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Research Report

Jitter Measurement Algorithm for Serial Links

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Abstract - **An algorithm is presented to determine jitter in a high-speed serial link operated with arbitrary user data. The horizontal eye opening is determined by evaluating the sample statistics obtained by means of a digital clock-data-recovery (CDR) receiver in the deserializer. The jitter measurement method proposed here was applied to a 2.5 Gb/s serial link.**

Introduction: The algorithm presented addresses the problem of measuring jitter in serial links that are part of application-specific integrated circuit (ASIC) modules. Such very large-scale integration (VLSI) ASIC modules typically have many hundreds of input/output (I/O) ports. The adjustment of the optimum transmission settings for each individual serial link, such as the tap weights of a pre-emphasis filter, might be quite challenging because the transmission channel length and thus the amount of intersymbol-

The proposed jitter measurement method is based on an evaluation of the sample statistics of a threefold-oversampled digital CDR receiver in a serial link. The sample statistics is applied to the transmission channel's jitter model in order to determine the link's total jitter (TJ) number and hence also the horizontal eye opening of the received data signal. Before deriving the jitter measurement algorithm, it might be instructive to review the theory of the jitter model applied [1].

Jitter model: The mathematical jitter model applied can be split into two components representing random jitter and deterministic jitter. Random jitter is characterized by a Gaussian distribution of the edge transitions in the data signal. It stems, for instance, from voltage-controlled oscillator (VCO) phase noise or power supply noise. The probability density function of random jitter (PDF_{RJ}) can be expressed as

$$PDF_{RJ} = \frac{1}{\sqrt{2\pi}RJ}\exp\left(-\frac{t^2}{2RJ}\right) . \quad (1)$$

The standard deviation RJ is also referred to as the random jitter number and represents the jitter contributions of all random processes in the serial link.

Deterministic jitter due to ISI or duty-cycle distortion is bounded in amplitude by a peak-to-peak value DJ, and its probability density function (PDF_{DJ}) can be modeled by a dual Dirac function as follows:

$$PDF_{DJ} = \frac{1}{2}\delta\left(t + \frac{DJ}{2}\right) + \frac{1}{2}\delta\left(t - \frac{DJ}{2}\right) . \quad (2)$$

The jitter numbers RJ and DJ are specified with respect to one unit interval (UI), which equals the nominal bit length. In order to get the total probability density function (PDF_{tot}) of the edge transitions at one of the two zero crossings in the data eye, the convolution of PDF_{RJ} and PDF_{DJ} must be calculated:

$$PDF_{tot} = PDF_{RJ} \otimes PDF_{DJ} = \frac{1}{2\sqrt{2\pi}}\left[\exp\left(-\frac{(t - DJ/2)^2}{2RJ}\right) + \exp\left(-\frac{(t + DJ/2)^2}{2RJ}\right)\right] . \quad (3)$$

To calculate the probability of error due to jitter, the area under the PDF tail on the error side of the sampling point must be calculated. This yields the cumulative distribution function CDF. For instance, for the left-hand side zero crossing of the data eye, the integration is carried out from the sampling point to $+\infty$:

$$CDF_{left} = \int_t^{\infty} PDF_{tot} dt = \frac{1}{4}\left(2 + erf\left(\frac{t - DJ/2}{\sqrt{2}RJ}\right) + erf\left(\frac{t + DJ/2}{\sqrt{2}RJ}\right)\right) , \tag{4}$$

where erf() denotes the error function. To determine the bit error rate (BER), the CDFs of both zero crossings in the data eye must be multiplied by the transition probability p_{trans}, which is approximately 0.5 for dc-free signaling:

$$BER = p_{trans} \cdot CDF_{left} + (1 - p_{trans}) \cdot CDF_{right} . \tag{5}$$

Equation (5) is also the mathematical description of the jitter bathtub curve that can be obtained by bit error rate tester (BERT) scan measurements. Once a jitter bathtub curve fit is performed, the horizontal eye width at a certain bit error rate boundary can easily be specified as

$$Eye\ width\big|_{BER} = 1 - TJ = 1 - \left(DJ + k_{\sigma} \cdot RJ\right) , \tag{6}$$

where k_{σ} denotes a scaling factor parameterized by the corresponding BER boundary (e.g. k_{σ}=14.1 for BER=10^{-12} [2]).

