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Quantifying Crosstalk Induced Jitter in Multi-lane Serial Data Systems

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Abstract

Multi-lane serial data links are susceptible to crosstalk from adjacent lanes as well as external aggressors. The resulting interference increases the jitter and noise on the victim lanes and can ultimately cause bit errors. While techniques such as network analysis using either TDR or VNA can measure the coupling between lanes, they cannot directly measure the impact of crosstalk on timing jitter for a given lane. This paper presents techniques that can be used to accurately measure the amount of jitter contributed by crosstalk independent of other jitter sources. Measurements on multi-lane scenarios for real-world and laboratory induced crosstalk will be presented as examples of this analysis.

Author(s) Biography

Martin T Miller, PhD, chief scientist at LeCroy Corp, has been a hands-on engineer and designer at the company for 30 years. His doctorate is from the University of Rochester (Rochester, NY) in high-energy physics. A native of Baltimore, Miller has contributed analog, digital, and software designs, during the last 16 years he has focused on measurement-and-display software capabilities for LeCroy scopes. He holds several US patents and has participated in task groups concerning jitter measurements.

Michael Schneckner holds an MSEE from the Georgia Institute of Technology and has 20 years of experience in the test and measurement industry. Mr. Schneckner specializes in signal integrity measurements including jitter and has been key in specifying and deploying the LeCroy SDA series instruments.

Summary

A real world consequence of crosstalk is an increase of R_j and D_j . Depending upon the nature of traffic on adjacent lanes the effects can be dramatically different. Conventional jitter analysis techniques employing digital oscilloscopes and other types of instruments provide a detailed breakdown of jitter components including periodic, data dependent and random jitter sources (P_j , DD_j and R_j). At the same time, crosstalk is fundamentally an amplitude coupling between signal lanes and causes a correlated and often higher level component of amplitude distortion. There are generally two types of crosstalk present in any given serial data system; uncorrelated or “alien” crosstalk and correlated crosstalk. The latter tends to appear in the form of data dependent jitter and random jitter while the former generally comes in the form of periodic jitter. An additional feature of crosstalk is that it directly impacts the amplitude of the signal. This impact can be seen as eye closure in the BER contour and as periodic variation in the amplitude of the signal. Examining the periodic amplitude variations helps to identify those components of the periodic jitter are due to uncorrelated crosstalk.

The measurement of random jitter in cases where crosstalk is present is a particularly difficult task. Depending on the type of interfering signal, crosstalk can result in a significant increase in the random jitter which is not generally measured accurately by most jitter measurement models. In particular, the presence of correlated crosstalk from delayed aggressors can contribute to random jitter at a very low statistical weight but with a high standard deviation. In these cases, examining several jitter measurement models can help reveal the true nature of the total jitter.

The separation of random and deterministic jitter is commonly expressed as the “Dual-Dirac” jitter model. Dual-Dirac models the jitter PDF as a single Gaussian convolved with a pair of Dirac delta functions each with a weight of $\frac{1}{2}$ and separated by the deterministic jitter. Other models are possible and can offer benefits in crosstalk scenarios. These alternate models include Dual Gaussian in which two separate Gaussians, each with its own standard deviation and a weight of $\frac{1}{2}$ and with mean values separated by the deterministic jitter are used to model the jitter PDF. A third method models the jitter as 2 Gaussians each with its own weight and standard deviation that are separated by the deterministic jitter. The three models allow increasing degrees of freedom for fitting the measured TIE and provide increasingly more accurate estimation of the jitter PDF and BER performance.

Three sets of experimental results will show the impact of the jitter components caused by specific types of crosstalk. The sources will be set up as a signal under test and aggressor in a structure that induces crosstalk. The first test will use simple clock-like patterns in the victim and aggressor and will establish the relationship between crosstalk and jitter. The second experiment will have a clock-like victim and an aggressor with a random pattern and the the final experiment will have both victim and aggressor with random patterns. In each of the experiments, the jitter results measured using two models will be correlated with a predicted value based on the measured peak to peak induced crosstalk voltage.

Total jitter and jitter breakdown

Timing jitter, by nature is a random process because it contains components that are produced by thermal noise. The most basic way of viewing jitter has been to use a random Gaussian noise model which can be analyzed in terms of its standard deviation. This simple model has been used to predict the long term error performance of serial data links in many applications including telecommunications standards such as SONET/SDH. As high speed serial data has migrated into lower-cost platforms such as PCs, however, the simple Gaussian model for jitter has become inadequate. This is mainly because the lower cost links can have more sources of so-called deterministic jitter which is not well modeled with a simple Gaussian.

The Dual-Dirac jitter model

The Fibrechannel committee first developed a more appropriate model for jitter in the MJSQ document [1]. This document introduced a statistical model that better represents real-world jitter by including both random and deterministic jitter. The model, known as the Dual-Dirac jitter model includes a Gaussian probability density function convolved with two Dirac delta functions which are separated by an amount proportional to the deterministic jitter. The model is shown in figure 1. Like the simple Gaussian model, Dual-Dirac seeks to predict the long term error performance of a serial data link and because it includes a deterministic component, it is much more accurate. Increased accuracy is important because the performance margins have become much smaller as the transfer rates of serial data links have increased.

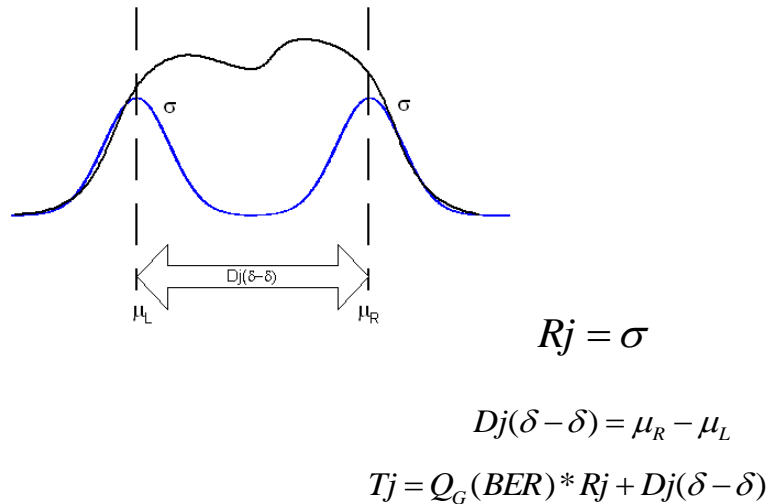


Figure 1: The Dual-Dirac jitter model shown with the model parameters. The function $Q_G(BER)$ is the number of standard deviations of a Gaussian corresponding to a given BER.

The Dual-Dirac jitter model is used in every modern serial data standard as the method for specifying timing margins. The reason for this is twofold; first, the simple model allows link budgets to be computed by adding the Dual-Dirac deterministic jitter (sometimes called $Dj(\delta-\delta)$) components and adding the square root of the sum of squares of the random components. Second, the model parameters can be measured by a variety of instruments including real time and sampling oscilloscopes and bit error rate test sets.

