Random Jitter Extraction Technique in a Multi-Gigahertz Signal

Chee-Kian Ong, Dongwoo Hong, Kwang-Ting (Tim) Cheng, Li-C Wang
Department of Electrical and Computer Engineering
University of California, Santa Barbara, CA 93106, USA
Email: ckong@ece.ucsb.edu

Abstract

In this paper, we propose a simple technique for estimating the standard deviation of a Gaussian random jitter component in a multi-gigahertz signal. This method may utilize existing on-chip single-shot period measurement techniques to measure the multi-gigahertz signal periods for the estimation. This method does not require an external sampling clock, nor any additional measurement beyond existing techniques. Experimental results show that this extraction method can accurately estimate the random jitter variance in a multi-gigahertz signal even with the presence of a few hundred-hertz sinusoidal jitter components.

1 Introduction

With marketing gimmicks pushing for higher processor speed and industry demanding faster and more reliable electronic communications, one important engineering task is to ensure that all the signals arrive at their destination at the appropriate time.

The demand for greater speed has pushed the processor operating frequency into the Radio Frequency (RF) hitting the multi-gigahertz range and edging upward. Systems performance limited by parallel-bus data transfer has motivated engineers to look for alternative expandable communication architecture, including multi-gigahertz serial communication architectures (e.g. Infiniband, 3GIO, SONET, SATA). Video-in-demand and other information-hungry applications have also propelled networks into the Gigabit Ethernet area. All these systems operate in the multi-gigahertz range, and to achieve reliable operation for these systems requires substantial understanding of timing jitter characteristics [1].

Jitter is the deviation of a signal event from its ideal position. Jitter affects different systems in different ways, and it can be introduced by every circuit element used to generate, convey or receive signals. Understanding the type and amount of jitter introduced by each element of a system is crucial for predicting overall system performance. For example, some systems can tolerate long-term drift in a signal frequency, whereas the same drift would be catastrophic if it occurred within two successive cycles.

However, most existing jitter analysis techniques have centered upon histogram-based analysis (including data-eye diagram analysis) [2,3,4,5,6]. Histogram-based analysis conceals the jitter spectral/sequential information and distorts the true random jitter component in a signal. Thus histogram-based analysis could not reveal behaviors of systems which readily adapt to some degree of drift in the signal frequency within a given period (for example a pair of serial communication transceivers). These systems are not adaptive to the jitter's random component, which changes each signal periods randomly. Hence, the random jitter component will significantly influence these systems' transmission quality. It will be shown later in Figure 2 that the histogram-based analysis could not determine the random jitter's standard deviation if the signal frequency is also slowly drifting.

The $\Delta\phi$ methods proposed in [7,8] could extract the peak-to-peak amplitude and RMS of a sinusoid jitter using external ATE. However, both methods depend on external equipment and external reference clocks to ensure accuracy. Intuitively, a signal with a sinusoidal and a random Gaussian jitter characteristic would generate a histogram with a double-delta power density function (PDF) (will be shown later in Figure 1). Assuming signal with a double-delta PDF jitter characteristic is inaccurate in estimating deterministic and random jitters, and hence, the performance of the system [9]. Thus, the jitter characteristics of a signal may be more complex than just a sinusoid.

The method reported in [10] claimed to perform jitter spectral analysis on high-speed signals. The principle of this method is to reconstruct a predetermined test pattern (i.e. a sequence of 0's and 1's) and perform spectral analysis on it. First the test pattern is repeatedly transmitted, and multiple timing measurements are taken from the first edge to the other edges of the test pattern. Thus, each pattern edge has a timing distribution to indicate its occurrence with respect to the first edge. Then, the test pattern is reconstructed based on the timing distribution of each pattern edge, and spectral analysis can be performed on the reconstructed pattern. However, this method may not accurately extract the signal jitter spectrum, as the frequencies of sinusoidal jitters need to be multiples of the re-constructed test pattern's repeating frequency. For such cases, this method would not correctly capture the periodicity of the jitter during the reconstruction process of the test pattern. In all, the mentioned methods did not explicitly provide information on extracting the random jitter.

