Jitter Fundamentals: Sources, Types, and Characteristics

Introduction

Jitter refers to how early or late a signal transition is compared with the time it should transition. This applies whether the time reference comes from the sampled data or an outside source. Transmission errors can occur when jitter causes a signal to be on the “wrong side” of the transition threshold at the sampling point. Therefore, causing the receiving circuit to interpret that bit differently than the transmitter intended (see Figure 1).

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

As this application note explains, understanding the type of jitter, its component characteristics, and measurement vantage points can help engineers identify its causes and diminish its effects on circuits and products.
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 as follows:

System phenomena

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

- cross talk from radiated or conducted signals
- dispersion effects
- impedance mismatch

Data-dependent phenomena

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

- intersymbol interference
- duty-cycle distortion
- pseudorandom, bit-sequence periodicity

Random noise phenomena

Some jitter phenomena randomly introduce noise in a system. These sources include the following:

- thermal noise, or $kT/B$ noise, which is associated with electron flow in conductors and increases with bandwidth, temperature, and noise resistance
- shot noise, which is electron and hole noise in semiconductors in which bias current and measurement bandwidth govern the magnitude
- “pink” noise, which is noise that is spectrally related to $1/f$

These phenomena occur in all semiconductors and components. You will encounter them in phase-locked-loop designs, oscillator topologies and designs, and crystal performance.
**Bounded and unbounded jitter**

The sources of jitter can be “bounded” or “unbounded.”

Bounded jitter sources reach maximum and minimum phase deviation values within an identifiable time interval. This type of jitter, called deterministic, 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. Jitter amplitude from these sources approaches infinity, at least theoretically. This type of jitter, also called random, results from random noise sources identified in the third group above.

The total jitter on a signal, specified by the phase error function $\phi(t)$, is the sum of the deterministic and random jitter components affecting the signal

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

where $\phi(t)^D$, 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.

The random jitter component, $\phi(t)^R$, 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, you must determine the Gaussian function representing this random jitter and evaluate its sigma.
Jitter Eye Diagrams

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. The waveform trajectory from the start of period 2 to the start of period 3 overlays on the trajectory from the start of period 1 to the start of period 2, and so on, for all bit periods.

Figure 2 shows an idealized eye diagram with 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.

Figure 3 shows an eye diagram of a waveform that is not ideal. But the characteristics of its irregular shape enable the viewer to learn much about it without resorting to 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 trajectories in the bottom, so at least four 0s in a row are possible. On top, there appear 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, 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.
Other Ways to View Jitter

Now that we have briefly described jitter, let’s examine some additional ways to measure and view it. Each of these measurement vantage points can provide insight into the nature of the jitter affecting a system or device. By mentally “integrating” the different viewpoints, you can acquire a more complete picture that will assist you in identifying the jitter sources and choosing ways to reduce or eliminate them.

The histogram

A histogram plots 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 it is useful in understanding a circuit and for diagnosing problems. In addition, histograms, particularly time interval error (TIE) histograms, are essential data sets for jitter-separation routines required by various digital bus standards.

For troubleshooting, you can create histograms for waveform parameters such as rise time, fall time, period, and duty cycle. These histograms clearly illustrate conditions such as multimodal performance distributions, which you can then correlate to circuit conditions such as transmitted patterns.

Figure 4. Histogram of bi-modal jitter dominated by Gaussian and periodic jitter

Figure 4 shows a histogram of bi-modal jitter dominated by Gaussian and periodic jitter. The leading and trailing edges of the histogram appear random/Gaussian in nature, but the two peaks/humps indicate a significant component of periodic jitter as well. Further analysis revealed that the instantaneous TIE of this serial bus signal was a result of sinusoidal modulation.
The bathtub plot

The “bathtub plot” provides another jitter viewpoint, as depicted in Figure 5. A bathtub curve, so named because its characteristic curve looks like the cross-section of a bathtub, is a graph of bit error rate (BER) versus sampling point throughout the unit interval. (Refer to the Appendix for more information about the unit interval.) Typically, an accompanying logarithmic scale illustrates the functional relationship between sampling time and BER.

![Bathtub plot diagram](image)

Figure 5. Bathtub plot

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, and deterministic jitter phenomena dominate. As the sampling point moves inward from both ends of the unit interval, the BER drops off precipitously. Random-jitter phenomena dominate these regions, and the sigma of the Gaussian processes producing the random jitter determines the BER. 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 more than $3 \times 10^8$ seconds to obtain that value.

The curves of the bathtub plot readily show the transmission-error margins at the BER level of interest. The farther the left edge is from the right edge at a specified BER — $10^{12}$ is common — the more margin the sign 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. You can also use the bathtub plot to separate random and deterministic jitter and determine the sigma of the random component.
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, provided by phase noise or jitter spectrum analysis, relates phase noise or jitter-versus-frequency offset from a carrier or clock.

Phase-noise measurements yield the most accurate appraisals of jitter because of 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 from 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. However, this is not directly convertible to peak-to-peak jitter as specified for data communications standards.

Figure 6 shows an intrinsic jitter spectrum of a phase-locked loop. Noise peaking occurs at a 2 kHz offset. Frequency lines also 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 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.
Appendix

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 $\phi(t)$, so the equation for a pulsed signal affected by jitter becomes

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

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 $\Delta \phi$ (peak or rms phase) by $2\pi$ expresses jitter in terms of the unit interval (UI) or bit period (for the pulses):

$$J_{(UI)} = \frac{\Delta \phi}{2\pi}$$

The unit interval expression $J_{(UI)}$ 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 into unit intervals by the frequency of the pulse (or multiplying by the bit period) yields the jitter in units of time:

$$J(t) = \frac{\Delta \phi}{2\pi f_d}$$
Conclusion

Resolving jitter is an essential part of product development. Bounded jitter, also known as deterministic, can arise from the system or be data-dependent. Unbounded jitter results from random noise. To analyze the collective impact of these jitter types, use jitter measurement vantage points such as eye diagrams, histograms, bathtub plots, and time-domain frequency to provide useful insights. This information can assist engineers in identifying the jitter sources and choosing ways to reduce or eliminate them to improve the transmission performance of their designs.

Related Information

Jitter: Measurements and Instrument Solutions — Application Note, literature number 5992-1638EN

Separating and Time-Correlating Deterministic Jitter Components — Application Note, literature number 5992-1639EN

Jitter Solutions for Telecom, Enterprise, and Digital Designs — Brochure, literature number 5988-9592EN

Finding Sources of Jitter with Real-Time Jitter Analysis - Application Note, literature number 5988-9740EN

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