

All About the Acronyms: RJ, DJ, DDJ, ISI, DCD, PJ, SJ, ...

Ransom Stephens, Ph.D.

Abstract:

Jitter analysis is yet another field of engineering that is pock-marked with acronyms. Each category and type of jitter has its own acronym and every one of them gives insight into problems that limit the bit error ratio of a system. In this paper, we define the categories and types of jitter, their origins and interrelationships, and how they can be used to diagnose and debug system hardware.

Acronyms seem like convenient abbreviations once we know them, but prior to that, they're a closed language that can feel like no more than a bunch of obfuscating terms when used by others. Of course, when we use them, acronyms are simply shorthand that "everyone knows." In this paper we err in the opposite direction. Rather than annoy you by using too many acronyms, I'm going to annoy you by spelling out every acronym almost every time I use it.

Understanding a system usually consists of separating it into simple bite-sized pieces which combine to form an arbitrarily complex system. The same is true of jitter analysis. If we're given a system whose Total Jitter at a Bit Error Ratio of 10^{-12} , i.e., $TJ(BER) = TJ(10^{-12})$, is larger than allowed by a product requirement or standard specification, it doesn't tell us anything about how to fix the problem [For a review of $TJ(BER)$, see the first installment in this series, *Part 1: The Meaning of Total Jitter*]. We need to re-categorize, analyze, and sort the system into successively more simple pieces, hence the acronyms.

The jitter "Family Tree," Figure 1, shows one way to categorize different types of jitter. The first branch separates Random (RJ) and Deterministic Jitter (DJ). The second branch splinters Deterministic Jitter (DJ) into Data-Dependent Jitter (DDJ), Periodic Jitter (PJ), and Bounded Uncorrelated Jitter (BUJ). The primary source of Data-Dependent Jitter (DDJ) is Inter-Symbol Interference (ISI), but the amount of ISI is affected by the level of Duty-Cycle Distortion (DCD) – hence the dotted line connecting DCD and ISI. Some people put Duty Cycle Distortion (DCD) under Data-Dependent Jitter (DDJ) because of the affect DCD has on Inter-Symbol Interference (ISI). I chose to put Duty-Cycle Distortion (DCD) under Periodic Jitter (PJ) – after all, DCD is an asymmetry in the clocking of logic transitions. Periodic Jitter (PJ) is on the uncorrelated side of the diagram. The terms "correlated" and "uncorrelated" in the diagram indicate

whether the amplitude of jitter changes with different transmitted data signals or data rates, that is, whether or not the jitter amplitude is “correlated to the data.” Generally Periodic Jitter (PJ) is uncorrelated, but Duty-Cycle Distortion (DCD) is a type of PJ that is correlated, so it’s on that side of the diagram. Sinusoidal Jitter (SJ) is the simplest type of Periodic Jitter (PJ) and is rarely correlated to the data.

There are many different ways that jitter can be categorized in a diagram like that in Figure 1. The important thing is not how we draw such a figure, but that we recognize the components, understand their causes, and appreciate whether or not one component can affect another.