Algorithm: The jitter monitoring algorithm is tailored to a threefold-oversampled digital CDR receiver. The width of a data bit can then be subdivided into three 1/3-UI-wide regions that are labeled early (E), nominal (N) and late (L) and that are delineated by the ideal sample positions according to Fig. 1. The available serial link hardware [3] provides ten consecutive samples that can be analyzed as illustrated in Fig. 2. An edge is detected whenever two consecutive sample values are different. For instance, if S4=0 and S5=1, a raising edge in the nominal region is detected. Next the occurrences of the edges falling in the E, N and L regions are summed and averaged by the total number of detected edges (TE). The resultant quantities Q_E, Q_N and Q_L are then linked to the jitter model described above as follows. Ideally in a jitter-free link, we find that Q_N=1 and that Q_E, Q_L are vanishing. At the occurrence of jitter, Q_N starts to decrease and the other two quantities start to increase. This is reflected by the following equation where the term on the right-hand side is derived from (4).

$$\frac{Q_N}{p_{trans}} = CDF\left(RJ, DJ, t = -\frac{1}{6}\right) - CDF\left(RJ, DJ, t = \frac{1}{6}\right) = 2\int_{t=0\,UI}^{t=\frac{1}{6}UI} PDF(RJ, DJ, t)\,dt \qquad (7)$$

A similar equation can be set up for Q_E and Q_L in the early and late regions, respectively. However, the information obtained thereof is redundant with respect to (7). The solutions of (7) represent straight lines parameterized by Q_N in the RJ-DJ plane. As outlined above, the transmission channel mainly represents deterministic jitter. Furthermore, it can even be assumed that the RJ jitter number is approximately constant within a certain family of serial links. The relationship between TJ and Q_N can then easily be obtained by solving (7) for constant RJ. Thereby the DJ and RJ jitter numbers are combined by (6) to get TJ with k_σ=14.1, which corresponds to a BER boundary of 10^{-12}. Figure 3 shows the resulting set of TJ versus Q_N curves parameterized by RJ. The curves show a relatively wide range of up to TJ≈0.3 UI (for RJ=0), where Q_E stays at its maximum value. The width of this region where the algorithm is insensitive towards changes of TJ is inversely dependent on the oversampling factor.

Application to Serial Link: The jitter monitoring algorithm described has been applied to a 2.5 Gb/s serial link test chip as an extension of a LabVIEW-based user interface. Figure 3 shows a verification measurement (dashed curve) at RJ=0.035 UI, which was carried out by jitter bathtub curve and eye diagram measurements on a board with differential FR-4 traces. The predicted TJ value based on the Q_N statistics and the TJ value obtained by the verification measurement are in good agreement. However, the practical usability of the algorithm for absolute measurements of TJ is restricted because of the relatively wide insensitive range towards lower TJ values. The algorithm shows a much better performance for relative measurements of TJ such as the optimization of pre-emphasis settings. Figure 4 shows the course of Q_N sweeping the first post cursor tap weight of the pre-emphasis FIR filter in the transmitter to equalize the deterministic jitter of a 40-inch (1-m)-long line on a FR4 board. It is clearly visible that the algorithm based on the Q_N statistics is able to detect the optimum tap weight where the horizontal eye opening is largest and the TJ jitter number is smallest.

Conclusion: A jitter monitoring algorithm for serial links has been presented that is based on the statistical evaluation of digital sample values in the CDR receiver. The algorithm can be used with user data (no training sequence or predefined pattern) at runtime of the serial link. Results from the implementation of the algorithm in a 2.5 Gb/s serial link have been shown.

References:

1 IEEE Draft P802.3ae/D4.0 Annex 48B, http://grouper.ieee.org/groups/802/3/ae

2 MAXIM, High-Frequency/Fiber Communications Group, 'Converting between RMS and peak-to-peak jitter at a specified BER', HFAN-4.0.2, 2000

3 Blue Logic High-Speed SERDES Family of Cores, IBM Microelectronics Divison, Publication number G522-0610-00

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Figure captions:

Fig. 1 Illustration of the jitter model and the partitioning of the threefold oversampled data bits into early, nominal and late regions.

Fig. 2 Illustration of the jitter monitoring algorithm.

Fig. 3 TJ-Q_N characteristic derived from jitter model (solid lines) and verification measurement (dashed line) based on jitter bathtub curve measurements.

