USB 3.0 Jitter Budgeting White Paper
Revision 0.5

Abstract

This document describes the methodology used to create the jitter budget for 5 Gb/s operation. The dual Dirac jitter model is introduced and the application of the model to the data channel is demonstrated. The effects of data scrambling on the channel jitter probability distribution is shown, and then is used to modify the channel jitter model by adding a random jitter component to the model. The system bit error ratio (BER) and jitter benefit of scrambling is demonstrated for USB SuperSpeed operation.

Introduction

The physical layer section (chapter 6) of the USB 3.0 specification defines the system jitter budget for SuperSpeed operation at 5 Gb/s. [1] This document describes the methodology used to create the budget, and shows how we use our knowledge of the characteristics of the jitter distribution of a channel over which scrambled data is transmitted to improve the performance of the system. We start by describing the system jitter model, the Dual Dirac model. We then show how the model applies to a typical high speed link. We then demonstrate how the jitter behavior of a data channel differs when carrying scrambled and non-scrambled data. Finally, we use our knowledge of the channel jitter behavior to modify the system jitter model in order to provide a more accurate jitter budget.

System Jitter Model

The jitter methodology for SuperSpeed USB follows the well known dual Dirac model. The model is described in more detail in references [2] and [3], so we offer a brief overview here. In the Dual Dirac model, the probability density function (PDF) of jitter for the system is described by equation (1)

$$JT(t) = RJ(t) * DJ(t) = \int_{-\infty}^{\infty} \left[\frac{1}{\sqrt{2\pi}\sigma_{RJ}} e^{-\frac{t^2}{2\sigma_{RJ}^2}} \right] \left[\frac{t - DJ_{\delta\delta}}{2} + \frac{t + DJ_{\delta\delta}}{2} \right] dt \qquad (1)$$

Where *JT(t)* is the total jitter PDF for the system

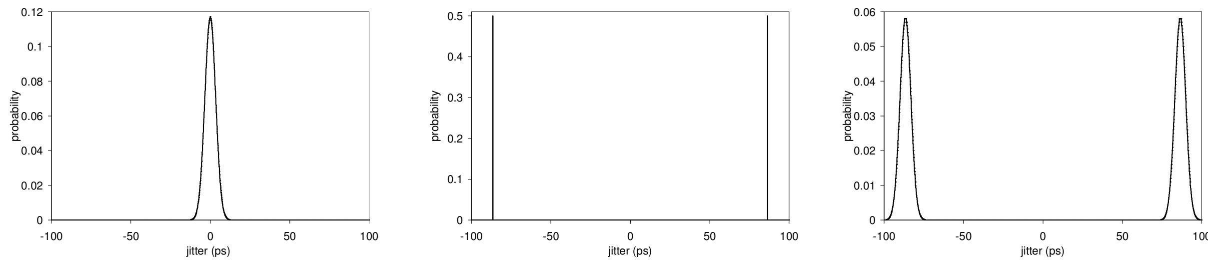
RJ(t) is the PDF for the random (Gaussian) jitter in the system

DJ(t) is the PDF for the deterministic (bounded) jitter in the system

σ_{RJ} is the root-mean-square (RMS) value of the RJ

$DJ_{\delta\delta}$ is the magnitude of the DJ when being described by a dual Dirac (delta) function

Essentially, *JT(t)* is the probability of having a jitter of magnitude *t*. The jitter is caused by both random (Gaussian) and deterministic (bounded) sources. The random jitter, RJ(t), is modeled by a normal distribution. The deterministic jitter, DJ(t), is modeled with a dual Dirac function, which as though it were distributed at the maximum values, as shown in Figure 1.



Random Jitter PDF σ_{RJ} = 3.422ps | Deterministic Jitter PDF $DJ_{\delta\delta}$ = 173ps | Total Jitter PDF σ_{RJ} = 3.422ps, $DJ_{\delta\delta}$ = 173ps

Figure 1. Dual Dirac model for system jitter PDFs

As mentioned above, this model is widely used in the industry. One example is described in reference [2].

