Jitter Analysis in Systems with Crosstalk

Ransom Stephens, Ph.D.

Abstract:

In many cases jitter can be analyzed independently of voltage noise, but not in the presence of crosstalk. Crosstalk is a source of bounded uncorrelated jitter that is notoriously difficult to identify and tends to confound jitter analysis algorithms. In this paper we introduce crosstalk as an example of a jitter source that doesn't fall conveniently under one of the standard jitter acronyms and presents a challenge that can be addressed by expanding from jitter analysis to the full two dimensions of phase noise and amplitude noise.

Noise is noise. Consider an eye diagram like that in Figure 1 – the plot of overlapping logic signals. Noise is evident on the signal in both the vertical (voltage) and horizontal (time-delay) directions. Since jitter is usually the source of Bit Error Ratio (BER) problems it's easy to fall into the trap of thinking that jitter is only caused by timing noise, but voltage noise also causes jitter. In many cases it is important to remember what I've mentioned several times over the course of this series:

Jitter analysis only considers one dimension of the two-dimensional noise problem.

Inter-Symbol Interference (ISI) is a good example of a noise source that obviously affects both the horizontal and vertical components of an eye-diagram.

In Part 3 of this series, *All About the Acronyms: RJ, DJ, DDJ, ISI, DCD, PJ, SJ,…* I referred to Bounded Uncorrelated Jitter (BUJ) as "all the types of jitter that we don't know how to measure." Crosstalk is perhaps the best example of BUJ.

We begin by showing how jitter and voltage noise are each caused by either or both of phase noise and amplitude noise. We then introduce crosstalk, describe how it affects signals and how differential signaling reduces the signal degradation. With that out of the way we discuss a few ways to tell when crosstalk is confusing your jitter analysis techniques and how crosstalk can be identified by simultaneously analyzing the jitter and voltage noise of a signal.

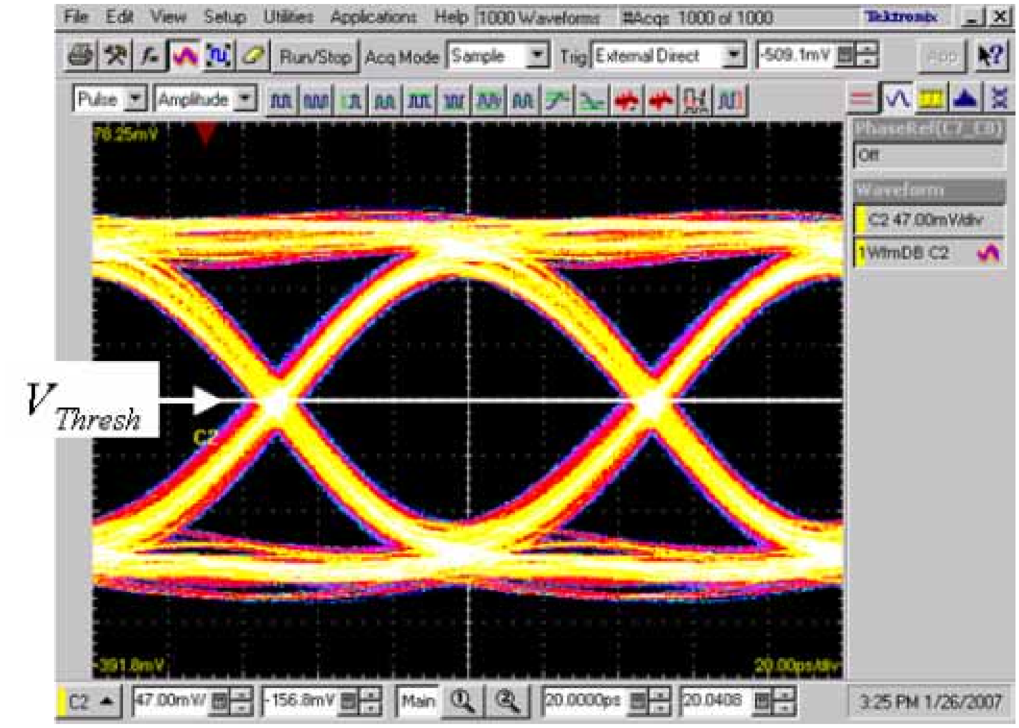

Figure 1: An eye diagram with a variety of causes of jitter and voltage noise.