Today, most schemes would require a sampling mechanism and a measurement mechanism to perform an accurate spectral analysis. A scheme in [11] proposed a jitter spectral analysis technique that uses a counter/divider as the sampling mechanism. Instead of generating a repetitive test pattern, the proposed technique only requires to transmit a signal in it's smallest period (i.e. a sequence of alternating 1's and 0's "101010…"). The transmission of this sequence allows the technique to extract the random and periodical jitter spectrum information without interference from non-single period transmission (commonly known to generate the data-dependent jitter). However, this

1530-1591/04 $20.00 (c) 2004 IEEE

scheme uses Fast Fourier Transformation (FFT) to estimate the random jitter and any other sinusoidal jitter components.

In this paper, we propose a simple technique to estimate the random jitter component in a signal from the collected period samples. This technique uses a sampling mechanism identical to that in [11] and a single-shot period measuring technique [12,13,14,15,16,17,18,19,20,21] to measure and collect the period samples. Instead of performing FFT to estimate the random jitter component by measuring the spectrum noise floor (as reported [11]), this technique estimates the random jitter component by computing the variance of the sampled periods' derivatives. Since computing the variance of samples is less demanding than performing FFT on the samples, this technique will be less computationally demanding than that in [11] when estimating the random jitter component is concern.

This paper is organized with the next section briefly describing the types of jitter and explaining how they are represented in a general form. Also presented in Section 2, is the general view of the spectral analysis technique proposed in [11]. Section 3 presents our proposed derivative technique to extract the random jitter while section 4 presents the experimental setup and results comparing the accuracy and the computational time of our technique with that of the Spectral Analysis technique proposed in [11]. We conclude in section 5, with discussion on the advantages, the limitations and the potential uses of this technique.

2 Background

2.1 Jitter and its Representation

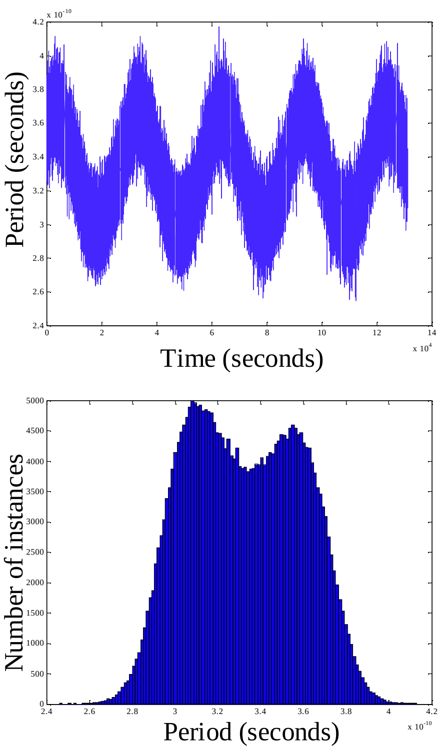

Figure 1 Signal periods with a sinusoidal and a random jitter.

In an electronic system, jitter can be generally classified into two categories – (1) non-deterministic/random jitter, and (2) deterministic jitter [3,4,5,6,9]. Non-deterministic jitter is best characterized by a random process with Gaussian probability density function (PDF). Many factors contribute to the deterministic jitter (for example, periodic and data-dependent jitters). However, we could represent the deterministic jitter with a general process commonly used to describe deterministic analog signal – the sum of sinusoidal signals with different amplitudes and frequencies as follows:

$$f_D = \sum_{i=1}^{n} a_i \sin(\omega_i t) \quad \textbf{(1)}$$

where n is the number of sinusoidal functions found in the deterministic process. a_i and ω_i are the i^{th} sinusoidal jitter's peak and frequency, respectively.

It is important to represent jitter in a general form, since it has been shown in [9] that the previous jitter distribution assumption does not reflect well in actual testing. Figure 1 shows the period transient plot (top) of a signal whose jitter characteristic is the sum of a sinusoidal process and a random Gaussian distribution process. The signal period distribution is shown on the bottom diagram of Figure 1. Note that the distribution diagram reflects that of a double delta distribution function mentioned in [9].