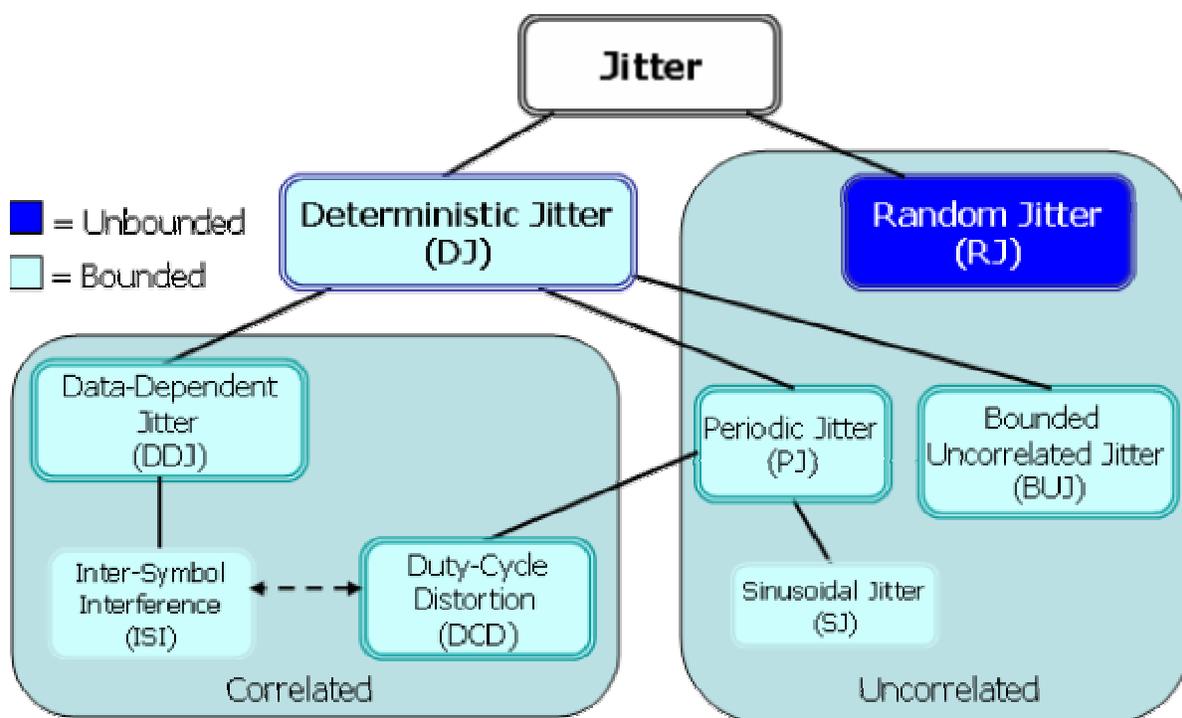


Figure 1: The jitter “Family Tree.”

In the following sections we’ll go through each type of jitter and sort out some of the different ways that jitter is categorized.

Random Jitter – RJ

As described in the first installment of this series, *The Meaning of Total Jitter*, Random Jitter (RJ) is caused by the combination of a huge number of sources, each of very small magnitude. According to the Central Limit Theorem, RJ should follow a Gaussian distribution, Figure 2.

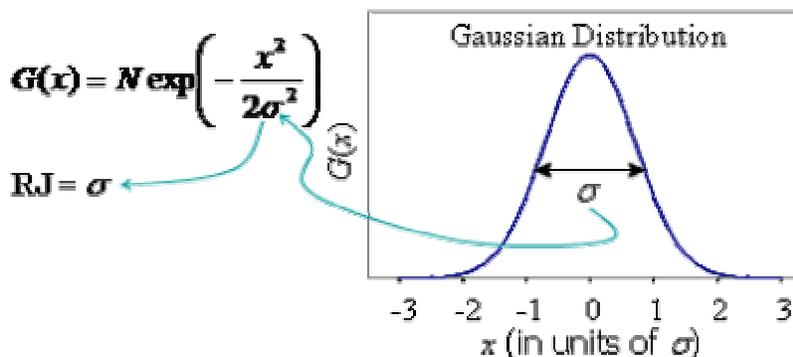
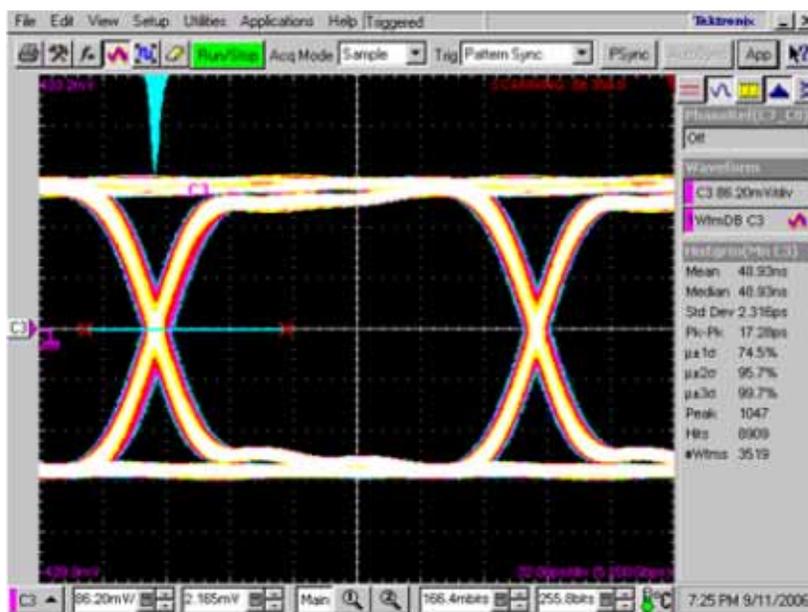


Figure 2: Random Jitter (RJ) follows a Gaussian distribution.