Phase Noise vs. Amplitude Noise – Jitter vs. Voltage Noise

Jitter is the variation in the timing of the significant instants of a digital signal. In other words, if we choose a voltage threshold in the eye-diagram, at say V_{Thresh} in Figure 1, then the time-delays at which each signal crosses that threshold are the "significant instants" and their variation over different logic transitions is what we think of as jitter.

Phase noise is the variation in the phase of a signal; we can think of it as noise that shifts the signal back and forth horizontally. Similarly, amplitude noise is the noise that shifts the signal vertically up and down. Jitter can be caused by either and, in general, is caused by both. In the limit of an ideal digital signal with zero rise and fall times (infinite slew rates), jitter would only be caused by phase-noise. In a real signal, logic transitions have continuous trajectories with finite slew rates and non-zero rise/fall times. Consider Figure 2a. The logic transition drawn with a solid line occurs at time t_0. If that same transition is shifted vertically downward, then the transition occurs at t_1. The vertical fluctuation causes jitter of $t_0 - t_1$. The slower the rise-time, the greater the impact of amplitude noise on jitter. Phase noise has the same effect on voltage noise only rotated by 90°, Figure 2b.

Figure 2: The effect of (a) amplitude noise on jitter and, (b), phase noise on voltage noise.

If the slope, or slew rate, of the signal is *dV/dt* and the voltage shift is δV, then the effective peak-to-peak jitter caused by the voltage shift is,

$$J_{PP} \approx \frac{\delta V}{dV/dt} . \qquad (1)$$

In analyzing voltage noise we can apply a bunch of acronyms just as we did for jitter (see Part 3 of this series, *All About the Acronyms: RJ, DJ, DDJ, ISI, DCD, PJ, SJ,…*):

- RJ → RN (random noise)
- DJ → DN (deterministic noise)
- DDJ → DDN (data-dependent noise)
- PJ → PN (periodic noise)

Further, we can discriminate between the horizontal (phase-noise) and vertical (amplitude noise) contributions to each type of jitter or noise. For example, we can distinguish RJ(h) and RJ(v). We'll see that expanding the analysis in the vertical direction provides useful tools for determining how much of a problem is caused by timing noise and how much by amplitude noise.

Crosstalk

Crosstalk occurs when one signal is affected by a neighboring signal. It is usually a capacitive coupling between nearest neighbors and can be reduced by shielding, increasing the space between signal-carrying conductors, limiting the slew rates of signals, and the use of differential signaling.

At high data rates a signal propagates more like a guided wave than a simple DC current. The wave is guided by the conducting trace but radiates through the dielectric medium. When more than one signal is present, every conducting trace on the board includes artifacts of the signals on every other trace. The common jargon is to say that an *aggressor* signal causes crosstalk on a *victim* signal. Crosstalk occurs when the signal of an aggressor is picked up by the conductor guiding the victim signal. Unavoidable discontinuities in circuit layout, like connectors and vias, where capacitive coupling is greatest, are critical points that act like antennas in generating crosstalk. Ultimately, crosstalk is a form of electromagnetic interference (EMI). Since electromagnetic fields are linear, the magnitude of the aggressor signal at the victim trace simply adds to the victim signal.