Measuring the Dual Dirac model parameters

While Dual-Dirac is a simple model, determining its parameters is far from trivial. Today, digital oscilloscopes are the primary instrument used for measuring jitter. The model parameters, Rj and Dj are found from the best fit to the tails of the measured jitter distribution. Oscilloscopes can measure the timing jitter of a number of transitions of a signal waveform and from this estimate the jitter distribution. One way to do this is to accumulate the timing error measurements into a histogram with a normalized area. The histogram estimates the probability density function for the observation time. Figure 2 shows a typical jitter track (sequence of timing error measurements) and histogram. The Rj and Dj parameters can be found by fitting this estimated PDF. As more measurements are added to the histogram, the estimates of Rj and Dj improve as they converge to stable values. A major problem is the amount of time required for convergence in this direct fitting to the estimated PDF. Traditionally, digital oscilloscopes have not been able to collect and process the very large data sets necessary to converge to a stable measurement in a reasonable amount of time.

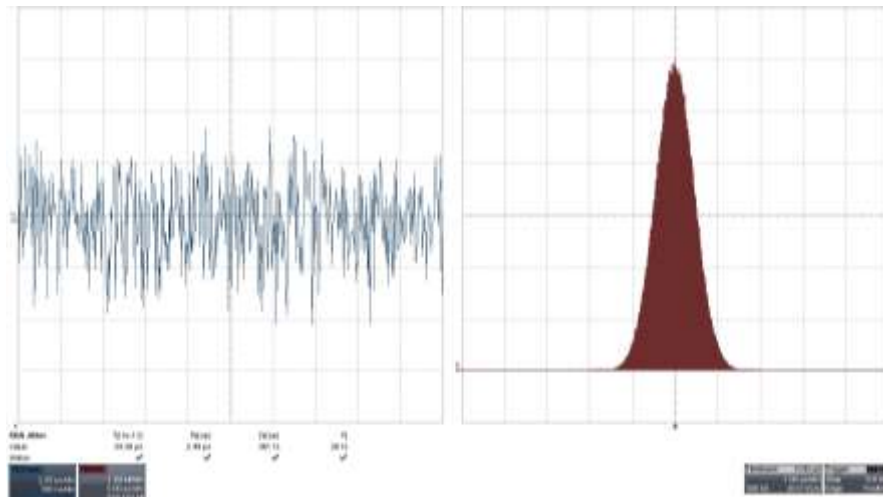


Figure 2: Jitter track (left) and histogram (right)

The so-called spectral method has been adapted to work around the limitations of the direct measurement. The spectral method transforms a sequence of timing error measurements to the frequency domain using an FFT and analyzes the resulting jitter spectrum to find the jitter parameters. The process works by identifying the parts of the spectrum that are random noise from those that are deterministic. This separation is performed by defining an amplitude threshold in the spectrum below which FFT bins are classified as coming from random noise and above which the bins are classified as

deterministic. The nature of deterministic jitter is that its frequency response is characterized by discrete “peaks”. The random jitter is found by adding up the FFT bins below the threshold as the root-sum-of-squares because they are assumed to be random and uncorrelated. The Rj computed in this way tends to converge very quickly and is repeatable both of which are good characteristics for a measurement. The Dj is found using a number of methods such as fitting to the jitter histogram or forming the complex sum of the FFT bins above the threshold.

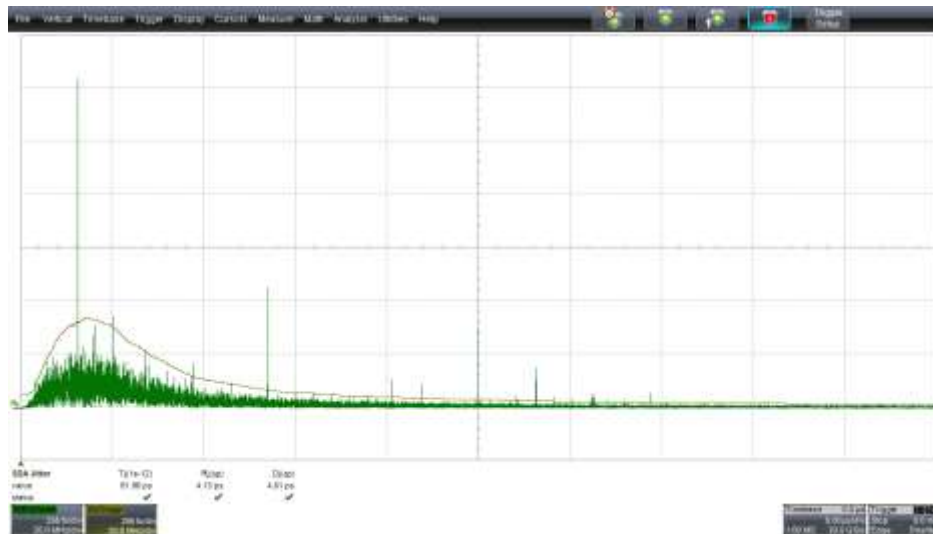


Figure 3: jitter spectrum with threshold. Bins whose amplitude is below the threshold are classified as random (Gaussian) noise.

The spectral method is the primary way of measuring the Dual-Dirac model parameters and it is very effective in virtually every situation. The trade-off made in the spectral method is the assumption that all random jitter is Gaussian. In general, of course, nothing is truly Gaussian but, rather, most random affects are very closely Gaussian at least for practical observation times. There are also classes of pseudo-random processes that appear random over a limited time interval but are, in fact, deterministic when viewed over a longer time. Still other processes are random but with a distribution other than Gaussian. In these cases, the assumption used in the spectral method breaks down and the Rj value can be bigger or smaller than it actually is.

Another problem encountered by the spectral method is random jitter which contains a number of Gaussian distributed sources. For example, each transition in a given signal can have a unique rise time resulting from the transitions which came before it. This is common in cases where limited bandwidth in the transmission channel causes intersymbol interference or ISI. In addition to reducing the amplitude of some bits, ISI also decreases the slew rate of the transitions. The lower slew rate causes more of the noise in the signal to transform to timing jitter. Depending on the data pattern, a minority of edges can have a higher random jitter resulting in a jitter distribution which has one dominant Gaussian and a smaller, lower statistical weight Gaussian. If the lower weight Gaussian has a higher standard deviation, then the true random jitter will take on this

value but the spectral method will only see the lower, higher weight Gaussian and will measure a smaller R_j .

Crosstalk falls into these categories. In some cases, crosstalk causes pseudo-random jitter when the aggressor is uncorrelated with the victim. In other cases, the aggressor is correlated with the victim but carrying a very long or non-repeating data pattern. In these cases, the jitter is pseudo-random but bounded causing the spectral method to over estimate the jitter.