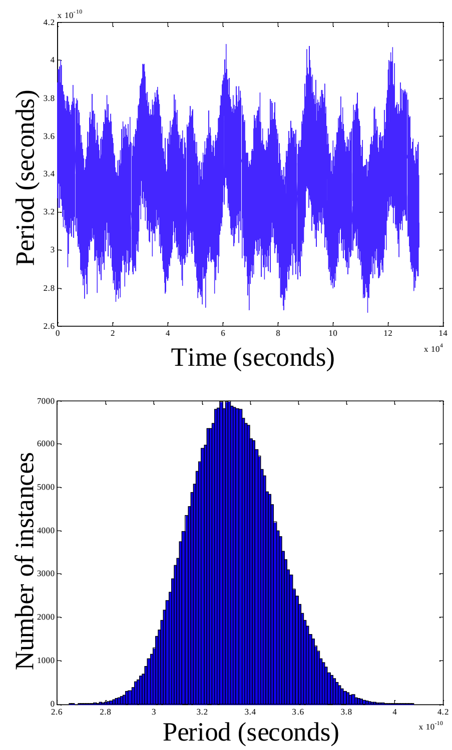

Figure 2 Signal Periods with three sinusoidal jitters and a random jitter.

Figure 2 shows the periods and its distribution of a signal whose jitter function is the sum of a random Gaussian distribution process and three sinusoid processes. Note that the distribution diagram at the bottom could not visibly reflect the three sinusoidal jitter components in the signal. It appears more like a Gaussian distribution whose standard deviation, σ, is larger than the random Gaussian process in the signal. The histogram analysis may not be the best choice for determining the performance of a system whose characteristic could endure the slow frequency drift caused by the three sinusoidal jitters. Hence, it is important to extract the signal jitter in the general form before making any conclusive system performance analysis [1].

2.2 The Spectral Analysis Technique [11]

To extract any signal spectral information, the signal amplitude needs to be periodically sampled over a given time. It is no exception for spectral analysis on the signal's jitter. However, one great challenge is to sample periods of a multi-gigahertz signal at *absolute periodic* intervals. A jitter-free sampling clock signal would be required to trigger the TMU to perform period measurement.

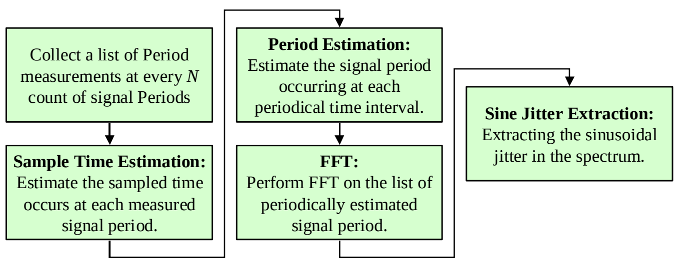

Figure 3 Simplified Technique flow overview

An overview of the jitter spectral analysis technique in [11] is illustrated in Figure 3. The technique does not require a sampling clock signal to perform spectral analysis on the signal. Instead, it collects a list of signal periods by measuring each signal period width on every *N* count of signal periods as elaborated in Figure 4. With each sampled period value, the technique has a simple *Sample Time Estimation* procedure to estimate the time T_n at which each period is sampled. With this procedure, every sampled period can be associated with an estimated sampling time T_n as shown in Figure 4.

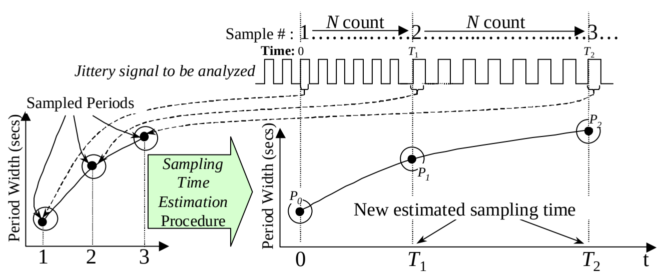

Figure 4 Estimate the sampled time of each measured Period

The next procedure in the technique [11] is to estimate the width of the signal period that occurs at periodic time intervals P_n to analyze the jitter spectrum. After generating a list of measured signal periods with their respective time incidences T_n, estimating a list of signal periods that occur periodically at P_n can be easily accomplished through interpolation using the *Period Estimation* procedure as shown in Figure 5.

For simplicity, a random jitter component was not included in Figure 4 and Figure 5. After generating a list of estimated signal periods at periodic intervals, the technique performs FFT on the list to extract any sinusoidal/periodic jitter that may be found in the signal. When random jitter component is included in the analysis, the random component can be estimated by measuring the noise floor of the jitter spectrum after the list is FFT. Please refer to the spectral analysis technique in [11] for the details of each algorithm, as it is not within the scope of this paper.