Fig. 4 Q_N and measured TJ versus tap weight of the pre-emphasis FIR filter in the transmitter of the serial link. The 40” (1 m) long channel on a FR4 board is optimally equalized when Q_N is maximum and TJ is minimum.

Figure 1

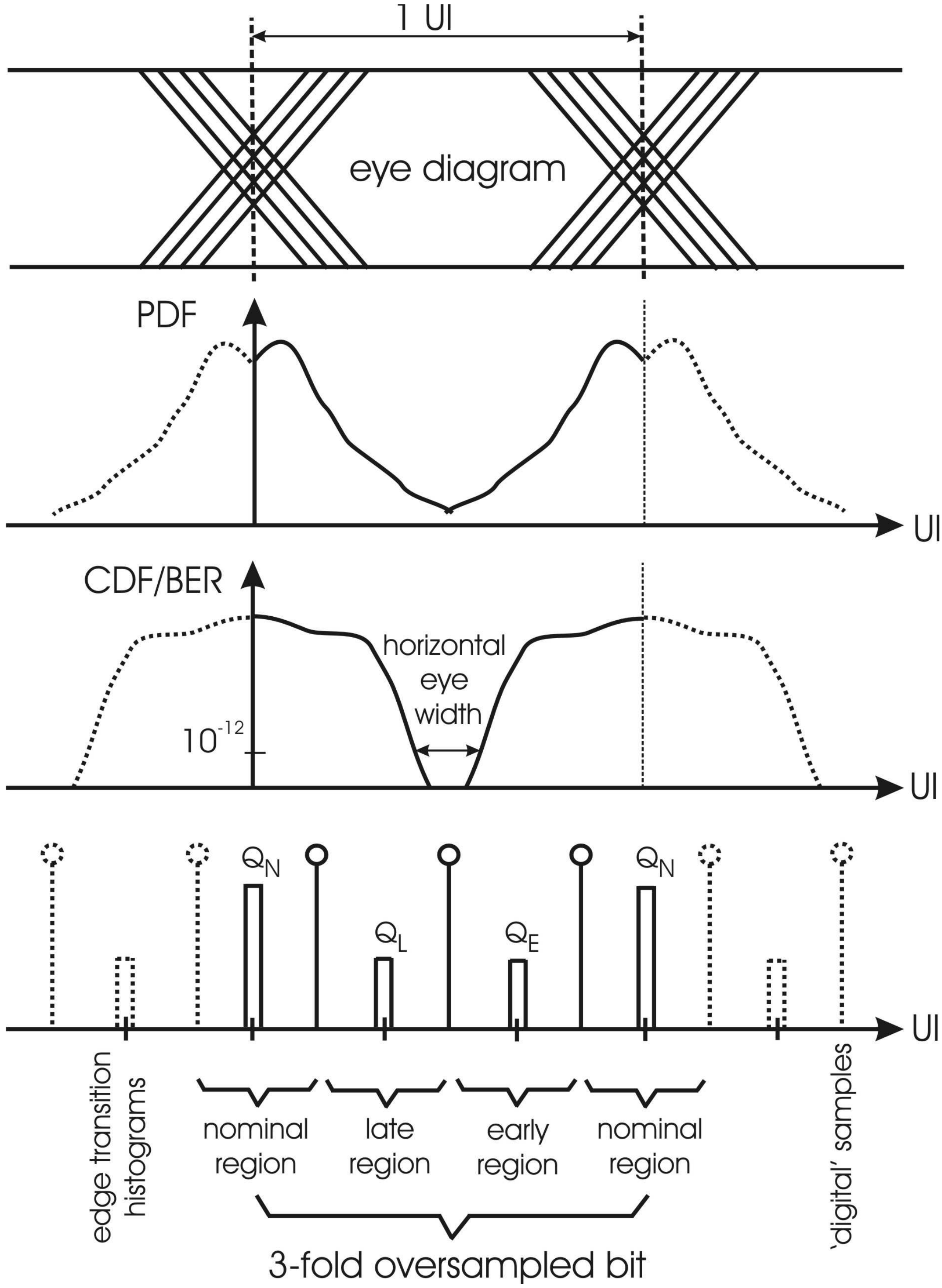

1 UI
eye diagram
PDF
UI
CDF/BER
horizontal eye width
10-12
UI
QN
QL
QE
QN
UI
edge transition histograms
nominal region
late region
early region
nominal region
3-fold oversampled bit
'digital' samples