SuperSpeed Jitter Budget

The jitter budget for USB SuperSpeed operation, taken from the USB 3.0 specification is shown in Table 1. The random jitter PDF for the system is constructed by convolving the individual random jitter PDFs. The RJ jitter sources are normally distributed with a zero mean. Since the individual PDFs are normally distributed with zero mean, the system RJ PDF will be, too. The expression for the system RJ PDF is

$$RJ(t) = \frac{1}{\sqrt{2\pi}\sigma_{System,rms}} e^{-\frac{t^2}{2\sigma^2_{Sysem,rms}}} \qquad (3)$$

where the RMS RJ for the system is

$$\sigma_{System,rms} = \sqrt{\sigma^2_{Tx,rms} + \sigma^2_{Channel,rms} + \sigma^2_{Rx,rms}} \qquad (2)$$

The deterministic jitter for the system is constructed by convolving the individual DJ PDFs. In this case, the individual PDFs are modeled with the dual Dirac distribution

$$DJ(t) = \frac{\delta\left(t - \frac{DJ_{\delta\delta}}{2}\right)}{2} + \frac{\delta\left(t + \frac{DJ_{\delta\delta}}{2}\right)}{2} \qquad (4)$$

where *δ(t)* is Dirac's delta function, $\delta(t) = \begin{cases} 0, t \neq 0 \\ 1, t = 0 \end{cases}$

Convolution of the individual PDFs is accomplished by adding the individual terms according the equation (5).

$$DJ_{\delta\delta,System} = DJ_{\delta\delta,Tx} + DJ_{\delta\delta,Channel} + DJ_{\delta\delta,Rx} \tag{5}$$

The budget in Table 1 was constructed using the method that we just described.

Table 1. SuperSpeed 5 Gb/s jitter budget

Jitter component	RJ[1,2]	DJ[3]	TJ[4]
Transmitter	2.42	41	75
Channel	2.13	45	75
Receiver	2.42	57	91
Total	4.03	143	200

Notes:

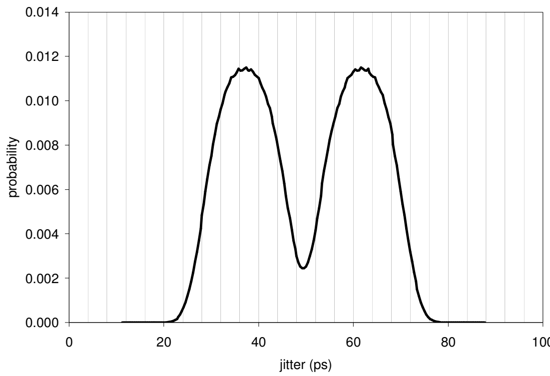
1. RJ is the sigma value assuming a Gaussian distribution.
2. Rj Total is computed as the Root Sum Square of the individual Rj components.
3. Dj budget uses the Dual Dirac method.
4. Tj at a 10^{-12} BER is calculated as 14.068 * RJ + DJ.

Channel Jitter & Data Scrambling

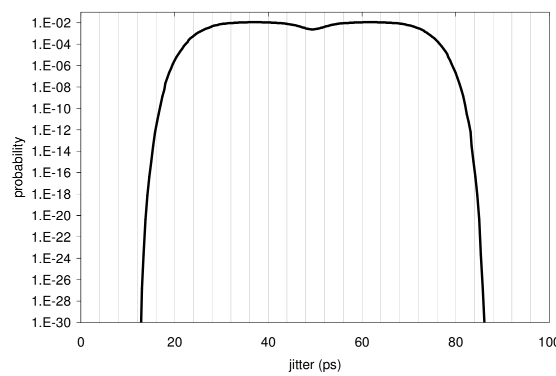
An unusual aspect of Table 1 is that it contains an entry for random jitter caused by the interconnect channel ($\sigma_{channel}$ = 2.13 ps). Typically, jitter budgets for high speed links include only deterministic channel jitter (i.e. $\sigma_{channel}$ is zero). Channel is modeled using DJ only for two reasons. First, it is truly deterministic, being dependent upon the data pattern being transmitted on the signal of interest, as well as on nearby signals that are coupled to it. Second, the worst case jitter, being dependent on the data pattern, can occur with high probability if the worst case data pattern tends to be repetitive.

However, with scrambling the channel jitter PDF tends to look more like the dual Dirac model, as Figure 2 shows. The figure was obtained via simulation with a representative SuperSpeed channel. The extremes of the PDF look Gaussian in nature, though as Figure 2(b) shows, the distribution is clearly bounded. As a result, we conclude that it is valid to model the channel jitter using both a DJ and an RJ component.

In order to illustrate the benefit the approach, we construct an alternate jitter budget in which we model the channel jitter as being composed solely of DJ. The budget is summarized in Table 2 , and it shows that with the DJ-only channel jitter model we would end up with a total jitter of 221 ps. In other words, the traditional (DJ-only) approach costs us 21 ps of margin when compared to the DJ+RJ approach that we use with USB SuperSpeed. This is also illustrated in Figure 3.