Computing jitter breakdown

The Dual-Dirac model is effective at estimating the long term error performance of a serial data link but the D_j parameter is not adequate for determining the root causes of deterministic jitter. Jitter measurement devices perform detailed analysis of the deterministic components of jitter in order to isolate specific causes. Figure 4 is a typical jitter breakdown tree. The deterministic jitter consists of data dependent and uncorrelated types. The data dependent jitter is generally caused by dispersion and attenuation in the channel (backplane, cable, connector, etc.) while uncorrelated jitter is coupled into the signal from outside sources such as power supply switching and crosstalk.

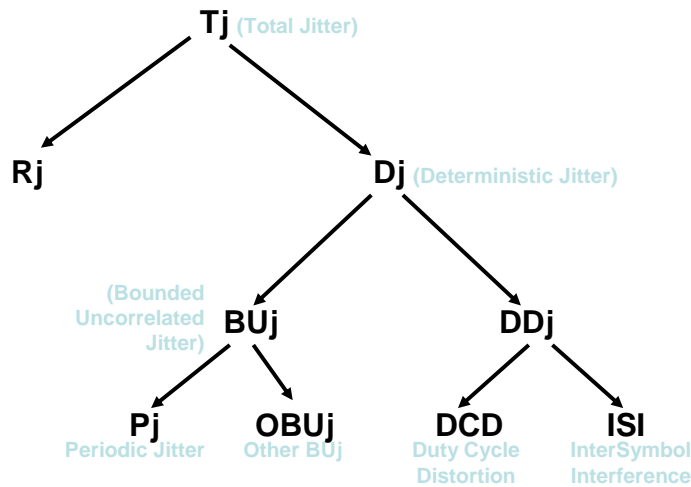


Figure 4: Jitter breakdown tree.

The uncorrelated jitter is known as bounded, uncorrelated jitter or BUJ. This type of jitter can generally be measured in terms of its frequency components in the jitter spectrum and its distribution is bounded in the sense that the peak to peak range of BUJ is limited and does not grow with observation time the way that Gaussian jitter does. Some bounded jitter does not appear as discrete frequency components because at least over the observation time, it appears random. This type of jitter is classified as other bounded uncorrelated jitter or OBUJ. It should be noted that some jitter models treat P_j as a separate form of jitter and not as a component of BUJ. However, MJSQ [1] includes P_j as

a component of BUj. This does not affect the overall breakdown since it is a matter of semantics whether BUj includes Pj. In either case, Pj is uncorrelated to the data pattern.

Signal integrity in the presence of crosstalk

Crosstalk is caused by a signal or signals coupling into another signal. The coupling is generally caused by electromagnetic radiation from the signal(s) known as the “aggressor(s)”. The radiation happens when the aggressor signal switches state as it transitions from a logic ‘1’ to ‘0’ or vice versa. During the transition, the voltage induced into the “victim” line is proportional to the rate of change of the voltage on the aggressor.

$$V_c(t) \propto \frac{dV_a(t)}{dt} \quad (1)$$

The subscripts “c” and “v” denote the voltage of aggressor and victim. The induced voltage has an impact on the timing or amplitude of the victim signal depending on when the transitions of the aggressor occur relative to those on the victim. Figure 5 shows this affect schematically.

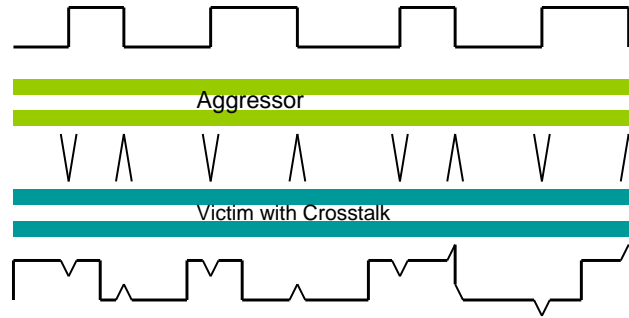


Figure 5: Schematic view of crosstalk. Distortion on the victim lane is a function of the relative timing of the aggressor and the polarity of the edges

Figure 6 shows the measured crosstalk signal induced into the victim line by the aggressor signal. The crosstalk trace is shown in the upper grid while the aggressor signal is in the lower grid. The scaled derivative of the aggressor (larger signal) is superimposed on the measured crosstalk to show that equation 1 does, indeed, predict the crosstalk.

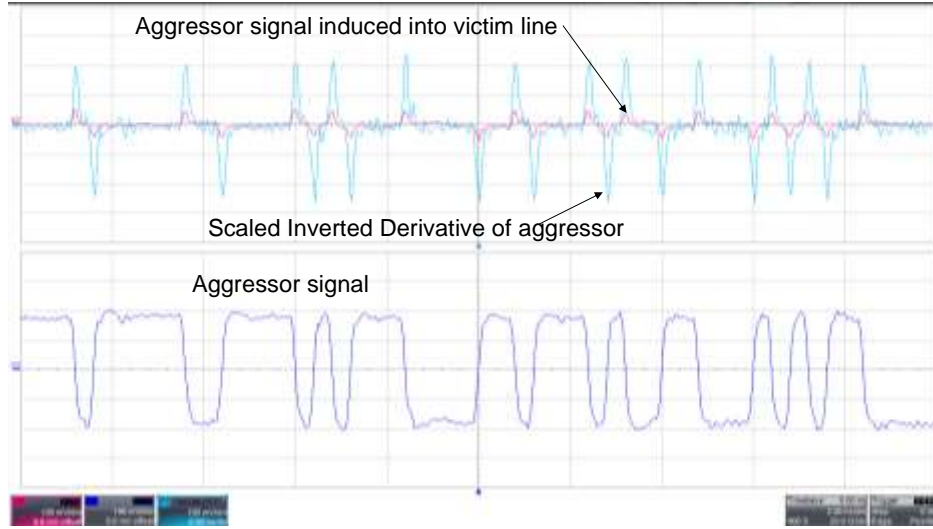


Figure 6: aggressor signal induced into the victim line

There are several forms of crosstalk including near end and far end (NEXT and FEXT) as well as alien which is unrelated in both frequency and time with the victim. Both NEXT and FEXT are correlated in the sense that they operate at the same data rate as the signal under test while alien crosstalk is generally at a different rate which is uncorrelated to the signal under test.

Timing affects

When the aggressor transitions at or near the transitions of the victim, the timing of the victim crossing is altered. The timing shift results when the amplitude of the victim is displaced by the induced voltage from the crosstalk. If the signal transitions were infinitely fast, then there would be no timing shift but because the transition time of the victim is finite its timing is shifted by an amount that is proportional to the crosstalk voltage. A rule of thumb given in [2] expresses the peak to peak jitter resulting from crosstalk as:

$$J_{p-p} \approx \frac{2V_{PPc}T_{rfv20-80}}{V_{PPv}} \quad (2)$$

The terms V_c and $T_{rfv20-80}$ are the peak to peak aggressor voltage induced into the victim and the 20% to 80% rise/fall time of the victim and V_v is the peak to peak voltage of the victim signal. Equation 2 assumes that the only consequence of crosstalk is an increase in deterministic jitter which is not entirely the case. The total transition time is approximated as 2x the 20% to 80% rise time [2]. The jitter induced by crosstalk is bounded because the amplitude of the voltage is a function of the slew rate of the aggressor (from equation 1) and the coupling between the victim and aggressor both of which are bounded.