Figure 2

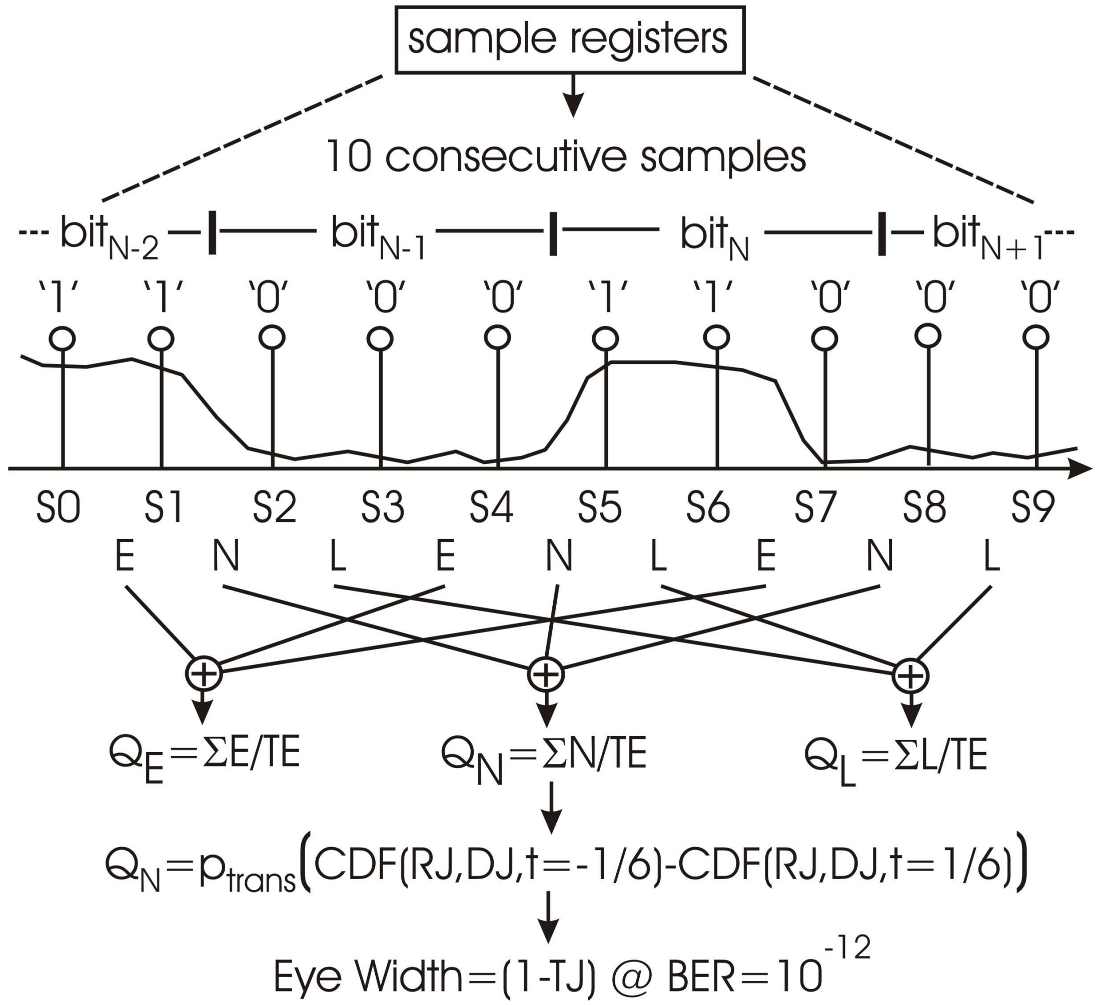
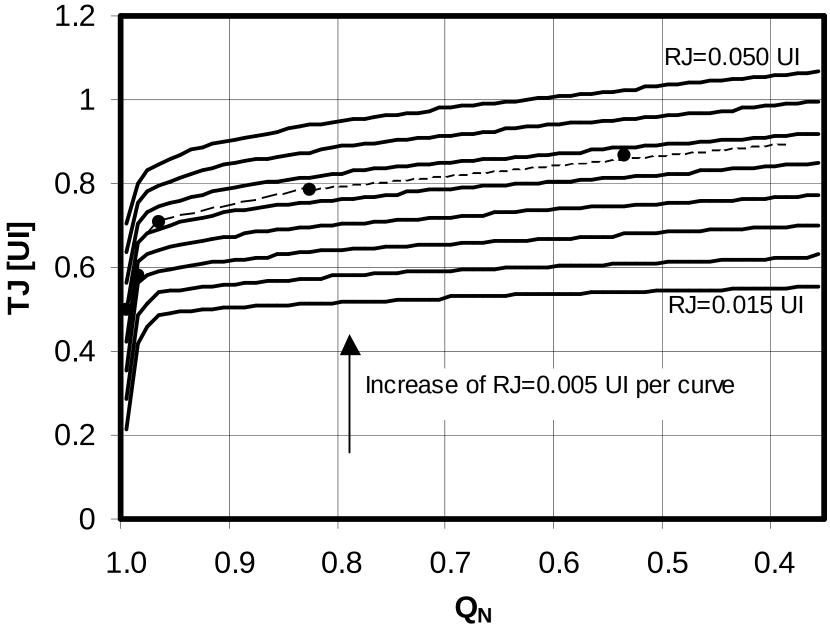
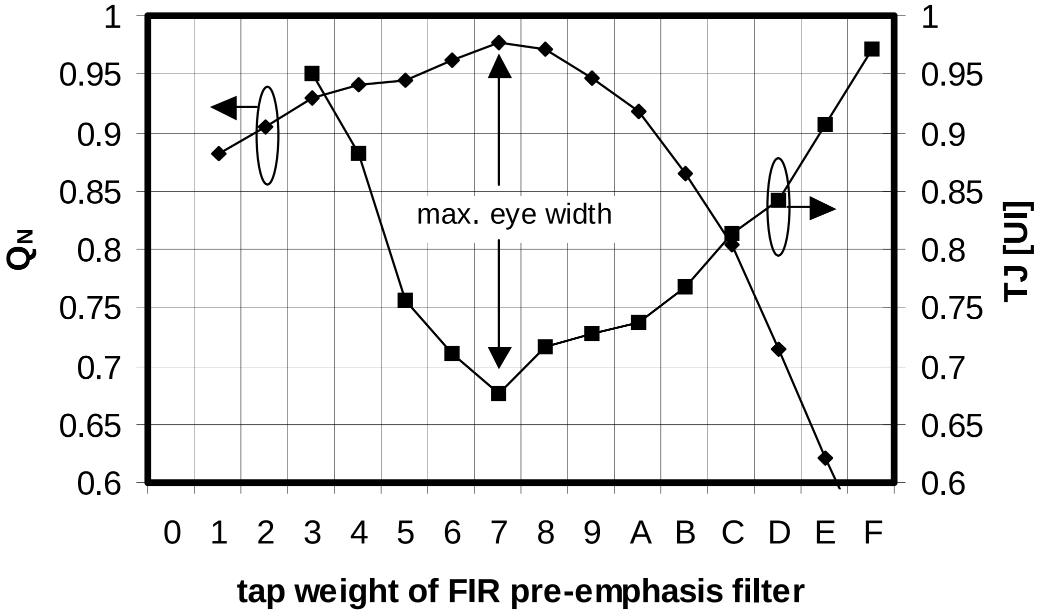

sample registers
10 consecutive samples
--- bitN-2 bitN-1 bitN bitN+1 ---
'1' '1' '0' '0' '0' '1' '1' '0' '0' '0'
S0 S1 S2 S3 S4 S5 S6 S7 S8 S9
E N L E N L E N L
QE=ΣE/TE
QN=ΣN/TE
QL=ΣL/TE
QN=ptrans(CDF(RJ,DJ,t=-1/6)-CDF(RJ,DJ,t=1/6))
Eye Width=(1-TJ) @ BER=10-12

Figure 3



1.2
1
0.8
0.6
0.4
0.2
0
TJ [UI]
RJ=0.050 UI
RJ=0.015 UI
Increase of RJ=0.005 UI per curve
1.0
0.9
0.8
0.7
0.6
0.5
0.4
Q_N

Figure 4


1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
Q_N
TJ [UI]
max. eye width
0 1 2 3 4 5 6 7 8 9 A B C D E F
tap weight of FIR pre-emphasis filter