Maxwell's equations show that electromagnetic radiation is caused by the acceleration of electric charge. If we think of digital signals as DC but with sharp transitions between logic levels, the greatest acceleration of charge is during the transitions. Thus the greatest amount of electromagnetic radiation is emitted during logic transitions. The amplitude of the radiation is proportional to the charge acceleration, given by the rate of change of the current, di/dt, which, by Ohm's law, is proportional to the slew rate of the aggressor, dV_{agg}/dt.

Think of a pulse of noise radiating through the circuit board. At every logic transition of the aggressor signal, crosstalk appears on the victim as a sharp jolt of amplitude noise. Since the amount of noise is proportional to the slew rate, crosstalk can be reduced by limiting the slew rate of signal transitions or, equivalently, setting a lower bound on rise and fall times.

Crosstalk is usually quantified as the ratio of the voltage of the largest crosstalk component induced by the aggressor to the victim voltage in decibels.

It is useful to keep in mind that crosstalk is highly directional. Crosstalk noise that propagates in the same direction as the victim signal is called Far End crosstalk (FEXT) and crosstalk that propagates in the opposite direction of the victim signal is called Near End crosstalk (NEXT). FEXT is usually attenuated by the expanse of dielectric between aggressor transmitter and victim receiver, making NEXT the more aggravating of the two.

The most common technique for reducing crosstalk in serial data systems is the use of differential signaling. A signal is transmitted by two very close conducting traces, one with a signal and the other with the inverse of the signal. Since the sum of the two is zero, no net radiation should propagate through the dielectric medium of the board. At the receiver, the voltage of one trace is subtracted from the other giving twice the voltage spread of the signal on either trace. Ideally no crosstalk noise can propagate in a differential system, but at high data rates the realities of nonzero skew between the two traces and the necessary non-zero separation of the traces allow some radiation to leak out.