Crosstalk jitter is only present in the victim when there is a transition in the aggressor that is coincident with a transition in the victim signal. Most situations where crosstalk is involved are where multiple lanes of serial data are being transmitted. In this case, the victim and aggressor are at the same bit rate.

In [3] an expression for the peak to peak BUj caused by crosstalk is derived. The analysis uses the assumption that the crosstalk induced by the aggressor shifts the amplitude of the victim signal in the neighborhood of its transitions by an amount equal to the crosstalk-induced voltage. The time shift of a transition in the victim is given by the following equation [3]:

$$\Delta T = -\frac{V_{PPa}}{m_v} = -\frac{V_{PPa} T_v}{V_{PPv}} \approx \frac{2V_{PPa} T_{rfv20-80}}{V_{PPv}} \quad (3)$$

The term V_{PPa} is the peak crosstalk-induced voltage in the victim and the approximation in equation 2 is applied. Equation 3 describes the crosstalk-induced timing shift when the aggressor transitions are aligned with those of the victim. The peak to peak jitter is limited to the amount of overlap in the transitions of the victim and aggressor. There is also an upper limit equal to the transition time of the aggressor which is reached when the amplitude of the crosstalk exceeds a certain level [3]. Figure 7 shows the amplitude shift caused by crosstalk. The vertical sections on the distorted edge reflect the limit of the crosstalk-induced jitter.

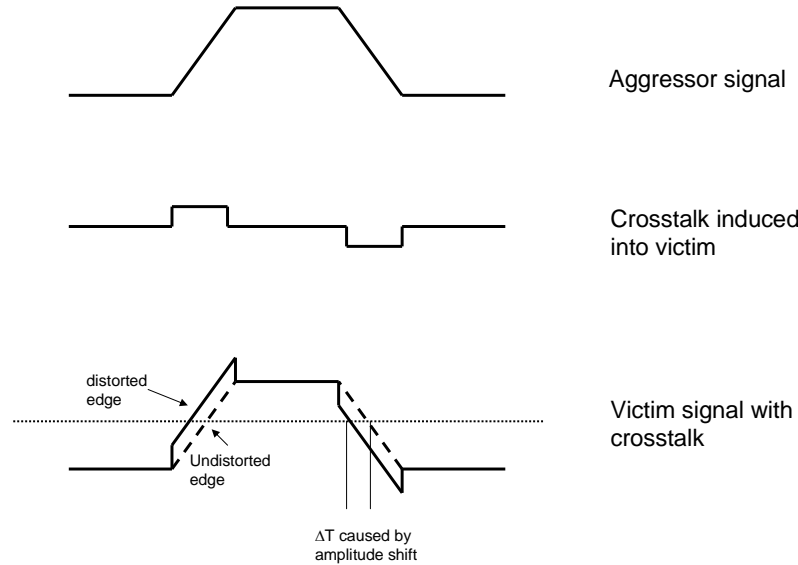


Figure 7: Idealized amplitude shift caused by crosstalk.

The model shown in figure 7 assumes that the induced crosstalk voltage has a square shape which is of course not true in practice. The shape of the crosstalk voltage is rounded by the impulse response of the coupling between the aggressor and victim which results in slightly less cross talk in practice than would be predicted by equation 3.

Another effect not predicted by equation 3 is the impact the crosstalk has on the slope of the victim when the aggressor transitions are not exactly in phase with those of the victim. In this case, the shape of the victim transition is altered resulting in larger and smaller slew rates. Vertical noise in the victim converts to jitter through the slew rate of the signal and lower slew rates result in increased random jitter. The relationship is given by:

$$Rj_n = \frac{N_{RMS}}{dV/dt} = \frac{N_{RMS}}{slewrate} \quad (4)$$

The terms N and Rj_n are the victim's baseline noise and random jitter caused by the noise while the slew rate is for the edge on which the jitter is being measured. The random jitter is the square root of the sum of squares of the timing jitter and the noise jitter.

Jitter measurements are made by observing a number of consecutive transitions of the signal under test and analyzing the sequence of measurements. The addition of crosstalk-induced jitter causes the sequence of timing measurements to vary with the edge timing of the aggressor. Equations 3 and 4 predict that crosstalk will result in an increase in the deterministic jitter proportional to the level of coupling between the victim and aggressor and an increase in random jitter proportional to the phase between the victim and aggressor.

Crosstalk Measurement Experiments

In order to measure the jitter induced via crosstalk, a set of experiments were set up using an ORT82G5 FPSC evaluation board from Lattice Semiconductor. Two SERDES outputs from one of the two quads on the chip were used as a victim and aggressor. Both signals operated at a bit rate of 3.125 Gb/s. The aggressor and victim were applied to a short pair of parallel PC board traces which were closely spaced to induce crosstalk. The coupling between the traces was measured using a TDR to compute the insertion loss a function of frequency. The insertion loss is pictured in figure 8. The insertion loss is 10 dB over a broad range of frequencies from approximately 2.5 GHz. Both the victim and aggressor were applied to the same end of the PC board traces making this a near-end measurement (NEXT). Also note that the coupling is zero at DC and increases with frequency which is predicted by equation 1.

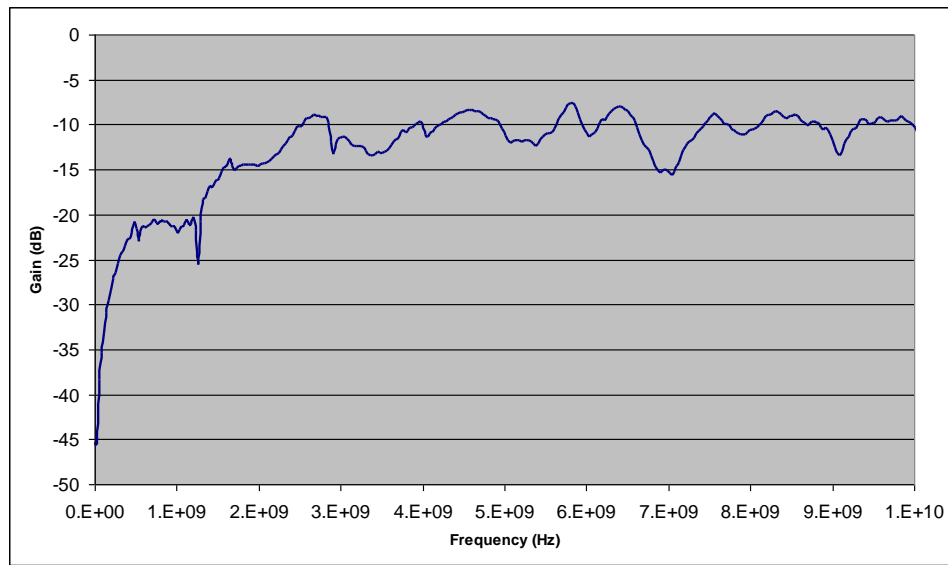


Figure 8: Insertion loss between aggressor and victim lines

Experiment 1 – clock pattern with half-rate clock aggressor

The first experiment used a 1100... aggressor pattern. A total of six different aggressor signal levels were used and the results were compared with the predicted value in equation 3. Table 1 summarizes this test.