(a) Linear scale



(b) Log scale

Figure 2. Example USB channel jitter PDF

Table 2. 5 Gb/s jitter budget w/ non-scrambled data assumptions

Jitter component	RJ[1,2]	DJ[3]	TJ[4]
Transmitter	2.42	41	75
Channel	0	75	75
Receiver	2.42	57	91
Total	3.42	173	221

Notes:

1. RJ is the sigma value assuming a Gaussian distribution.
2. RJ Total is computed as the Root Sum Square of the individual Rj components.
3. DJ budget uses the Dual Dirac method.
4. TJ at a 10^{-12} BER is calculated as 14.068 * RJ + DJ.

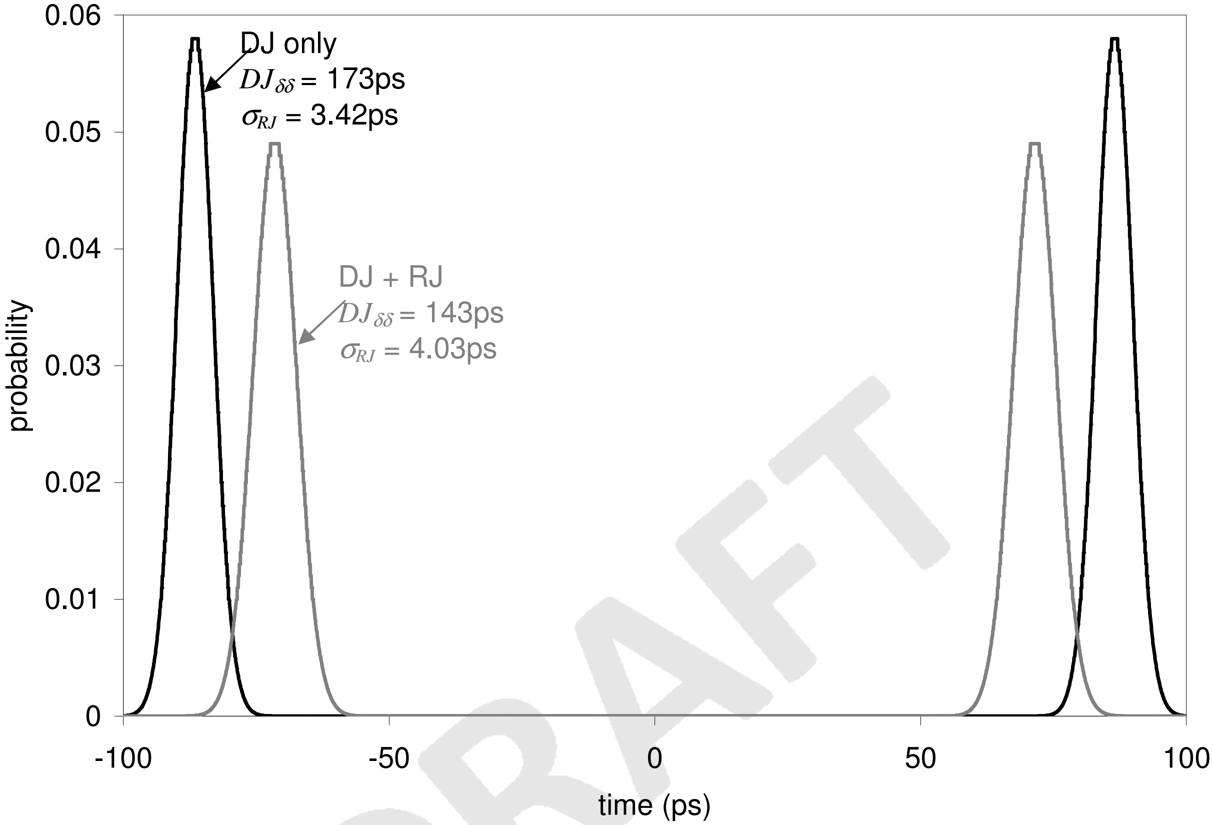


Figure 3. Comparison of channel jitter PDFs

We could also look at the impact on bit error ratio. We calculate the BER for the leading and trailing edges of the data eye using equations (6) and (7). The BER "bathtub" plots for both cases are plotted in Figure 4. We can interpret the figure in two ways. First, we can see that the BER rate that we obtain using the budget in Table 2 is between 10^{-4} and 10^{-5}, which is far short of the target BER (10^{-12}). On the other hand, the BER for the budget in Table 1 is projected to meet the target of 10^{-12}.