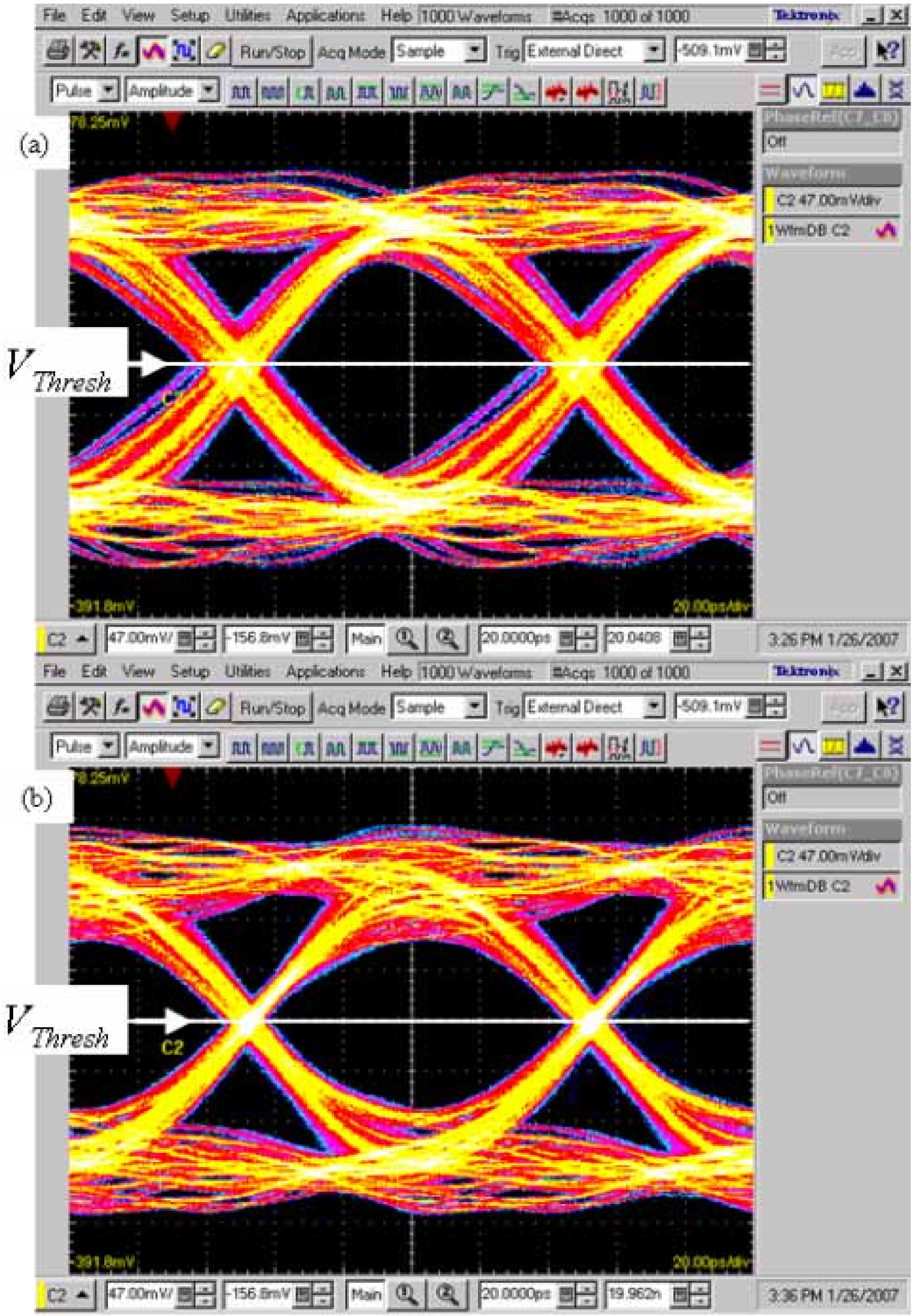

Figure 3: Crosstalk with a frequency-locked aggressor. In (a) pulses of crosstalk noise coincide with logic transitions and, in (b), pulses of crosstalk noise close the center of the eye.

At higher data rates, trying to reduce crosstalk by limiting transition slew rates is impractical. Differential signaling is still effective at reducing crosstalk, but the crosstalk problem itself is so much larger that differential signaling isn't enough.

If the crosstalk aggressor and the victim signal are governed by the same reference clock then they are probably both frequency and phase locked – that is, they are transmitted at precisely the same underlying phase and have a fixed phase relationship. When the aggressor and victim are frequency and phase locked, the crosstalk signature appears in an eye diagram as a localized region where the trajectory splinters into separate trajectories over a short period, as shown in Figure 3. An upward pulse occurs when the aggressor has a 0 → 1 transition, there's no effect when the aggressor does not undergo a transition and there is a downward pulse when the aggressor experiences a 1 → 0 transition. Design engineers are usually conscious of this possibility and, when possible, design a relative skew of the victim and aggressor traces so that the signature occurs during the victim's logic transitions as in Figure 3a. This way the effect is concentrated at the crossing point, as far from the eye-center as possible so that the effect on the receiver decision circuit is minimized. In other words, systems are designed to minimize the voltage noise at the expense of maximizing the jitter. Figure 3b shows the effect at the eye-center.

