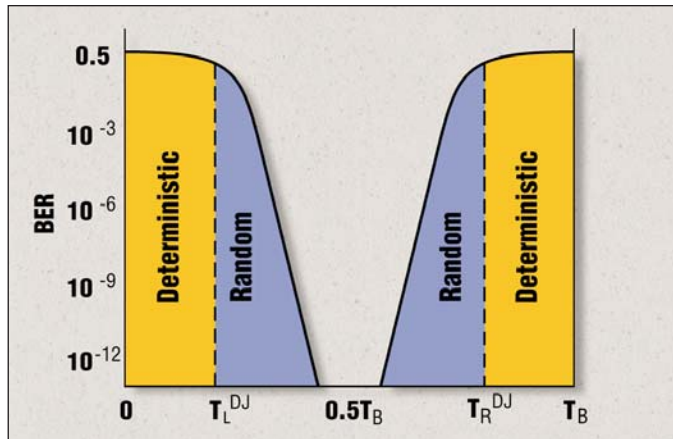
bit transitions in a waveform capture.

The TIE histogram is also of particular value in separating random from deterministic jitter, as described in Reference [1].

The Bathtub Plot

Another viewpoint of jitter is provided by the "bathtub plot," depicted in Figure 5. It is so named because its characteristic curve looks like the cross-section of a bathtub. A bathtub curve is a graph of BER versus sampling point throughout the Unit Interval. (See the Note at the end of this article for a discussion of Unit Interval.)

A bathtub plot is typically shown with a log scale that illustrates the functional relationship between sampling-time and BER.

When the sampling point is at or near the transition points, the BER is 0.5—equal probability for success or failure of a bit transmission. The curve is fairly flat in these regions, which are dominated by deterministic jitter phenomena.

As the sampling point moves inward from both ends of the unit interval, the BER drops off precipitously. These regions are dominated by random-jitter phenomena and the BER is determined by the sigma of the Gaussian processes producing the random jitter. As one would expect, the center of the unit interval provides the optimum sampling point.

Note that there is BER measured for the middle sampling times. Again with an "eyeball" extrapolation we can estimate that the curves would likely exceed 10^{-18} BER at the 0.5 point of the unit interval. In this case, even for a 10 Gb/s system it would take over 3×10^8 seconds to obtain that value.

The curves of the bathtub plot readily show the transmission-error margins at the BER level of interest. The further the left edge is from the right edge at a specified BER—10^{-12} is commonly used—the more margin the
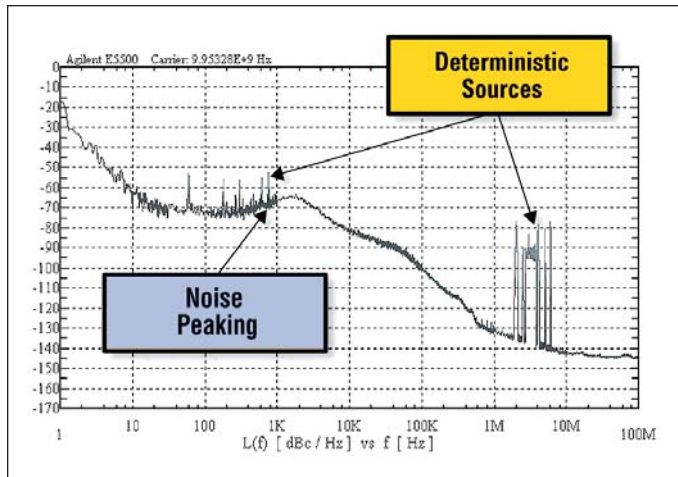
Figure 6. · Intrinsic jitter spectrum.

design has to jitter. And of course, the closer these edges become, the less margin is available. These edges are directly related to the tails of the Gaussian functions derived from TIE histograms. The bathtub plot can also be used to separate random and deterministic jitter and determine the sigma of the random component, as described in Reference [1].

Frequency-Domain Jitter Vantage Points

Viewing jitter in the frequency domain is yet another way to analyze its sources. Deterministic jitter sources appear as line spectra in the frequency domain. This frequency-domain view is provided by phase noise or jitter spectrum analysis and relates phase noise or jitter-versus-frequency offset from a carrier or clock.

Phase-noise measurements yield the most accurate appraisals of jitter due to effective oversampling and bandwidth control in measurement. They provide invaluable insights into a design—particularly for phase-locked-loop or crystal oscillator designs—and readily identify deterministic jitter due to spurs. Such measurements are helpful for optimizing clock recovery circuits and discovering internal generators of spurs and noise.

Phase-noise measurements can also be integrated over a specific bandwidth to yield total integrated jitter, although this is not directly convertible to peak-to-peak jitter as specified for data communications standards.

Shown in Figure 6 is an intrinsic jitter spectrum of a phase-locked loop. Noise peaking occurs at a 2 kHz offset. There are also frequency lines that identify deterministic jitter sources. These lines, ranging from 60 Hz to approximately 800 Hz, are power-line spurs. Frequency lines evident in the range of 2 to 7 MHz are most likely to be clock-reference-induced spurs, causing deterministic jitter.

Another method of obtaining a frequency-domain viewpoint of jitter is to take a fast Fourier transform

(FFT) of the TIE data. The FFT has much less resolution than the low-level phase-noise view, but is an excellent method of viewing high-level phenomena quickly and easily.

Part 2 of this series will cover the selection of instruments for jitter measurements, jitter measurements at high data rates, and issues that are essential in assuring the accuracy of jitter measurements.

References

1. *Measuring Jitter in Digital Systems*, Application Note 1448-1, available at www.agilent.com

2. *Jitter Solutions for Telecom, Enterprise, and Digital Designs*, Product Note 5988-9592EN, available at www.agilent.com

Note

Unit Interval—By representing jitter in terms of phase perturbation only, it is possible to consider different domains for analysis. In mathematical terms, the phase error (advance or delay) is generalized with the function $\varphi_j(t)$, so the equation for a pulsed signal affected by jitter becomes:

$$S(t) = P[2\pi f_d t + \varphi_j(t)]$$

where P denotes a sequence of periodic pulses and f_d is the data-rate frequency.

This leads to mathematically-equivalent expressions for jitter. Since the argument of the function is in radians, dividing $\Delta\varphi$ (peak or rms phase) by 2π expresses jitter in terms of either the unit interval (UI), or bit period (for the pulses):

$$J(\text{UI}) = \Delta\varphi/2\pi$$

The Unit Interval expression $J(\text{UI})$ is useful because it provides an immediate comparison with the bit period and a consistent comparison of jitter between one data rate or standard and another. Dividing the jitter in unit intervals by the frequency of the pulse (or multiplying by the bit period) yields the jitter in units of time:

$$J(t) = \Delta\varphi/2\pi f_d$$

Author Information

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