Table 1: jitter results for half-rate clock aggressor

p-p aggressor voltage	peak to peak aggressor voltage induced in victim	victim slew rate (mV/ps)	p-p Tj(nq) (ps)	RMS Rj(nq) (ps)	p-p Dj(nq) (ps)	p-p Tj(sp) (ps)	RMS Rj(sp) (ps)	p-p Dj(sp) (ps)	-Vp/Mv
277	48.4	0.92	115.2	4	58.5	108.8	3.8	55	52.6087
197	36.7	0.92	106.5	4.5	42.4	97.7	4	43.1	39.8913
142	28.1	0.92	89.42	4.04	32.35	86.38	3.94	31.13	30.54348
103	23.8	0.92	88.06	4.57	24.22	81.35	3.88	26.36	25.86957
81	18.1	0.92	81.29	4.5	17.99	74.04	3.82	20.19	19.67391
52.4	15.1	0.92	72.61	3.99	16.32	70.35	3.81	16.69	16.41304

The phase between the victim and aggressor was maintained as close to zero as possible for this test and the results closely follow the predicted level. Two methods were used to measure the jitter; spectral (sp) and normalized q-scale (nq). As figure 9 shows, the measured and predicted values line up almost exactly.

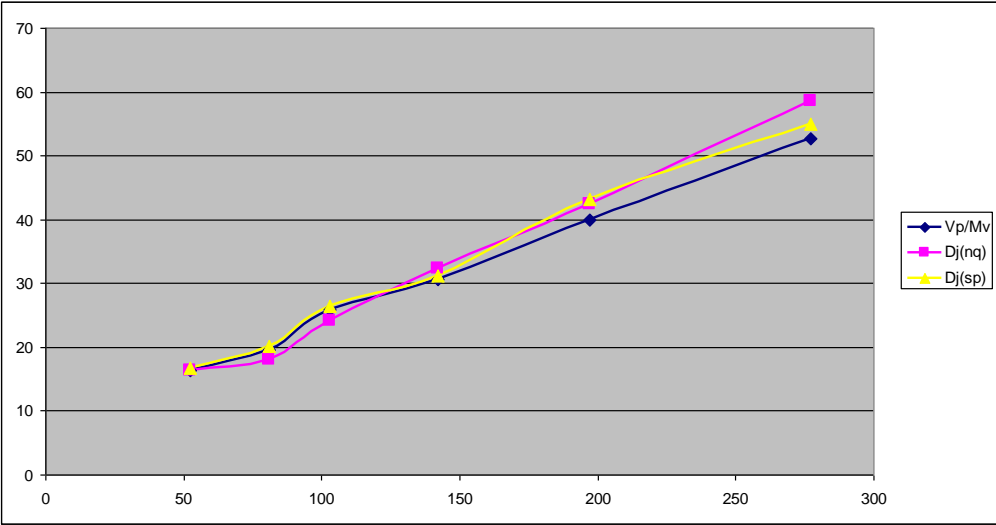


Figure 9: Measured and predicted deterministic jitter vs. crosstalk level

The crosstalk signal is a very simple pattern whose spectrum consists of a set of discrete peaks and is easily measured using either method because all of the aggressor jitter is above the jitter noise threshold. The jitter spectrum for this case is shown in figure 10. The random jitter for this experiment remained constant which is expected considering that the phase between the victim and aggressor was fixed.

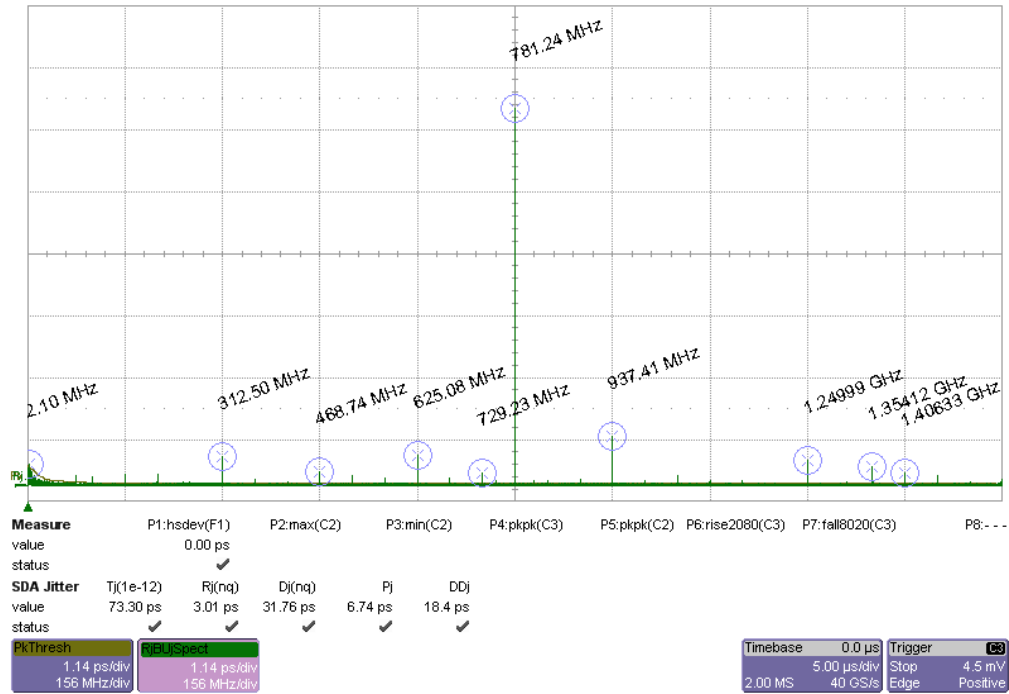


Figure 10: Jitter spectrum for 3.125 Gb/s victim signal and half-rate clock jitter

The random and deterministic jitter was also measured for different phase relationships between the victim and aggressor. These results are shown in figure 11. The deterministic

jitter reaches a peak where the victim and aggressor edges line up and the D_j falls off as the delay between them increases. This is true for both methods but the spectral method has a less pronounced change with phase. The random jitter measured by the spectral method is constant over phase while that measured by the normalized q-scale has a minimum when the edges are lined up and increases with phase difference. This result reflects the affect that the crosstalk has on the slope of the victim and is not seen in the jitter spectrum because the spectral noise is dominated by the edges which are not affected by the crosstalk or whose rise time was increased by the crosstalk. These edges account for roughly 75% of the measured jitter. Note that the rise time of the 3.125 Gb/s signal was approximately 160 ps (50% of a UI) for this experiment. The shape of these curves would be sharper for faster rise times.

