On the Impact of Channel Loss on CDR Locking

Javier Ardila, javier.ardila@correo.uis.edu.co, Elkim Roa, efroa@uis.edu.co

***Abstract*—This paper shows that under certain conditions of incoming jitter in clock and data recovery circuits (CDR), the bang-bang phase detector (BBPD) gain can rise even for increments in the channel loss. Even more, it is shown how the BBPD gain can increase when sinusoidal and uniform jitter noise are combined; impacting on the CDR dynamic response. These observations are not clearly reported in the literature and here are presented in two approaches. First, direct measurements by using an extraction procedure that allows get the BBPD gain and second, by presenting an explanation through the convolution of probability density functions.**

I. Introduction

Several high speed links applications incorporate CDR circuits at the receiver end (RX); USB3.1, PCIexpress and serial advanced technology attachment (SATA) are examples of those applications. Digital phase-locked loop (DPLL) based CDR is widely used due to the power efficient, flexibility and effective functionality for Gb/s data links over analog counterparts [1]–[4]. Addressing the design of DPLL-based CDR requires clear understanding and proper simulation of the basic equivalent linear model shown in Fig. 1; where K_{PD}, K_V, K_{DPC}, P and F are the BBPD gain, majority voting gain, digital to phase converter (DPC) gain, proportional and frequency path gains respectively. The parameter N represents the latency for the whole system loop, ϕ_{in} and ϕ_{out} are the input data phase and output clock phase respectively.

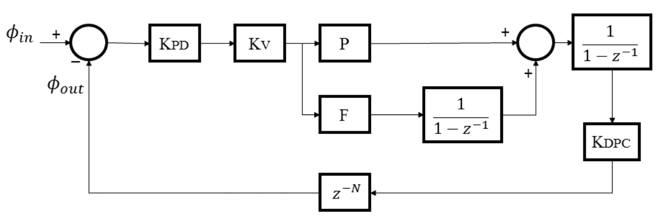


Fig. 1. Traditionally discrete linear model of a CDR system.

Open loop transfer function is determined by the following equation:

$$H_o(s) = \left(\frac{K_{PD}K_V K_{DPC}}{1-z^{-1}}\right)\left(P + \frac{F}{1-z^{-1}}\right)z^{-N} \quad (1)$$

K_{PD} is the representation of a nonlinear block and is one of the most sensitive parameter in Eq. (1); it changes under different operation conditions such as jitter noise, transition density (TD) and inter symbol interference (ISI) [3], [5]. This parameter has high influence on the CDR dynamic response, hence, the extraction of a proper K_{PD} value is critical in order to obtain correlated results between the linear model and the actual behavior of the CDR. One scenario where K_{PD} can change is in the synchronization process. When CDR starts-up, the data eye diagram is too closed, then, lots of bits are lost and the data TD differs considerably from the average value of 0.5 for random data. Once the CDR circuit approaches to the lock state the data eye diagram is opened, TD increases and K_{PD} increases too. On the other hand, K_{PD} value also changes depending of the incoming jitter noise. Both the amplitude and the type of noise, modify this gain and therefore the system frequency response.

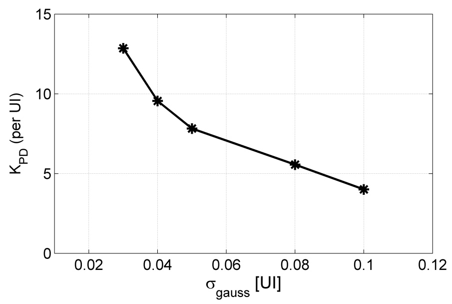
II. Jitter Noise and Extraction Procedure

In the industry it is widely accepted that jitter is decomposed into random and deterministic components that comprise the end to end connections in a transmission link, example of that is the standard for USB 3.1 [6]. Random sources exist as gaussian noise generated by the transmitter and receiver PLL; deterministic sources, are typically referred as uniform jitter inherent to ISI in the channel and sinusoidal jitter from the power supply [3], [7]. For example, Fig. 2 shows the effect of noise on K_{PD} gain for different types of noise sources. Fig. 2(a) corresponds to gaussian noise which is characterized by the standard deviation σ_{gauss}UI (Unit Interval); Fig. 2(b) refers to uniform noise with Dj_{pp}UI and sinusoidal noise described through Sj_{pp} which are the peak-peak amplitude of the distributions. For all cases, as noise level increases K_{PD} decreases in a nonlinear manner.