RJ is primarily caused by thermal processes, microscopic variations in the resistance and impedance of circuit traces which can be caused by the inevitable small variations of trace width, dielectric properties such as asymmetries in the weave of FR-4, and many other microscopic effects that are statistically impossible to isolate.

Since RJ follows an unbounded distribution it is quantified by the width, or standard deviation, σ , of its distribution.

- RJ is unbounded – there is a finite probability that random effects could cause a logic transition to appear *anywhere*, though, of course, the probability of an extremely large amount of RJ on a given transition is increasingly small. For example, the probability of RJ causing jitter greater than seven times the standard deviation of its distribution is one in a trillion.

- RJ is uncorrelated to the data – the amount of RJ on a given transition is not related to the transmitted data signal or data rate.
- RJ is aperiodic – RJ is random in nature and doesn't occur with any predictable regularity.
- RJ is independent of the other sources of jitter in the sense that changing RJ has no effect on the magnitudes of other types of jitter.

Deterministic Jitter – DJ

Deterministic Jitter (DJ) is the jitter that remains after Random Jitter (RJ) has been removed. In principle, though almost never in practice, DJ can be calculated from a complete understanding of the circuit and its environment. Since DJ can be composed of all the other types of jitter, it doesn't follow a given distribution function the way that Random Jitter (RJ) follows a Gaussian. On the other hand, since DJ is composed of a finite number of deterministic processes its distribution is bounded.

We usually characterize DJ by either its peak-to-peak value, $DJ(p-p)$, or a model dependent version of the peak-to-peak value that is derived from the remarkably convenient dual-Dirac model, $DJ(\delta\delta)$ – which is described in the second part in this series, *The Dual-Dirac Model, What it is and What it is Not*.

Problems caused by DJ can be diagnosed by further resolving it into its constituents.

- DJ is bounded but doesn't follow a general distribution function.
- DJ may include both periodic and aperiodic components that may or may not depend on the transmitted data signal. That is, the DJ of a given logic transition may or may not affect the jitter of another transition.

Duty-Cycle Distortion – DCD

Duty-Cycle Distortion (DCD) is a measure of the asymmetry in the duty cycle of the transmitter. In Figure 3, the one in the sequence 00001000 is of a different width than the zero in 11110111 – the duty-cycle is distorted. Another manifestation of DCD is the difference in the rise and fall times of a signal resulting in a fixed time displacement of the rising and falling edges. In either case, in the absence of Inter-Symbol Interference (ISI), DCD follows a simple bimodal distribution. Equivalently, the amplitude of DCD is given by the difference of the average positions of rising and falling edges.

DCD is usually caused by an asymmetry in either the clock signal driving the transmitter or in a limiting amplifier within the transmitter.

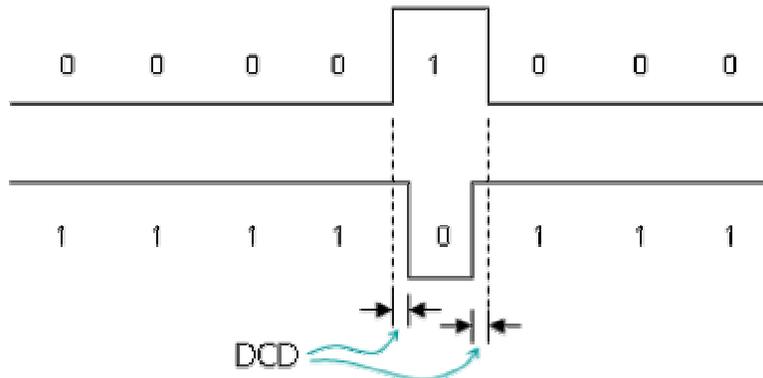


Figure 3: Simple example of Inter-symbol interference.

DCD is correlated with Inter-Symbol Interference (ISI) in the sense that changing ISI can result in a change in DCD, and vice versa. Another way to think of the correlation is in the sense of interference; DCD and ISI interfere with each other. Because of this correlation or interference, DCD is sometimes categorized with Inter-Symbol Interference (ISI) under Data-Dependent Jitter (DDJ). In a system with no Inter-Symbol Interference (ISI), the level of DCD is explicitly independent of the transmitted data signal and so is not really “data-dependent.”