The second way in which we can interpret the plot is to look at the margin at the target BER. From the plot, we see that the leading and trailing edge curves of the bathtub plot for the RJ+DJ case intersect at the target BER, from which we conclude that there is zero margin. The curves for the DJ only case show a margin deficit of 21ps. Either way of looking at the BER curves demonstrates the benefit of our SuperSpeed approach.

$$BER_{lead}(t) = 0.5\left[erfc\left(\frac{t - \frac{DJ_{\delta\delta}}{2}}{\sqrt{2}\sigma_{RJ}} \right) + erfc\left(\frac{t + \frac{DJ_{\delta\delta}}{2}}{\sqrt{2}\sigma_{RJ}} \right) \right] \qquad (6)$$

$$BER_{trail}(t) = 0.5\left[erfc\left(\frac{UI - t - \frac{DJ_{\delta\delta}}{2}}{\sqrt{2}\sigma_{RJ}} \right) + erfc\left(\frac{UI - t + \frac{DJ_{\delta\delta}}{2}}{\sqrt{2}\sigma_{RJ}} \right) \right] \quad (7)$$

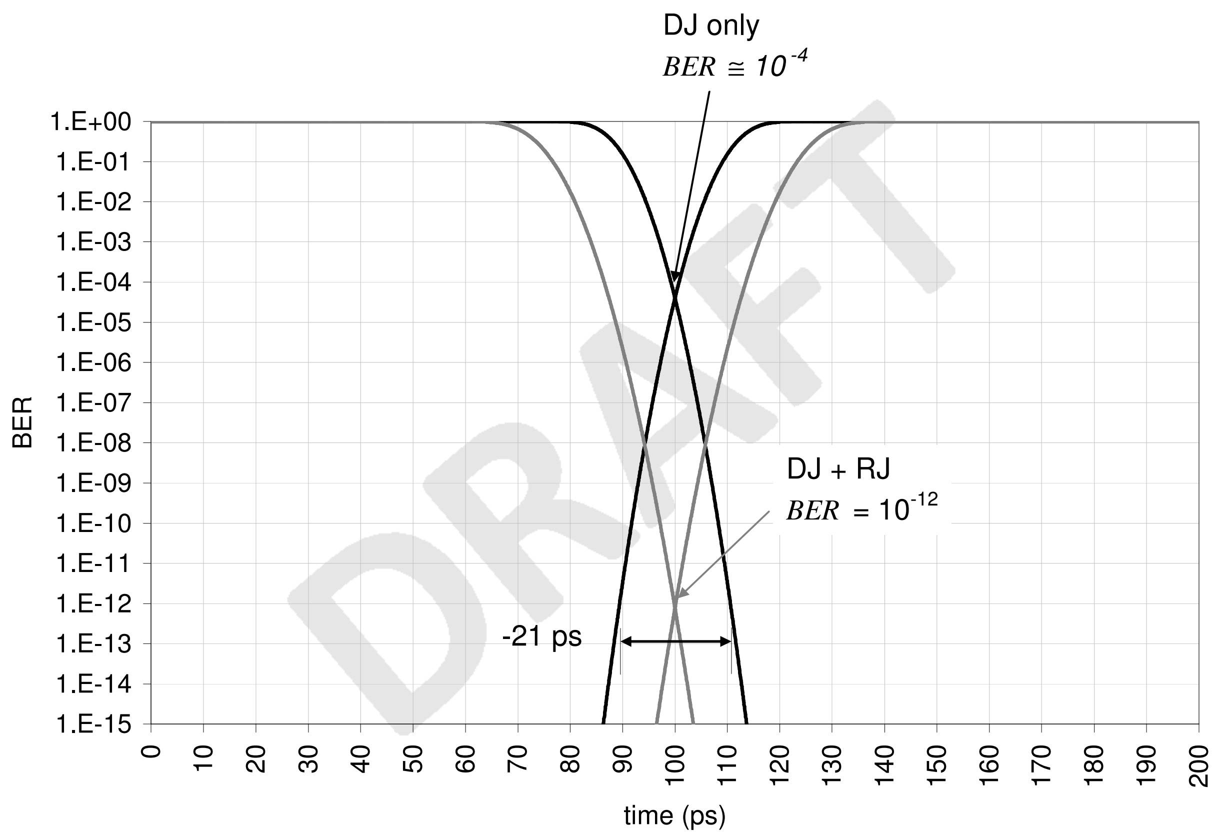


Figure 4. BER Comparison

Conclusion

In this paper, we have described the jitter budgeting method used for SuperSpeed USB. Data scrambling allows us to model the channel jitter PDF as a true dual Dirac distribution, thereby improving the system jitter margin.

Related Documents

1. *Universal Serial Bus 3.0 Specification, revision 1.0.*
2. *PCI Express™ Jitter and Bit Error Rates*, Revision 1.0, PCI-SIG, February 11, 2005.

3. *Jitter Analysis: The dual-Dirac Model, RJ/DJ, and Q-Scale*, Agilent Technologies, doc. no. 5989-3206EN, December 31, 2004.