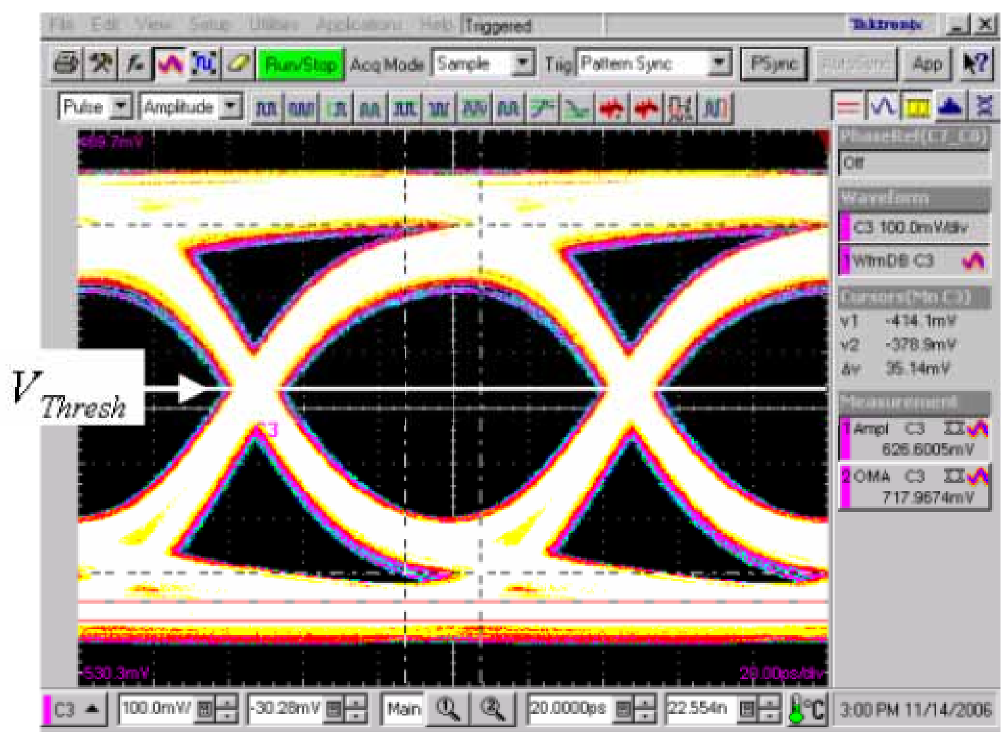

Figure 4: Crosstalk without a frequency-locked aggressor.

When the aggressor and victim are not governed by the same reference clock or, for whatever reason, are not frequency and phase locked, then, in an eye-diagram, crosstalk looks like an excess of voltage noise, Figure 4.

In the frequency domain, if the victim and aggressor are frequency and phase locked crosstalk appears as a set of spikes at subharmonics of the data rate, Figure 5a. Spectrally-based analysis techniques appropriately identify crosstalk as both Periodic Jitter (PJ) and Periodic Noise (PN). Tail-fitting techniques, whether applied to bathtub plots or jitter histograms, would mistake the crosstalk for RJ, dramatically increasing their extrapolated Total Jitter defined at a Bit Error Ratio, TJ(BER), estimates.

On the other hand, if the victim and aggressor are not frequency and phase locked, then the situation is more complicated. On real-time sampling equipment, where the frequency components are not aliased, the jitter and voltage noise spectra have subharmonic peaks that, rather than appearing as sharp lines, are smeared into broad resonance shapes. On under-sampling equipment, like an equivalent-time sampling oscilloscope, where the spectrum is aliased, crosstalk appears as continuous noise, Figure 5b. In both cases spectrally-based jitter analysis techniques that measure RJ by integrating the jitter-spectrum continuum, mistake at least some crosstalk for RJ and RN. In this case too, tail-fitting techniques mistake crosstalk for RJ and, in both cases TJ(BER) is overestimated.

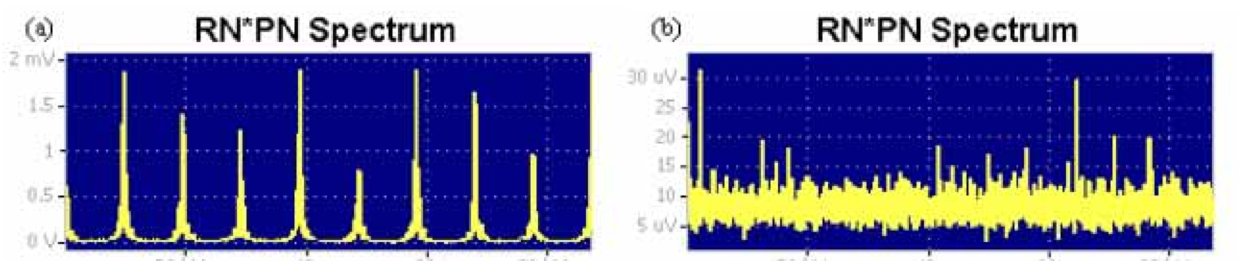

Figure 5: Frequency domain view of (a) frequency and phase locked crosstalk, and, (b) neither frequency nor phase locked crosstalk.