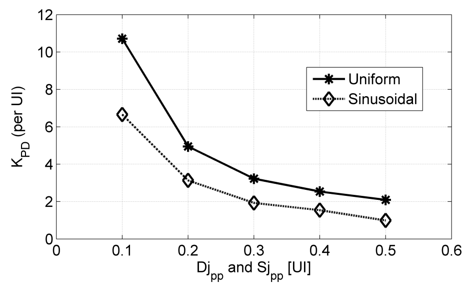
Several analyses have been performed to relate the gaussian and uniform jitter noise with the K_{PD} gain and are well summarized in references [8]–[10]. However, the nonlinear reduction for the sinusoidal case is not clearly reported in the literature. This paper shows and explains how the K_{PD} can increases even for higher values of incomming jitter or channel loss when the sinusoidal jitter is taking into account. In order to accomplish that, first of all, an extraction procedure that allows to extract the K_{PD} gain is implemented.

The diagram to accomplish the task of extracting K_{PD} are shown in Fig. 3. TX module represents the transmitter. This module contains a clocked pseudo-random binary sequence (PRBS) that can be programmable; in this work a PRBS-7 is used. The clock is generated by the *Clk* module and it is possible to select between clean or noisy clock through *Noise sources* routines. Then, random data is passed to the testing block composed by *Test for BBPD* a BBPD implementation and another *Clk* module. To perform time simulation of the procedure shown in Fig. 3 it is needed to select a proper time step. In order to accomplish this, it is suggested at

978-1-5090-0916-9/16/$31.00 ©2016 IEEE



(a)



(b)

Fig. 2. K_{PD} gain vs noise for: a) gaussian, b) uniform and sinusoidal case.

least an oversampling ratio (OSR) greater than 2. The *Test for BBPD* block takes the data and clock and stimulates the BBPD shifting the clock phase over all phases specified in the system. The output average is taken and saved to compute one point in the transfer curve of BBPD. The *Post-processing* block calculates the K_{PD} gain. The *Noise Sources* block allows to select among any of the three types of noise mentioned before in order to generate noisy clock signal.

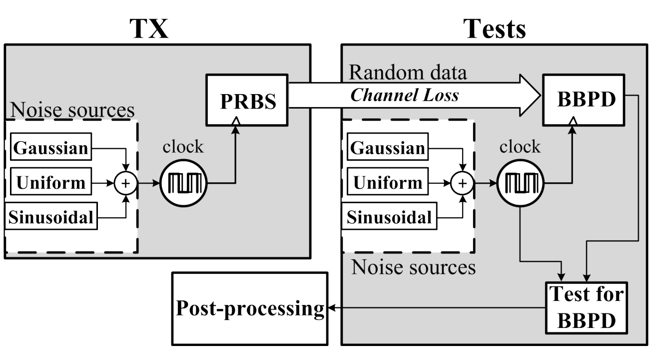


Fig. 3. General view of the implementation.

III. Impact of Channel Loss on K_{PD}

Channel loss is modelled with a simple linear first-order low pass filter. This filter is characterized by a DC gain equal to 1 and a cut frequency denoted by f_c. It is out of the scope of this work to make a more precise modelling of the channel, but the implementation of the linear filter is enough to extract some results related to the impact on the performance of CDR system. The magnitudes for input jitter noise used through the rest of the paper are reasonable values based on the jitter budgeting for the standard USB 3.1 [6].

A. Channel Loss with Gaussian Noise

Several cases are evaluated for different levels of gaussian jitter noise. Fig. 4 shows the behavior of K_{PD} as a function of the degraded input data. Data degradation is quantified as a relation between f_c of the channel loss representation and the data rate (Drate); denoted by $f_c/Drate$. In this test, Drate is equal to 10 Gb/s and $\sigma = [0.03, 0.04, 0.05]$UI. Simulations are performed using the extraction procedure of Section II.

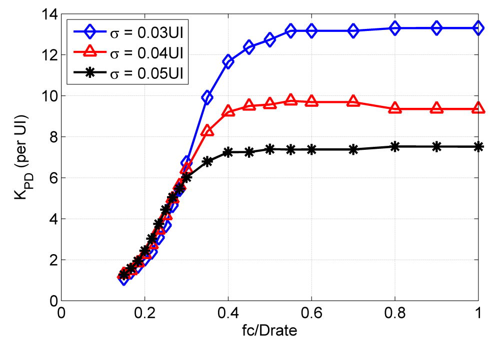


Fig. 4. K_{PD} dependence on $f_c/Drate$ taking into account gaussian jitter noise and channel loss.