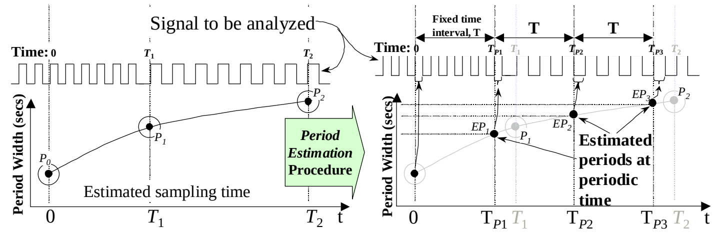

Figure 5 Estimate the signal periods at periodic time interval

3 The Random Jitter Estimation Principle

This section presents the principle behind our proposed derivative technique for estimating the random jitter component in the jittery signal. It can be mathematically proven that the variance of a signal's *derivatives* is dominated by the higher-frequency components within the signal. Thus, we could estimate the variance of the signal's Gaussian random component if the frequency of any sinusoidal component within the signal is significantly lower than that of the sampling signal. For example, if the frequency of a sinusoidal jitter component within a 3G Hz signal is 500K Hz and the sampling frequency for the jitter component is 23MHz (128 times lower than the 3 GHz signal), the sampling frequency is approximately 50 times higher than the sinusoidal jitter frequency. It can be shown in the next section that the contribution of this sinusoidal jitter is only less than 1% to the total variance of the signal's derivatives. Thus the variance of the signal periods' derivatives would be dominated by the random jitter component if the frequencies of sinusoidal jitter components were relatively lower than the sampling frequency.

3.1 The Technique's Mathematical Representation

This section presents the mathematical representation of the random jitter estimation technique. The effect of the random component and the low-frequency component on the variance of the signal derivatives will be shown mathematically in this section. First, some basics on the variances of signals' derivative are presented before we present the variance of signal periods' derivatives.

If a signal *Z* is represented by the sum of signal *X* and signal *Y*, then the variance of Z is equal to the sum of two signals' variance and two times the covariance of the two signals as depicted below:

$$Z = X + Y$$
$$\mathrm{VAR}(Z) = \mathrm{VAR}(X) + \mathrm{VAR}(Y) + 2\mathrm{COV}(X,Y)$$

If *X* and *Y* are independent signals, then the covariance of *X* and *Y* is zero. Then the variance of *Z* will be solely the sum of *X*'s variance and *Y*'s variance:

$$\mathrm{VAR}(Z) = \mathrm{VAR}(X) + \mathrm{VAR}(Y)$$

Hence, the variance of Z's derivatives would be the sum of the variances of the two signal *X's* and *Y's* derivatives:

$$\mathrm{VAR}(Z') = \mathrm{VAR}(X') + \mathrm{VAR}(Y')$$

Variance of a Sinusoid's Derivatives. If *X* is a sinusoidal signal, itself and its variance can be represented by:

$$X = A\sin\left(2\pi \frac{f_x}{f_s} n\right)$$

$$\mathrm{STD}(X) = \left(A/\sqrt{2}\right)$$

$$\mathrm{VAR}(X) = A^2/2$$

where, f_x is the signal frequency, f_s is the sampling frequency, *A* is the amplitude of the signal, and *n* the sample number. Therefore, the derivative of the signal *X* and its variance would be:

$$X' = 2A\pi \frac{f_x}{f_s} \cos\left(2\pi \frac{f_x}{f_s} n\right)$$

$$\mathrm{STD}(X') = \sqrt{2} A\pi \left(\frac{f_x}{f_s}\right)$$

$$\mathrm{VAR}(X') = 2\left(A\pi \frac{f_x}{f_s}\right)^2$$

Note that the variance of the sinusoid's derivative is associated with a factor. The factor is the square of the sinusoidal frequency to the sampling frequency ratio. If this ratio were smaller than a unit, then the variance of the sinusoid's derivative would be reduced by twice the ratio amount.