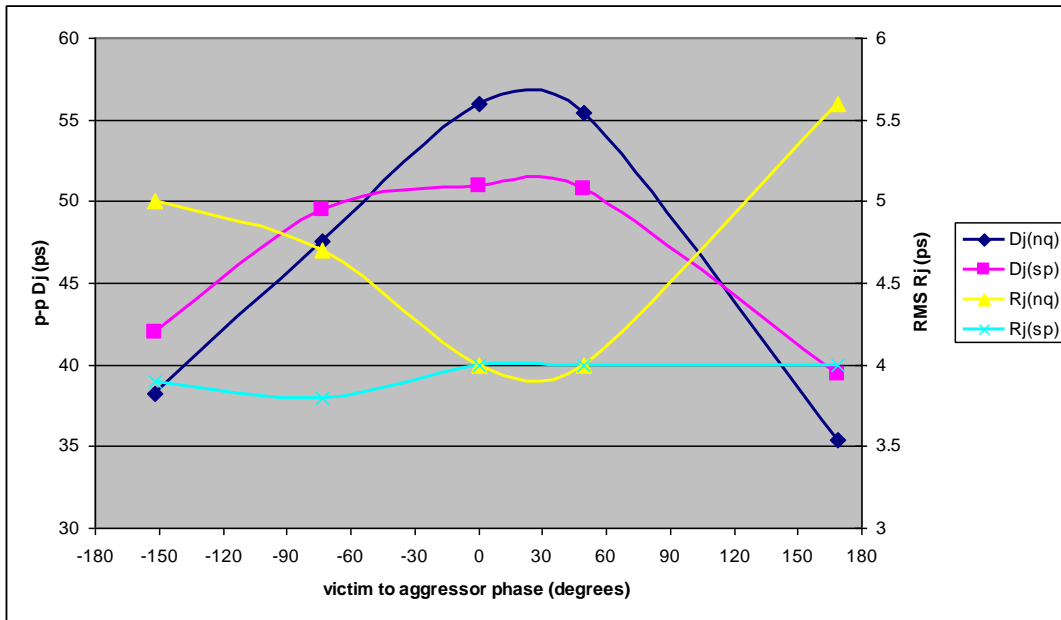


Figure 11: Deterministic and random jitter as a function of the relative delay between the victim and aggressor. The victim and aggressor rise times were approximately 50% of a UI

Experiment 2 – clock pattern with non-repeating data pattern aggressor

A second experiment using an aggressor with a random data pattern was run to measure the affect of random crosstalk. This type of crosstalk has a far more complex impact on the jitter than the simple clock pattern because, in addition to random transitions in the aggressor, the rise time and phase error between the victim and aggressor vary as well.

The results for this test are summarized in table 2 and figures 12 and 13. The random jitter is slightly higher overall for the normalized q-scale results and this is a result of the broad range of phase variation over the aggressor signal causing slower rise times in the victim. The most noticeable affect is the increase in random jitter and decrease in deterministic jitter as the aggressor level increases. This is expected because the jitter

spectrum of the aggressor consists of many closely spaced lines which appear continuous in the jitter spectrum due to the finite frequency resolution. The affect can be clearly seen in the jitter spectrum shown in figure 14 where the noise floor which has a shape that is consistent with a square pulse.

The predicted jitter based on equation 3 is larger in all cases compared with the normalized q-scale result. To understand why, we look to equation 1 which states that the crosstalk level is proportional to the derivative of the aggressor. Fast edges tend to have a larger delay relative to slower ones so we would expect the phase difference to be greatest between the victim and aggressor. Since the bigger phase errors result in a lower peak crosstalk-induced jitter, the prediction based on the peak to peak crosstalk voltage should be an overestimate.

p-p aggressor voltage	peak to peak aggressor voltage induced	victim slew rate	p-p Tj(nq) (ps)	RMS Rj(nq) (ps)	p-p Dj(nq) (ps)	p-p Tj(sp) (ps)	RMS Rj(sp) (ps)	p-p Dj(sp) (ps)	-Vp/Mv
302	66.5	0.92	136.4	5.9	53	212.7	15	0	72.28261
230	46.3	0.92	115.3	5.2	42.7	171.6	12.1	1.2	50.32609
161	30.6	0.92	94.74	4.94	25.04	119.42	8.28	3.45	33.26087
122	24	0.92	88.41	4.98	18.23	101.6	6.66	7.62	26.08696
84	18.4	0.92	82.94	4.81	15.13	87.22	5.48	10.17	20
63	14.3	0.92	78.23	4.61	13.12	78.01	4.65	12.46	15.54348

Table 2: Jitter results for aggressor with non-repeating data pattern

Figure 13 shows the total jitter measured using the spectral and normalized q-scale methods as well as a predicted jitter using the baseline random jitter of 4.61 ps and the deterministic jitter predicted by equation 3. The jitter measured using the normalized q-scale very closely follows the predicted level while the spectral method over-estimates the jitter due to its inability to accurately separate the BUj from Rj. This level of agreement between the predicted and measured total jitter is predicted by figure 11. The reduction in deterministic jitter is exactly matched by an increase in the random jitter as the aggressor phase shifts from zero.

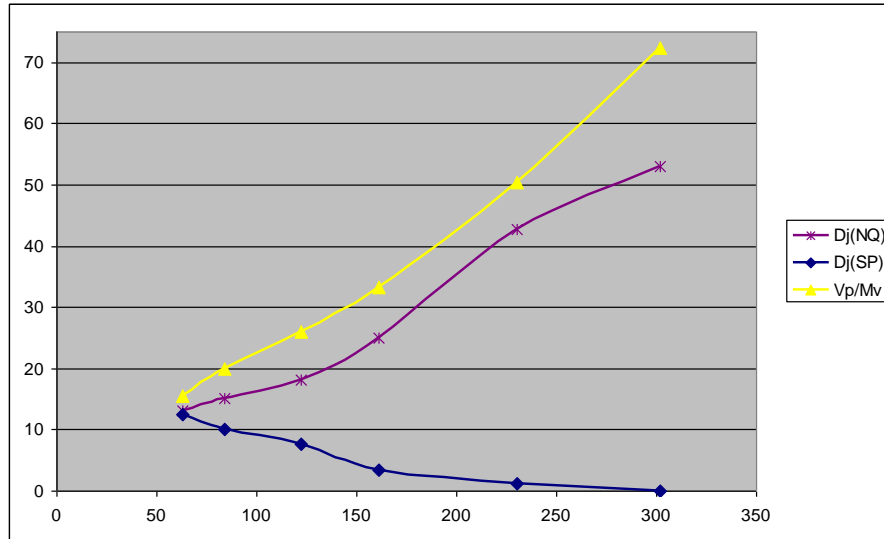


Figure 12: Deterministic jitter as a function of crosstalk level for a random aggressor data pattern