The flat region in the curve corresponds to low channel losses and the K_{PD} values obtained in this region are different because of the different noise levels used. On the other hand, as the losses increase (low $f_c/Drate$) the gain obtained decreases due to the lots of transitions that are lost in the sampling process done by the BBPD, especially for frames of Nyquist data (10101...). For example, K_{PD} decreases from 11.5 per UI at $f_c = 4$GHz to only 2 per UI at $f_c = 2$GHz for a $\sigma = 0.03$UI noise level. However, for low levels of $f_c/Drate$ also it exists an increment of gain for high noise values. The explanation of this effect is postponed until subsection D, so far, it is enough to note that is due to the channel loss nature.

B. Channel Loss with Uniform Noise

Fig. 5 shows the simulation results when only the uniform noise is considered. In this case, the injected jitter levels are $Dj_{pp} = [0.3, 0.4, 0.5]$UI and Drate corresponds to 10 Gb/s. For low channel loss, it is observed that K_{PD} is higher for less injected noise; however, gain falls drastically when $fc/Drate \leq 0.25$ for all noise levels. Also, the gain is no longer higher for less noise; moreover, channel losses make this gain to be higher for higher injected noise in some cases. For example, $K_{PD} = 2.1$ per UI when $f_c/Drate = 0.18$ and $Dj_{pp} = 0.2$UI, but for the same $f_c/Drate$ and $Dj_{pp} = 0.3$UI, the gain has a little increment to 2.5 per UI. Thus, as in the gaussian case, the behavior of the gain for high levels of channel loss is not easy to predict.

2016 IEEE 59th International Midwest Symposium on Circuits and Systems (MWSCAS), 16-19 October 2016, Abu Dhabi, UAE

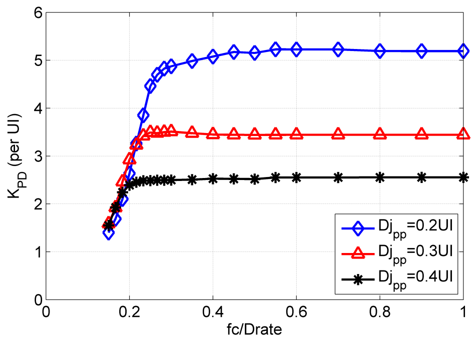


Fig. 5. K_{PD} dependence on $f_c/Drate$ taking into account uniform jitter noise and channel loss.

C. Channel Loss with Sinusoidal Noise

Fig. 6 shows simulation results for sinusoidal jitter noise. Here, the gain increases as the channel loss does, before the gain starts to fall, this is not evident from the behavior expected and is explicit shown in the peaks of the curves. Below some point, different for each noise level, the gain decreases considerably. Also, similar to gaussian and uniform noise, gain increases when the noise level injected is higher at low $f_c/Drate$ values.

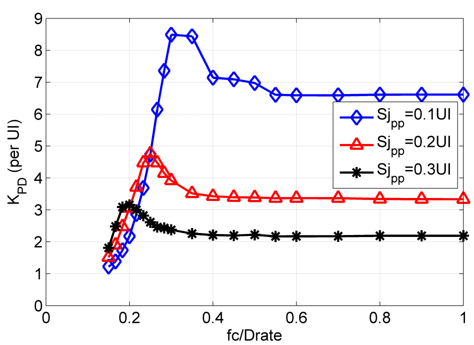


Fig. 6. K_{PD} dependence on $f_c/Drate$ taking into account sinusoidal jitter noise and channel loss.

The presence of these peaks when the channel losses increase is due to the nature of the sinusoidal jitter noise. Interesting explanation arises when the probability density function (PDF) of noise is studied. The convolution of the noise PDFs presented in the system allows to extract the K_{PD} in a theoretical manner [8]. The K_{PD} gain corresponds with the value of this convolution at 0 UI [3], [9]. Due to the asymptotic behavior in the tails of a sinusoidal PDF, the total convolution of all types of noise presented in the system shows an irregular behavior at 0 UI. For example, Fig. 7 presents the results obtained when sinusoidal and uniform noise are faced at same time, which is a first approach when sinusoidal jitter noise is injected to data corrupted by the channel losses. In this case, the sinusoidal jitter noise is fixed at $Sj_{pp} = 0.4$UI level and the uniform Dj_{pp} ranges from 0.2 to 0.5 UI; also, low R_j is added only for smoothing the curves. It is observed in the curves that represent the total convolution that K_{PD} increases even if uniform jitter is increased as it is shown for Dj_{pp} from 0.2 to 0.4 UI. This behavior is highlighted using an extra curve that takes the K_{PD} values from convolution and plot them as a function of uniform noise. Finally, at some point between 0.4 and 0.5UI the gain reaches its maximum and goes down. Therefore, the peaking of gain due to the increment of channel losses is due to the interaction between these losses and sinusoidal noise.