- DCD is bounded
- DCD follows a simple bimodal distribution
- DCD is usually caused by a clock asymmetry or limiting amplifier imperfection and so is periodic at the data-rate
- DCD is correlated with Inter-Symbol Interference (ISI) – a change in DCD causes a change in ISI and vice versa

Data-Dependent Jitter – DDJ

Data-Dependent Jitter (DDJ) encompasses all jitter whose magnitude is affected by the transmitted data signal. For example, as illustrated in Figure 4, when the jitter of a 0 → 1 transition that follows a sequence of alternating bits, e.g., 01010101, differs from a 0 → 1 transition that follows a long string of identical bits, e.g., 00000001, that jitter is called data-dependent.

DDJ is caused primarily by a combination of macroscopic impedance mismatches, the resistance and frequency response of the transmission path, and asymmetries in the rising and falling edges of the transmitted signal. DDJ is usually associated with Inter-Symbol Interference (ISI) but is affected by Duty-Cycle Distortion (DCD). The result, as shown in Figure 5, is a waveform that differs significantly from the ideal.

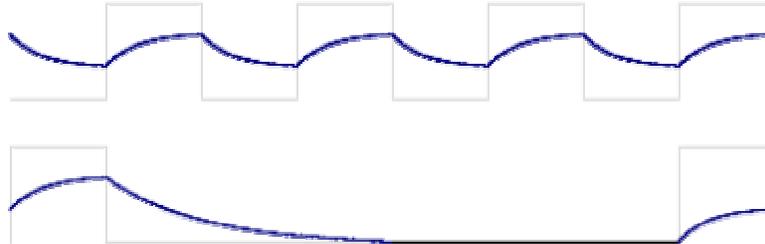


Figure 4: Example waveform of simple Data-Dependent Jitter (DDJ).

Generally two random variables are *correlated* if changing one of the variables causes the other to change. Correlation is an important concept which appears in two separate contexts in jitter analysis. First, as already described, jitter is said to be correlated to the data if the amplitude of jitter is affected by the transmitted data signal or the data rate. Second, the primary source of DDJ, Inter-Symbol Interference (ISI) is correlated to, or interferes with, Duty-Cycle Distortion (DCD) – a change in the ISI of a signal changes the DCD of that signal and vice-versa.

DDJ is a type of “correlated jitter” by virtue of its dependence on the transmitted data signal.

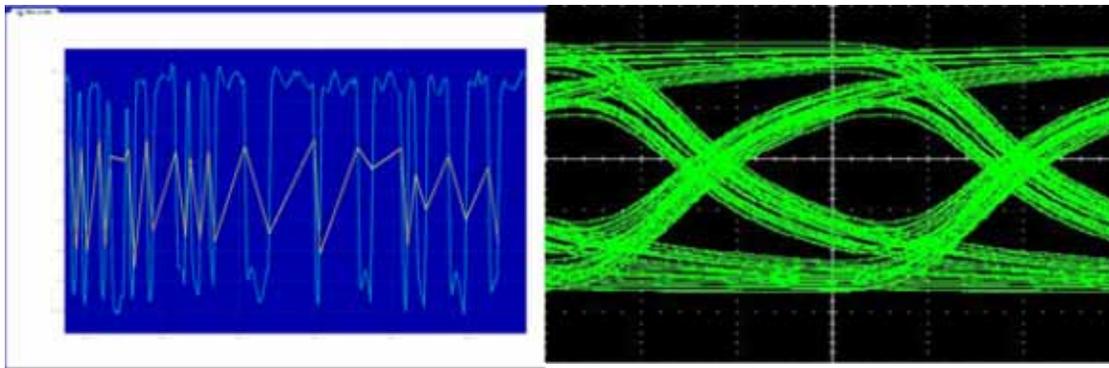


Figure 5: Data-dependent jitter and eye diagram.

- DDJ follows a distribution that can't be described by any single global distribution function
- DDJ is also known as “correlated jitter” because data-dependent is equivalent to “correlated to the transmitted data signal”

Inter-Symbol Interference – ISI

Inter-Symbol Interference (ISI) is the primary cause of Data-Dependent Jitter (DDJ). The situation is complicated by the correlation of ISI and Duty-Cycle Distortion (DCD).