Variance of a Random Signal's Derivative. If *Y* is a random signal, itself and its variance can be represented by:

$$Y = B \cdot \mathrm{random}(t)$$

$$\mathrm{STD}(Y) = B$$

$$\mathrm{VAR}(Y) = B^2$$

Hence, the derivative of the random signal *Y* and their variance can be represented with:

$$Y' = (B \cdot \mathrm{random}(t) - B \cdot \mathrm{random}(t-1))$$

$$\mathrm{VAR}(Y') = (\mathrm{VAR}(B \cdot \mathrm{random}(t)) + \mathrm{VAR}(B \cdot \mathrm{random}(t-1)))$$

$$= 2\mathrm{VAR}(Y)$$

We assumed that the derivative of a random signal is equivalent to adding/subtracting two random signals, since the current value of the random signal is independent of its previous value. Thus, the variance of the random signal's derivative is twice the variance of the random signal.

Variance of Signal Periods' Derivative. The general form of signal jitter is represented by the sum of a Gaussian random process and multiple sinusoidal processes as follows:

$$J_{sig} = P_{random}(\sigma) + \sum_{i=1}^{n} a_i \sin\left(2\pi \frac{f_i}{f_s} n\right)$$

Thus, the derivatives of the jittery signal periods can be represented by:

$$J'_{sig} = P'_{random}(\sigma) + \sum_{i=1}^{n} 2a_i\pi \frac{f_i}{f_s} \cos\left(2\pi \frac{f_i}{f_s} n\right)$$

Finally, the variance of the signal periods' derivative is:

$$\mathrm{VAR}(J'_{sig})$$

$$= \mathrm{VAR}(P'_{random}(\sigma)) + \sum_{i=1}^{n} \mathrm{VAR}\left(2a_i\pi \frac{f_i}{f_s} \cos\left(2\pi \frac{f_i}{f_s} n\right)\right)$$

$$= 2 \cdot \mathrm{VAR}(P_{random}(\sigma)) + 2\sum_{i=1}^{n}\left(a_i\pi \frac{f_i}{f_s}\right)^2$$

$$\mathrm{VAR}(J'_{sig}) \approx 2 \cdot \mathrm{VAR}(P_{random}(\sigma)); \text{ if } a_i\pi f_i \ll f_s \quad \textbf{(2)}$$

Note that the variances of the sinusoidal derivatives are determined by three variables, namely the sampling frequency f_s, the sinusoidal jitter's frequency f_i, and the sinusoidal jitter's amplitude a_i. Since the sampling frequency is likely to be much larger than the product of a_1, π, and f_s, the variance of the signal periods' derivative will be less dominated by variances of the sinusoidal derivatives. Hence, the variance of the random jitter component can be estimated as half the variance of the signal jitter's derivative.

3.2 The Random Jitter Estimation Flow

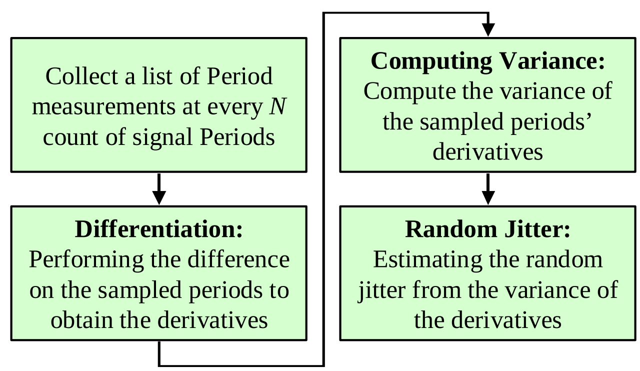

Figure 6 The Random Jitter Estimation Technique

Figure 6 shows the flow of our proposed technique to estimate the variance of random jitter component from a jittery signal. Since we are not extracting the sinusoidal jitter parameters from the jittery signal, the procedures in [11] are not required to estimate the signal periods' width occurring at periodical interval. However, the signal periods are sampled using a counter as in [11], to ensure some extend of periodical sampling is maintained. This quasi-periodical sampling will attenuate the variance of the low-frequency sinusoidal jitter in the derivatives of the sampled periods. Thus, the variance of the sampled periods' derivative will still be dominated by the random jitter component whose variance can still be estimated using the previously derived equation – (2).

First the signal periods are sampled and measured using a counter to trigger the available single-shot period measurement techniques. The difference of the sampled periods is a list of the periods' derivatives. Then, the variance of the periods' derivatives is computed. Finally, we can determine the variance of the random jitter component using the computed variance and the equation in (2).