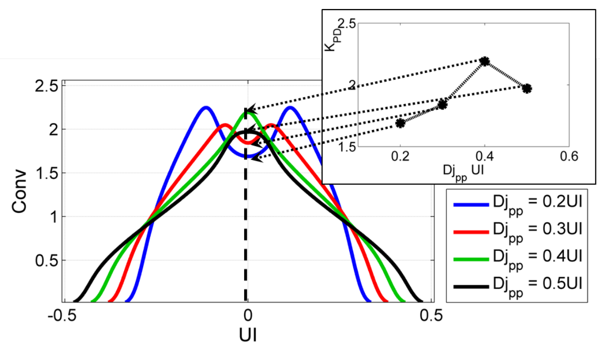


Fig. 7. Total convolution of PDFs fixing $Sj_{pp} = 0.4$ and $Rj = 0.02$. Upper-right plot indicates K_{PD} values as function of Dj_{pp}.

The unexpected behavior of K_{PD} for high channel losses with sinusoidal noise impacts on the dynamic of the system. Here, the case for $Sj_{pp} = 0.1$ UI presented in Fig. 6, is exercised for no channel loss and for $f_c/Drate = 0.35$ which correspond to the peaking in K_{PD}. Parameters others than K_{PD} in the model of Fig. 1 are taken from the 5 Gb/s experiment presented in [1]. The jitter transfer function (JTF) for the digital CDR model is:

$$J_{TF} = \frac{H_o}{1 + H_o}, \tag{2}$$

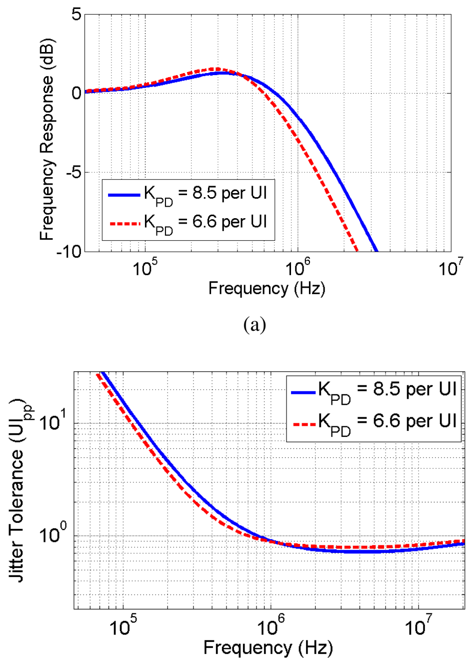
where H_o is the open loop gain given by the Eq. (1).

The results are presented in Fig. 8. In the first case, no channel losses are considered and the K_{PD} associated is 6.6 per UI (flat region in Fig. 6), producing a frequency response with a 1MHz bandwidth. In contrast, case for $f_c/Drate = 0.35$ produces a K_{PD} of 8.5 per UI and a bandwidth of 1.3 MHz approximately. These results show that even with more channel loss, the CDR bandwidth is higher, an unexpected result that is not reported in the literature. The jitter tolerance function (JTOL) is given by the following equation:

$$J_{TOL}(z) = \left| \frac{\gamma}{1 - J_{TF}(z)} \right|, \tag{3}$$

where γ is the timing margin in the data eye in terms of UI and J_{TF} is given by Eq. 2.

For high frequencies $JTOL$ is limited by γ margin and is related directly with the amount of noise; it is shown in Fig. 8(b) that for higher noise levels the margin is less. However, for low frequencies, the case that corresponds to higher sinusoidal noise presents a higher $JTOL$.



(a)

(b)

Fig. 8. Impact of channel loss reflected on a) JTF and b) JTOL.

D. Channel Loss Probability Density Function

Probability density function for channel losses is a type of deterministic noise, but modelling it with merely an uniform PDF does not allow to understand the another interesting behavior observed at low values of $f_c/Drate$ in Figs. 4, 5 and 6. For some low values of $f_c/Drate$ the channel loss seems to be dominant and the gain is higher even for greater injected noise. This phenomenon suggests that channel losses are not well modelled with an uniform distribution. For this reason, the actual PDF implemented here is extracted and added to the total convolution of PDFs in order to explain the results observed with time simulation measurements at low levels of $f_c/Drate$.