ISI is caused by a combination of the design of the trace and circuit geometry, the media composing both the conductor and dielectric of the circuit, and the waveform of the transmitted signal. In much of the literature, the design of the transmitter itself, including package design, is neglected as a source of ISI. It is important to keep in mind that the ISI of the transmitted waveform can interfere with the ISI introduced by the transmission path. A lot of confusion erupts from comparison of ISI measurements on a given cable but with different transmitters.

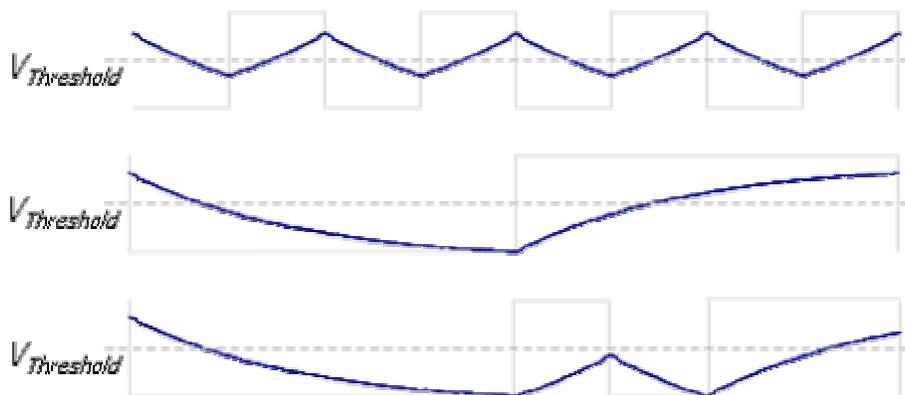


Figure 6: Simple example of Inter-Symbol Interference (ISI). $V_{Threshold}$ is the logic-decision threshold, if the observed voltage is greater than $V_{Threshold}$ then the bit is identified as a 1, if less than $V_{Threshold}$, a 0.

A good example of ISI is the modification of the pulse-shape of different bits in a signal as they traverse a transmission line. Transmission lines at data rates above about 100 MHz are better thought of as complicated waveguides in a dielectric medium. The resistance of the conducting traces cause signal attenuation and the frequency-dependence of the dielectric medium causes non-uniform frequency response. The non-uniform frequency response subjects the signal to a filtering effect. The dominant frequency component of a given bit is determined by the identity of the bits that surround it. Consider the data sequences shown in Figure 6 where a simple Resistor-Capacitor (RC) time constant is used to illustrate ISI. In Figure 6a, the data signal, 01010101, is a clock signal at half the data rate. The response of the circuit to the transmitted data signal is sufficient for each bit to cross the logic-decision voltage threshold and be accurately identified. In Figure 6b, the data signal, 00001111 is a clock signal at one-eighth the data rate. Over the string of Consecutive Identical Bits (CIB or CID) the time constant is sufficiently short for the signal to reach the voltage rail but, in so doing, does not permit enough time for the signal to cross the voltage threshold during the first logic 1 following the string of 0s. In fact, the 00001111 string would be identified as 10000111. A mixed example is shown in Figure 6c; here the 00001011 signal would be identified as 10000001.

Now combine the unavoidable non-uniform frequency response of the dielectric, like Flame Retardant Type-4 (FR-4), with the interference of signals from discrete impedance mismatches that cause multiple reflections and multiple paths from input to output and you can see how ISI can cause complex problems, Figure 7. The result is that the waveform of any bit in a data signal can differ depending on the number of Consecutive Identical Bits (CIB or CID) preceding it. Data coding, for example 8b10b coding, is used in many technologies, e.g., PCI Express, to prevent the occurrence of long strings of Consecutive Identical Bits (CIB or CID). An important feature of ISI is that it affects both the amplitude and timing of the signal. In other words, it is a source of amplitude noise as well as jitter.