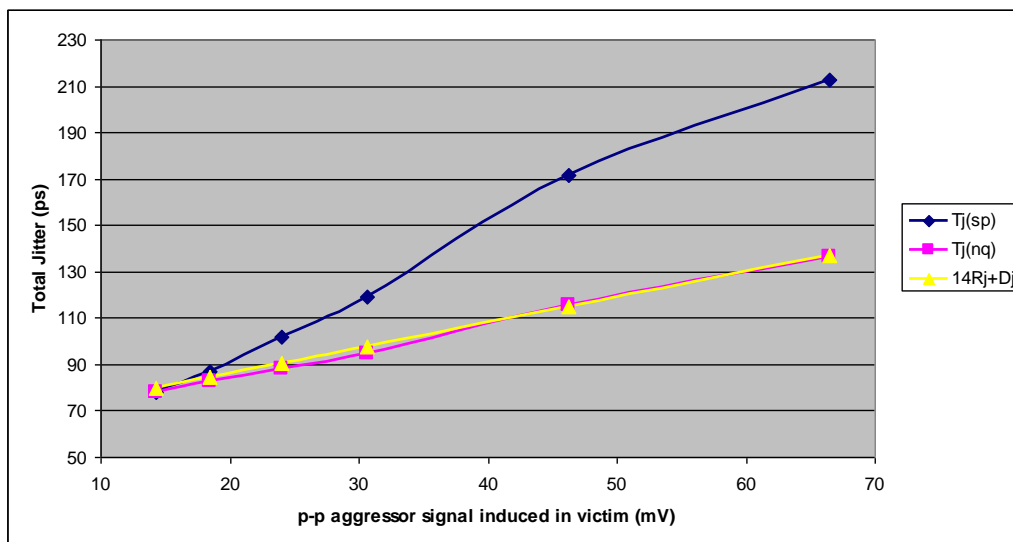


Figure 13: Total jitter vs. aggressor level for clock victim and non-repeating aggressor

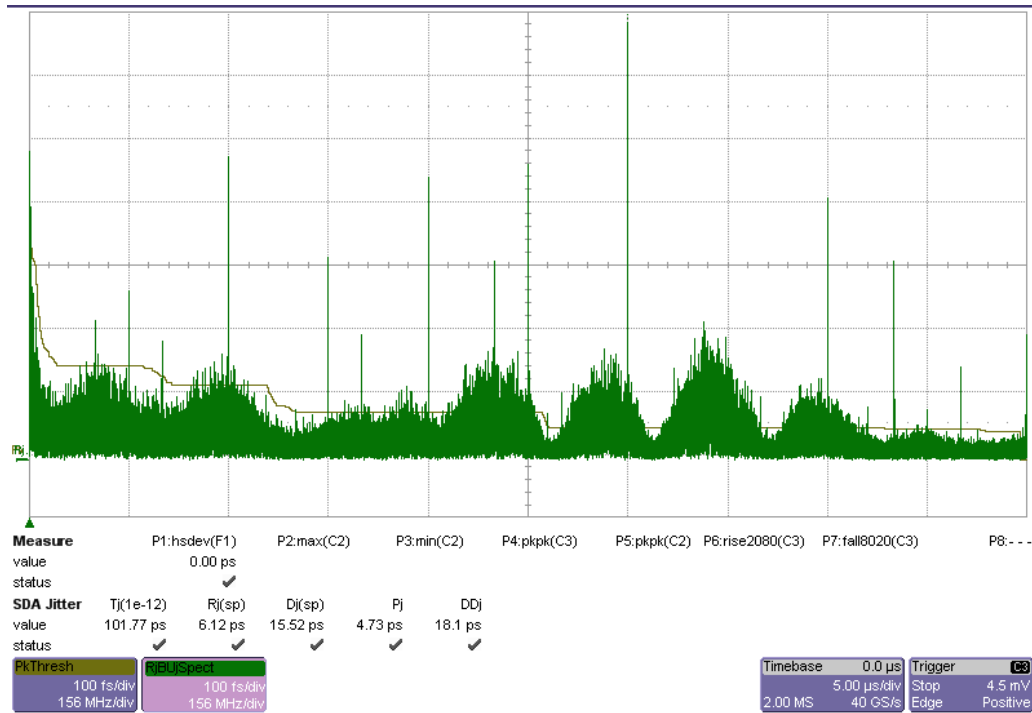


Figure 14: jitter spectrum of victim signal for case with aggressor signal carrying a random pattern.

Experiment 3 – Victim and aggressor with non-repeating data patterns

A third experiment was performed using both the victim and aggressor carrying random data. Since both the victim and aggressor have significant amounts of ISI, the phase difference between them covers a wide range. The results are summarized in table 3 and figures 15 and 16. The random jitter is higher in this case at approximately 10 ps RMS compared with 4 ps for the case where the victim is carrying a clock pattern. The Dual-Dirac jitter model uses a Gaussian PDF convolved with 2 impulses to model the measured jitter histogram. The data dependent jitter for the random pattern has a distribution that is Gaussian over a long observation time so the Dual-Dirac model fits an appropriately large R_j to the measured data. The DD_j parameter shows the peak to peak data dependent jitter which is modeled as random jitter in the Dual-Dirac model. Figure 15 shows the jitter measurement for the victim signal with no aggressor.

The deterministic jitter in this case is lower than the level predicted by equation 3 because the transitions of the aggressor are very rarely in phase with the victim. As figure 11 predicts, a larger part of the crosstalk will be in the form of random jitter. The total jitter measurements are plotted in figure 16 for this case and the normalized q-scale measurement is much closer to the predicted total jitter using 14 times the baseline R_j plus the D_j predicted by equation 3. The larger error in this case compared to the case where the victim is a clock pattern is the result of the large ISI-induced random jitter in the signal.

peak to peak aggressor voltage induced in victim	victim slew rate (mV/ps)	p-p Tj(nq) (ps)	RMS Rj(nq) (ps)	p-p Dj(nq) (ps)	p-p Tj(sp) (ps)	RMS Rj(sp) (ps)	p-p Dj(sp) (ps)	-Vp/Mv
66.2	0.887	193.3	11.5	37.5	239.9	17.2	0	74.6336
44.2	0.887	176.8	11.3	22.3	206.4	14.9	0	49.83089
21.8	0.887	130.32	8.79	9.06	136.9	9.8	1.4	24.57723
13.5	0.887	125.08	8.59	6.01	157.22	11.35	0.224	15.21984
9	0.887	134.49	9.31	6.26	143.44	10.4	0	10.14656
6.6	0.887	131.79	9.22	4.15	138.37	9.99	0	7.440812