Time simulations are used to extract jitter noise due only for channel losses, then, a fitting procedure is made to obtain the PDF. To validate the correct model implemented, theoretical extraction of K_{PD} is contrasted with simulation results using the extraction procedure. For instance, Fig. 9 shows regions for low $f_c/Drate$ conditions using the gaussian case of Fig. 4. In this region, K_{PD} is no longer less for high injected noise. Using the extracted PDF for channel loss, total convolution includes this PDF and are added in the plot in order to show the correlation with the time simulations. Fig. 9 corresponds to gaussian noise plus channel loss, in this figure $f_c/Drate \approx 0.23$ was selected for explanation; this value corresponds to a set of three PDFs, one for each gaussian noise condition. Results presented by time simulations (left) are the same obtained with the convolution approach (right); thus, the model used for channel loss is better than use only uniform PDF and can explain the unexpected behavior for low levels.

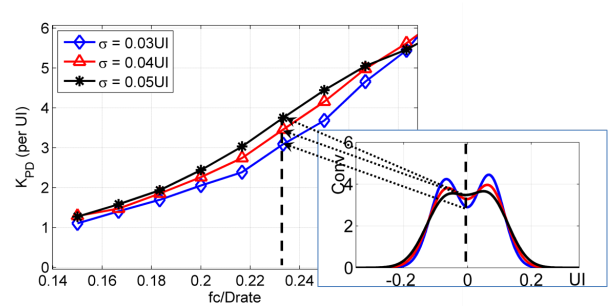


Fig. 9. Time simulations results vs convolution approach for gaussian noise at low $f_c/Drate$ levels. The $Conv$ graph in the right corresponds to the convolution of gaussian PDF and the extracted PDF at $f_c/Drate \approx 0.23$.

IV. Summary

An extraction procedure was used to get actual value of the K_{PD} under different conditions of incoming jitter and channel loss. Nonevident increasing in K_{PD} for some cases where the incoming jitter is increased too, is explained through the extraction and analysis of the PDF for channel loss. Also, an increment on K_{PD} where sinusoidal and uniform jitter are combined is explained and its impact on the CDR dynamic response is presented. As a final comment, maximum K_{PD} value is not always reached at 0UI and this suggests that for some conditions, phase sampling point of the data can be changed from 0 UI to the point where a maximum occurs, improving CDR response.

References

[1] L. Sonntag, J. Stonick, "A Digital Clock and Data Recovery Architecture for Multi-Gigabit/s Binary Links", IEEE J. Solid-State Circuits, VOL. 41, No. 8, Aug. 2006

[2] M. Talegaonkar, R. Inti and P. K. Hanumolu, "Digital clock and data recovery circuit design: Challenges and tradeoffs," 2011 IEEE Custom Integrated Circuits Conference (CICC), San Jose, CA, 2011, pp. 1-8.

[3] A. Zargaran-Yazd and W. T. Beyene, "Discrete-time modeling and simulation considerations for high-speed serial links," 2014 IEEE 23rd Conference on Electrical Performance of Electronic Packaging and Systems, Portland, OR, 2014, pp. 165-168.

[4] M. t. Hsieh and G. E. Sobelman, "Architectures for multi-gigabit wire-linked clock and data recovery," in IEEE Circuits and Systems Magazine, vol. 8, no. 4, pp. 45-57, Fourth Quarter 2008.

[5] B. Razavi, "Design of Integrated Circuits for Optical Communications", 2nd ed. Wiley, 2012.

[6] Universal Serial Bus 3.1 Specification. Revision 1.0, July 26, 2013

[7] Alan Blankman. Understanding SDAII Jitter Calculation Methods, White Paper, Sep. 2012 v 2.01

[8] Jri Lee, K. S. Kundert and B. Razavi, "Analysis and modeling of bang-bang clock and data recovery circuits," in IEEE Journal of Solid-State Circuits, vol. 39, no. 9, pp. 1571-1580, Sept. 2004.

[9] Jri Lee, K. S. Kundert and B. Razavi, "Modeling of jitter in bang-bang clock and data recovery circuits," Custom Integrated Circuits Conference, 2003. Proceedings of the IEEE 2003, 2003, pp. 711-714.

[10] Gabr, A.; Kwasniewski, T., "Unifying approach for jitter transfer analysis of bang-bang CDR circuits," Electronics and Information Engineering (ICEIE), 2010 International Conference On , vol.2, no., pp.V2-40,V2-44, 1-3 Aug. 2010