3.3 Implementation of Signal Period Sampling

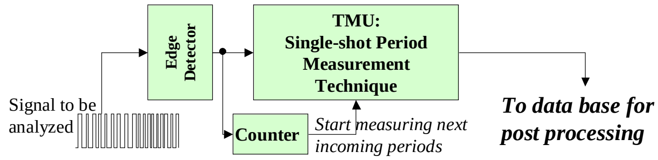

Figure 7 Block diagram for the technique implementation

This section presents the sampling mechanism, which is both utilized in [11] and our proposed derivative technique. In order to measure the signal period at every *N* count, the implementation would require some kind of counter to trigger the Time Measuring Unit (TMU). Figure 7 shows how the sampling of signal periods may be implemented. However, implementing a counter operating at the multi-gigahertz range would be very challenging.

In order to ease the counter implementation, we suggest the count N to be equal to 2^n, where n is any positive integer number. In this way, the counter can be implemented using n clock dividers, which are much simpler and cost-effective than implementing an arbitrary counter operating at the multi-gigahertz range. With the sampling of the signal period at an interval of *N* periods resolved, the key remaining issue for the deployment of the technique is the implementation of the TMU. The TMU employs existing single-shot period measurement technique which some have claimed to achieve sub-picoseconds accuracy [20].

Since the TMU may require some time to determine the signal period measurement, the count value *N* is selected so that the time taken to complete the count should be longer than the required time for the TMU to perform the measurement.

4 Experiment Setup and Results

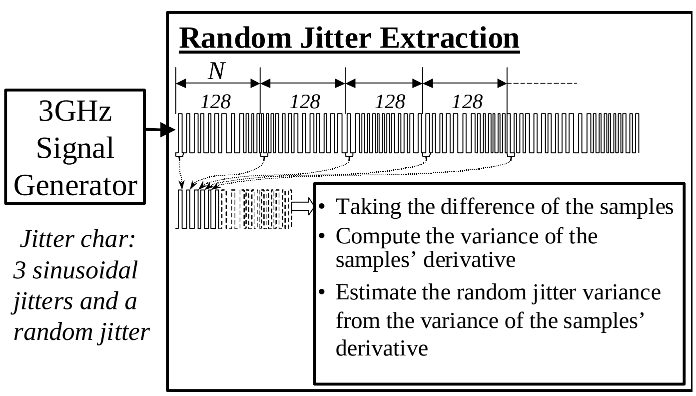

Figure 8 Experiment Setup

The experiment setup, shown in Figure 8, is realized in the MATLAB environment to validate the accuracy and robustness of the random jitter extraction technique. The signal generated in the experiment is a 3G Hz signal with a jitter characteristic, which can be represented as the sum of three sinusoidal processes and a random Gaussian distribution process. Each sinusoidal process peak is 10% of the signal period. The sinusoidal frequencies are in the 100K Hz frequency range with the maximum being 500K Hz. The count N is set to 128 making the periods' average sampling frequency approximately equivalent to 23.4M Hz (3G/128 Hz). With this sampling frequency, a 500K Hz sinusoidal jitter component will generate a maximum error of 1×10^{-24} sec when estimating the random jitter variance. In the experiment, the variance of the random jitter component is set to 1.4×10^{-22} sec. Hence, we are expecting a less than 1% error when we use our proposed technique to estimate the random jitter variance.