Signal Analysis with Crosstalk

The best way to deal with crosstalk problems, of course, is to anticipate the problem and design around it. If the differential *S*-parameters between aggressor and victim lanes are evaluated in a simulation before the board is built, then aggressor voltages at the signal trace can be calculated and the design revised until the crosstalk problem is resolved. Similarly, on an existing circuit, if the differential *S*-parameters can be measured (for example by Time Domain Reflectometry) then the crosstalk problem can be calculated. Tektronix offers a package for network parameter measurements, IConnect, that automatically calculates up to eight aggressors. The next best approach is to apply a signal to neighboring lines and measure the response on the victim line using a setup like that in Figure 6. The ratio of the crosstalk voltage at the victim trace to the victim's signal voltage, usually expressed in decibels, is the crosstalk signal.

Once you have the maximum aggressor voltage at the signal trace, you can estimate the maximum jitter caused by crosstalk with Eq. (1) by using the smallest slew-rate, *dV/dt*, of the signal trajectories.

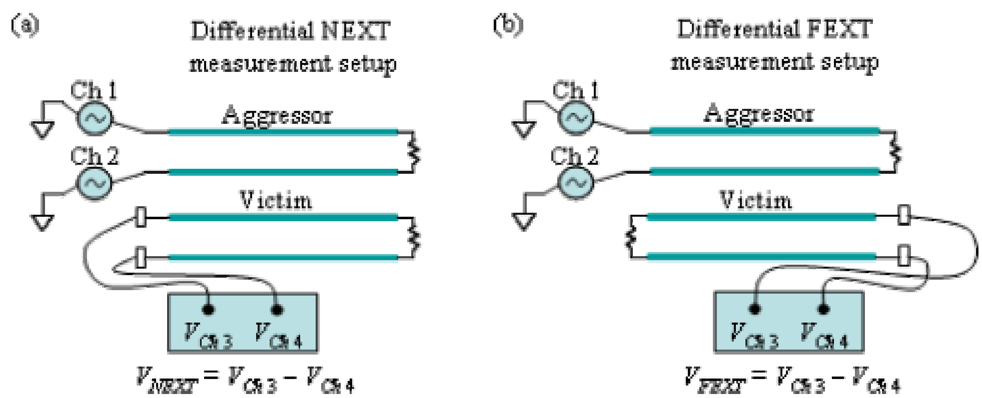

Figure 6: Setup for measuring crosstalk in differential systems. (a) For Near End Crosstalk (NEXT) and (b) for Far End Crosstalk (FEXT).

Let's turn to the more annoying situation: We're given a system whose Bit Error Ratio is too high and we don't know why – the unfortunate but usual case for those of us in the signal integrity analysis business.

In performing a simple one-dimensional jitter analysis there are few ways to tell if crosstalk is the problem. If the data on neighboring lines is governed by the same reference clock so that the signals are frequency and phase locked, then an obvious crosstalk signature is the combination of a comb-like structure of subharmonics in the jitter spectrum, as in Figure 5a, and the eye diagram splintering at the crossing point as in Figure 3.

If potential aggressors don't share a reference clock with the victim then the situation is more difficult. The first clue is if the jitter analyzer reports an inordinately large RJ measurement. It is rare that thermal effects, the ultimate cause of RJ, manage to conspire to greater than 3 ps RMS. If the RJ reported is larger than 3 ps then it's likely that crosstalk is causing problems.