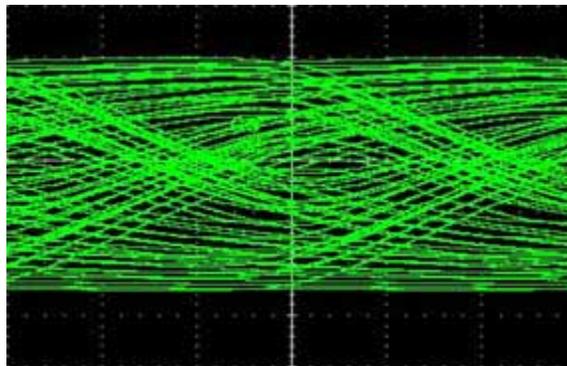


Figure 7: A signal with a great deal of Inter-Symbol Interference (ISI).

It is difficult to combine the ISI introduced by different circuit elements. For example if the transmitted signal has a given level of ISI, then the ISI introduced by the transmission path will be different than if the transmitted signal had no ISI. In other words, the ISI of consecutive circuit elements interferes with one another – it is *correlated*.

ISI provides a good example of what it means to be “deterministic.” Time Domain Reflectometry (TDR) can be used to measure the frequency and attenuation characteristics of a circuit resulting in the impulse response as represented, for example, in the Scattering parameters (S-parameters), from which the circuit’s transfer function can be calculated. The transfer function can then be applied to any data sequence to yield the ISI waveform. That is, the transfer function is the complete understanding of the circuit and its environment and, with it, we can predict the jitter of any given logic transition – exactly what is meant by *deterministic* jitter. Due to its predictable nature, it is possible to correct ISI at the receiver using equalization techniques.

There are two types of diagnostic techniques that can be used to reduce ISI. First, before a circuit is even built, the ISI of different designs can be compared by calculating the Scattering parameters (S-

parameters) in a simulation. Second, Time Domain Reflectometry (TDR) can be used to locate discrete impedance mismatches like those often found at vias and connectors.

- ISI is bounded
- ISI is only periodic if the signal is a repeating pattern
- ISI is caused by the geometry and media of the conductor and dielectric
- ISI is also caused by discrete impedance mismatches like those found at vias and connectors which result in multiple reflections
- ISI can be introduced by the transmitter
- ISI of different circuit elements are correlated to each other – they interfere
- ISI can be predicted from the impulse response, such as can be derived from the Scattering parameters (S-parameters) as measured through Time Domain Reflectometry (TDR)

Periodic Jitter – PJ

Periodic Jitter (PJ) includes any jitter at a fixed frequency or period. PJ is ultimately an example of periodic phase modulation and may be the most useful category of jitter. It's easy to measure accurately and appears in the jitter-frequency spectrum as distinct peaks. The jitter-frequency is the offset frequency of the jitter with respect to the data rate. When a PJ peak is identified it can usually be associated with a noisy circuit element operating at that same frequency. The classic example is power supply feed-through, but PJ can also be caused by crosstalk from neighboring data lines or any other type of Electromagnetic Interference (EMI).

PJ is always bounded and may have components that are correlated to the data, such as Duty-Cycle Distortion (DCD).

- PJ can have a variety of wave shapes (e.g., square-wave phase modulation is PJ that results in a dual-Dirac distribution) with corresponding jitter-frequency spectra
- PJ is bounded and follows a distribution that can be calculated if the amplitudes, frequencies, and relative phases of all harmonics and PJ sources are measured
- PJ is easy to measure accurately
- PJ is useful in diagnosing jitter problems

Sinusoidal Jitter – SJ

Sinusoidal Jitter (SJ) is Periodic Jitter (PJ) at just one frequency. A tremendous amount of work has been done in SONET/SDH jitter analyses to precisely calibrate jitter analyzers by applying SJ of known frequency and amplitude and using the classic Bessel null technique.

In the time domain, SJ follows an easily identifiable “suspension bridge” structure as shown in Figure 8.