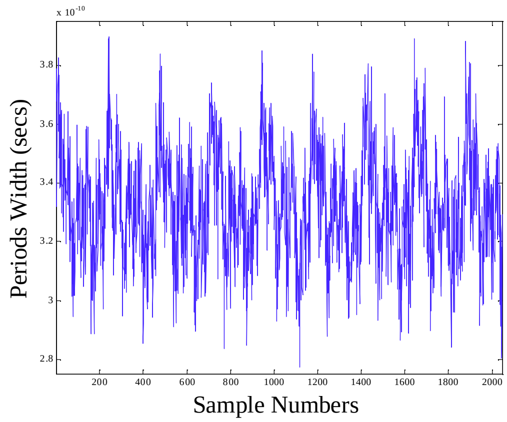

Figure 9 Sampled periods transient plot

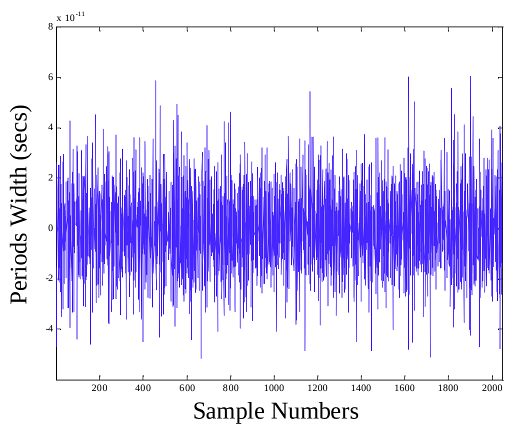

Figure 10 Sampled periods' derivatives transient plot

Table 1 Experimental Result

Sample Length	Spectral Analysis Mean Err	Derivative Est. Mean Err	Spectral Analysis 3σ	Derivative Est. 3σ	FFT Computation time	Variance Computation time	Speed up Ratio
2^{11}	-0.0697	-0.0026	0.0790	0.0572	0.0017	0.0010	1.6833
2^{12}	-0.0659	0.0004	0.0693	0.0383	0.0050	0.0023	2.1429
2^{13}	-0.0688	0.0016	0.0498	0.0265	0.0114	0.0062	1.8356
2^{14}	-0.0637	0.0031	0.0379	0.0183	0.0252	0.0160	1.5707
2^{15}	-0.0608	0.0037	0.0222	0.0138	0.0686	0.0374	1.8350
2^{16}	-0.0591	0.0032	0.0179	0.0100	0.1475	0.0810	1.8221
2^{17}	-0.0557	0.0029	0.0138	0.0073	0.3038	0.1592	1.9077

Figure 9 shows the transient plot of the signal periods after sampling at every 128-period count. As one might have observed, the samples' transient plot reflects some of the sinusoidal jitter's periodicity, which is hardly observed in the derivatives' plot in Figure 10. This is in accordance to our hypothesis and mathematical derivations.

The experiment was conducted in seven different sample lengths shown in the first column of Table 1. For each sample length, the experiment was conducted hundred times to assess the technique's mean error and accuracy. In order to compare the accuracy and computation time of our derivative technique with that of the Spectral Analysis technique [11], Table 1 show the estimation error and the computation time of both technique.

Column two shows the mean error when using the Spectral Analysis technique to estimate the standard deviation of the random jitter component in the signal. Our proposed technique's mean estimation error, shown in column 3, is at least an order more accurate than that of the Spectral Analysis technique. We use the three-sigma 3σ to compare the accuracy (or consistency) of our proposed technique with that of the technique in [11]. Approximately 99.7% of the population would contain within the range, which is indicated by $\pm 3\sigma$ off the population mean. The 3σ of the Spectral Analysis technique and our proposed derivatives technique are shown in column 4 and column 5, respectively. Overall, the 3σ of the derivatives technique are approximately half of that of the Spectral Analysis technique. This indicates that at least 99.7% of derivatives technique estimations are twice more accurate that the Spectral Analysis technique for the same sample length. Column 6 and 7 shows the computation time required to perform the FFT process and the variance process, respectively. The FFT process is utilized by the Spectral Analysis technique while the variance process is utilized by our proposed derivative technique. The average speed up of our technique is on average 1.8 times when compared to the Spectral Analysis technique.

5 Conclusion

In the MATLAB simulation based experiment, the proposed derivative technique proves to be superior to the Spectral Analysis Technique. The derivative technique requires only a quarter of the sample length that is required by the Spectral Analysis technique to achieve the same 3σ estimation error range. Considering the fact that the derivative technique uses faster computation process and uses shorter sample length than the Spectral Analysis technique, the derivative technique is approximately 8 times faster than the Spectral Analysis technique. However, we assume that the sinusoidal jitter frequency is relatively low compared to the sampling frequency in this derivative technique assumes. If the sinusoidal frequency becomes high enough to substantially change the variance of the sampled periods' derivatives, than this derivative technique to estimate the random jitter variance becomes inaccurate. Thus when using this technique to estimate the random jitter variance, the frequency of any sinusoidal jitter component should be relatively low compared to the sampling frequency so that the factor associate to the sinusoid's derivatives is much smaller than a unit.