Table 3: Jitter measurements for non-repeating victim and aggressor

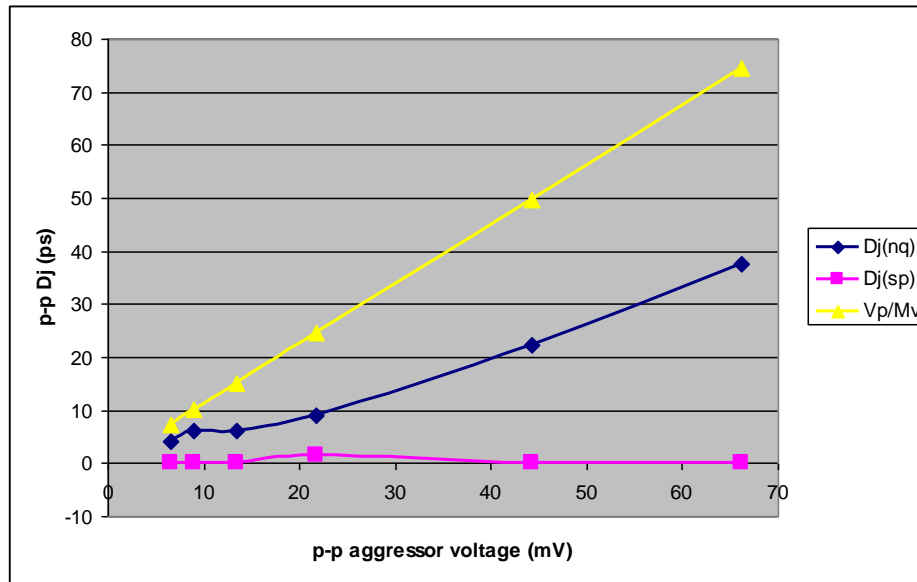


Figure 15: peak to peak Dj vs. aggressor level for random victim and aggressor

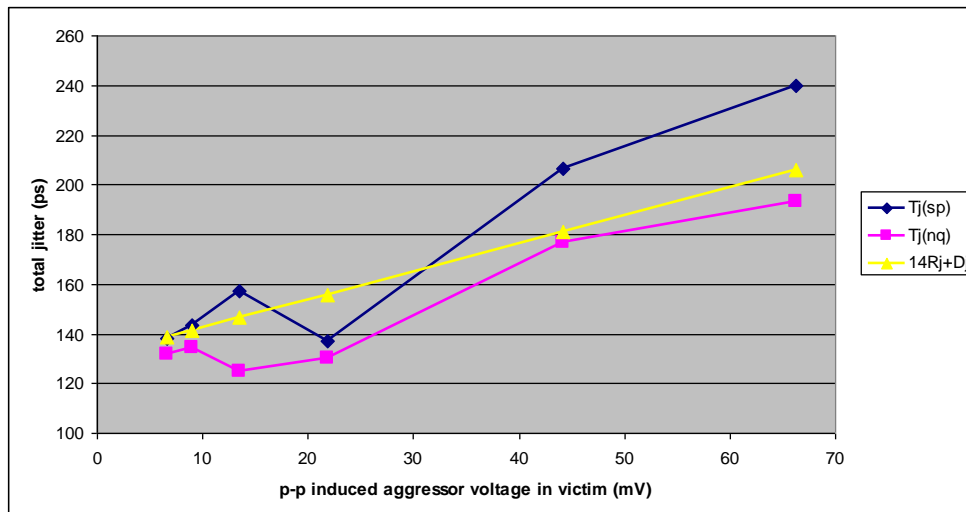


Figure 16: Total jitter vs. aggressor level for non-repeating victim and aggressor

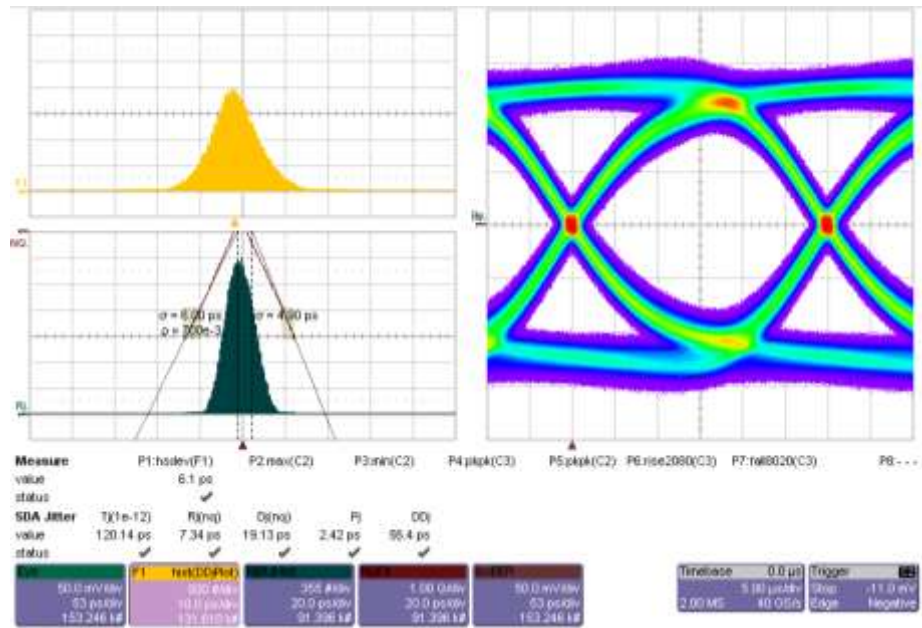


Figure 17: jitter measurement and DDj histogram (upper left) showing the nearly Gaussian shape

Conclusion

Treatments of crosstalk to date have concentrated on its impact on deterministic jitter and while this remains a very important aspect of this type of distortion, the impact on random jitter is also significant. Deterministic jitter caused by crosstalk is dominant when the transitions in the victim signal are in phase with the aggressor however this is rarely the case in real systems. More often than not, the transitions are at a number of phases and the crosstalk affects the shape and slew rate of the victim leading to increased random jitter. Directly measuring the tails of the jitter histogram more accurately determines this type of jitter because it dominates the statistics far away from the mean and is often at a lower statistical weight.

While jitter analysis in the frequency domain is the preferred method for measuring jitter on oscilloscopes, it suffers from severe limitations when used to measure signals with crosstalk. The jitter spectrum noise floor is dominated by the highest statistical weight random jitter component which masks any lower-weight contributors like crosstalk-induced random jitter. Combining the spectral method with direct measurement of the jitter histogram leads to a more robust solution in the presence of crosstalk. The combination of the two methods aids in recognizing the presence of crosstalk by comparing the random jitter between the two methods; differences indicate potential crosstalk.

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