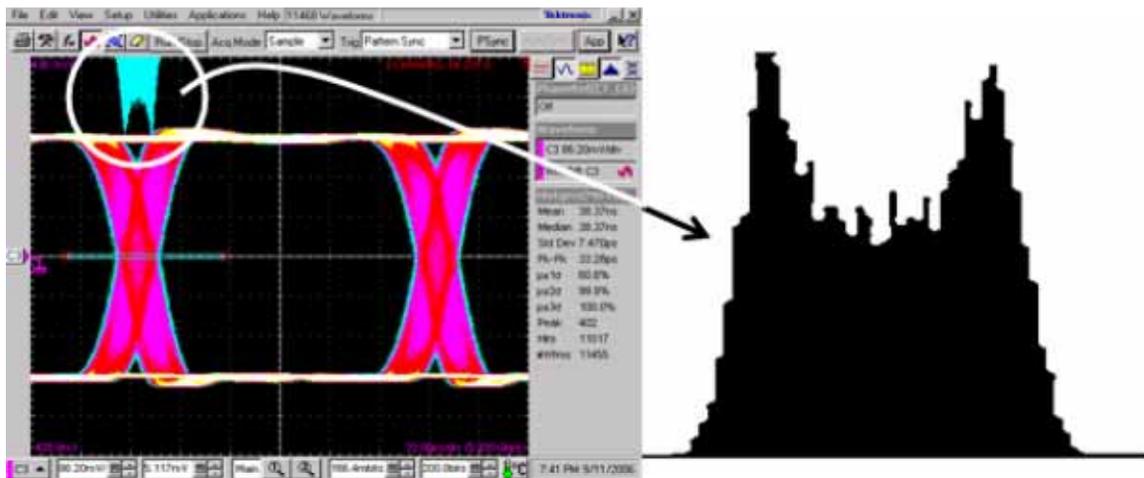


Figure 8: Sinusoidal jitter.

- SJ is Periodic Jitter (PJ) at just one frequency
- SJ is bounded and uncorrelated to the data
- SJ is easy to measure accurately
- SJ can be applied to a signal for use in calibrating test equipment

Bounded Uncorrelated Jitter – BUJ

Bounded Uncorrelated Jitter (BUJ) is a category used by most of the industry for organizing ignorance. That is, most of the literature uses BUJ to represent all the types of jitter that we don't know how to measure. We assume that the only unbounded jitter is Random Jitter (RJ), by implication BUJ is deterministic.

The two most debated flavors of BUJ are non-stationary jitter and the jitter-effects of crosstalk. Non-stationary jitter is sporadic – neither periodic nor data-dependent – over the possible measurement time scales. A good example is the state-dependent jitter of complex gate arrays where certain data patterns

present a repeatable, but rare, switching transient. Crosstalk presents a more challenging problem for jitter analysis, one where the distinction between amplitude noise and timing jitter can't be neglected.

Strictly speaking the most easily measured type of jitter, Periodic Jitter (PJ), is both bounded and uncorrelated and so could accurately be categorized as BUJ. One manufacturer of test equipment uses the acronym BUJ for Periodic Jitter (PJ). It is semantically accurate, but inconsistent with the vast majority of jitter literature, an unfortunate choice that has caused a lot of confusion.

- BUJ bounded and uncorrelated to the data
- BUJ is usually used as a receptacle for the jitter we can't measure
- The two most commonly discussed sources of BUJ are non-stationary jitter and the jitter effects of crosstalk

Conclusion

There are many ways to categorize jitter. The most common criteria are:

- Random Jitter (RJ) vs Deterministic Jitter (DJ) which is equivalent to unbounded vs bounded
- correlated vs uncorrelated
- data-dependent vs data-independent
- periodic vs aperiodic

There is room to argue about whether some types of jitter, like Duty-Cycle Distortion (DCD), should be categorized the way they I did here, but these arguments distract from the important issues. Namely, how measurements of the different types of jitter can be used to reduce the Bit Error Ratio (BER) of a system.

	acronym	bounded/ unbounded	correlated/ uncorrelated	periodic/ aperiodic	Example cause
Random Jitter	RJ	Unbounded	Uncorrelated	Aperiodic	Thermal noise
Deterministic Jitter	DJ	Bounded	Either	Either	Inter-Symbol Interference
Periodic Jitter	PJ	Bounded	Either	Periodic	Power supply feed-through
Sinusoidal Jitter	SJ	Bounded	Uncorrelated	Periodic	Electromagnetic interference
Data-Dependent Jitter	DDJ	Bounded	Correlated	Aperiodic	Impedance mismatch
Duty-Cycle Distortion	DCD	Bounded	Correlated	Periodic	Clock asymmetry
Inter-Symbol Interference	ISI	Bounded	Correlated	Aperiodic	Non-uniform frequency response of a transmission line
Bounded Uncorrelated Jitter	BUJ	Bounded	Uncorrelated	Aperiodic	Crosstalk

Table 1: Summary of jitter acronyms.