Thorough characterization of a signal in the presence of crosstalk requires simultaneous voltage-noise and jitter analysis. Tektronix offers a software option, JNB, that runs on their equivalent-time sampling oscilloscopes. JNB performs the full two-dimensional noise analysis by, essentially, applying the same algorithms along the voltage axis to get RN, DN, et cetera that are used along the time-delay axis to get RJ, DJ, et cetera (see Pavel Zivny's white paper at the Tektronix web site for the details) and then extends the analysis to its logical conclusion, generating the two-dimensional version of a bathtub plot – a BER contour diagram.

Generally, when the rms random voltage noise, RN, in an eye-diagram approaches the rms jitter, RJ, it indicates that the problem is dominated by amplitude noise, rather than phase noise. Since RN is measured in Volts and RJ is measured in seconds, we can compare the relative contributions to RJ and RN through ratios of the contributions from horizontal (phase) and vertical (amplitude) noise. If

$$RN(v)/RN(h) >> RJ(h)/RJ(v) \quad (2)$$

then the problem is caused by amplitude noise. Since crosstalk appears to the analysis techniques as random noise when the victim and aggressors have separate reference clocks, when Eq. (2) holds it is a strong indicator of crosstalk.

Other tricks to identifying crosstalk require more control over the aggressor channel than you might have. For example, if it's possible to turn off the suspected aggressor signal, then you can compare the RJ measurement with and without a signal on the aggressor. If RJ-with aggressor > RJ-without then the problem is crosstalk. A work-around in this case is to use the measurement of RJ with the aggressor off and the measurement of dual-Dirac DJ with the aggressor on in the dual-Dirac model to estimate the Total Jitter of the system at the BER of interest, TJ(BER) (see Part 1 and 2 of this series for background on TJ(BER) and the dual-Dirac model respectively).

Since crosstalk is BUJ, it follows a bounded distribution. The bounded nature of the distribution is obscured by the complexity of the data pattern. The seemingly random distribution of 1s and 0s causes different amounts of voltage noise to be transmitted on each aggressor-signal transition. When crosstalk is combined with other types of jitter, particularly Data-Dependent Jitter (DDJ), pretty soon the central limit theorem comes into play and the jitter Probability Density Function (PDF, e.g., as represented by the crossing point histogram) appears to follow a Gaussian distribution.

If it is possible to control the data pattern of the aggressor, transmitting an alternating signal, 1010, would make it easier to identify crosstalk. The regularity of the pulses of crosstalk noise on the victim would sit at just the one frequency. In the frequency and phase-locked case the crosstalk would jump out as PJ and PN. In the unlocked case, it would be somewhat trickier. If the analysis were preformed on data-rate sampling equipment, like a real-time oscilloscope, then the smeared frequency peak should be observable; if the spectrum were aliased, it's harder to say. In either case, though, the distributions of uncorrelated jitter and noise, RJ∗PJ and RN∗PN, respectively, would not follow Gaussian distributions. The combination of a non-Gaussian distribution and no obvious PJ or PN peaks would indicate something funny is going on and odds are good that funny thing is crosstalk.

Conclusion

There are many approaches to the problem of jitter analysis on signals with crosstalk. None of them provide compartmentalized one-button-push results the way we can expect from, for example, measurements of DDJ and PJ. The main thing to keep in mind is that crosstalk is a type of amplitude noise, not phase noise. It creeps into signal analysis as jitter by virtue of the finite slew rate of real digital signals. Signals with crosstalk should be analyzed in the full two-dimensional space of phase noise and amplitude noise or jitter and voltage noise.

Use of a combined jitter and noise analysis technique makes it possible to identify crosstalk from analysis of a victim signal alone.

In general, even if it's not known whether or not crosstalk is on a signal, the TJ(BER) estimated from a combined jitter and noise technique is much more accurate than one can reasonably expect from a one-dimensional jitter analysis. It's one of the many ugly "features" of BUJ.