Reference

1 M. Lauterbach, and T. Wey, "Analyze jitter to improve high-speed design," In *IEEE Spectrum*, Vol. 37, pp 62 – 67, July 2000.

2 W. Dalal and D. Rosenthal, "Measuring of High Speed Data Channels Using Undersampling Techniques," In *Proc. of International Test Conference*, 1998, pp 819 – 23.

3 M. Li and et al, "A New Method for Jitter Decomposition through its Distribution Tail Fitting," In *Proc. of International Test Conference*, 1999, pp 788 – 94.

4 S. Jie, M. Li, and J Wilstrup, "A demonstration of deterministic jitter (DJ) deconvolution," In *Proc. of Instrumentation and Measurement Technology Conference*, 2002, pp 293 – 8.

5 Y. Cai, B. Laquai, and K. Luchman, "Jitter Testing for Gigabit Serial Communication Transceivers," In *IEEE Design & Test of Computers*, Vol. 19, pp 66 –74, Jan. – Feb. 2002.

6 Y. Cai, et al, "Jitter Testing for Multi-Gigabit Backplane SerDes – Techniques to decompose and Combine Various Types of Jitter," In *Proc. of International Test Conference*, 2002, pp 700 – 9.

7 T. Yamaguchi, et al, "Extraction of Peak-to-Peak and RMS Sinusoidal Jitter Using an Analytic Signal Method," In *Proc. of VLSI Test Symposium*, 2000, pp 395 – 402.

8 T. Yamaguchi, et al, "Timing Jitter Measurement of 10 Gbps Bit Clock Signals using Frequency Division," In *Proc. of VLSI Test Symposium*, 2002, pp 207 – 212.

9 M. Li, and J. Wilstrup, "On the Accuracy of Jitter Separation From Bit Error Rate Function," In *Proc. of International Test Conference*, 2002, pp 710 – 6.

10 J. Wilstrup, "A Method of Serial Data Jitter Analysis Using One-shot Time Interval Measurements," In *Proc. of International Test Conference*, 1998, pp 819 – 23.

11 Submitted to ASPDAC… left out for blind review

12 E. Räisänen-Ruotsalainen, et al, "Time interval measurements using time-to-voltage conversion with built-in dual-slope A/D conversion," In *IEEE International Symposium on Circuits and Systems*, Vol.5, pp 2573 – 2576, June 1991.

13 M. Hsiao, et al, "A low-cost CMOS time interval measurement core," In IEEE International Symposium on Circuits and Systems, Vol. 4, pp 190 – 193, May 2001.

14 E Räisänen-Ruotsalainen, "A low-power CMOS time-to-digital converter," In *IEEE Journal of Solid-State Circuits*, Vol. 30, pp 984 – 90, Sept. 1995.

15 P. Chen, and S.-I Liu, "A cyclic CMOS time-to-digital converter with deep sub-nanosecond resolution," In *Proc. of IEEE Custom Integrated Circuits*, May 1999, pp 605 – 8.

16 A. Chan, and G. Roberts, "A synthesizable, fast and high-resolution timing measurement device using a component-invariant vernier delay line," In *Proc. of International Test Conference*, Oct 2001 pp 858 – 67.

17 N. Abaskharoun, G. Roberts, "Circuits for on-chip sub-nanosecond signal capture and characterization," In *Proc. of IEEE Custom Integrated Circuits*, May 2001, pp 251 – 4.

18 D. Chu, "Double vernier time interval measurement using triggered phase-locked oscillators," *US Patent #4164648 assigned to Hewlett-Packard Company*, Aug 14 1979.

19 A. Frisch and T. Rinderknecht, "Jitter measurement system and method," *US Patent #6,295,315 assigned to Fluence Technologies*, Sep 25 2001.

20 S. Tabatabaei, and A. Ivanov, "An embedded core for sub-picosecond timing measurements," In *Proc. of International Test Conference*, Oct. 2002, pp 129 – 137.

21 A. Chan, G. Roberts, "A deep sub-micron timing measurement circuit using a single-stage Vernier delay line," In *Proc. of IEEE Custom Integrated Circuits Conference*, May 2002, pp 77 – 80.