Application Note:

HFAN-3.0.2

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Optical Receiver Performance Evaluation

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1 Introduction

In an optical transmission system, one essential parameter in determining the system power budget is the optical receiver sensitivity, which is defined as the minimum average optical power for a given bit-error-rate (BER). To make a good optical receiver design, it is critical to understand the different parameters that will cause impairments in the overall receiver sensitivity. This application note provides an in-depth analysis of the complete receiver optical sensitivity and the potential power penalties related to the accumulation of random noise and inter-symbol interference (ISI) in both amplitude and timing. The analysis is based on normal receiver sensitivity assuming an ideal input signal with negligible impairment such as ISI, rise/fall time, jitter, and transmitter relative intensity noise (RIN).

2 Q-factor in the presence of ISI

A typical optical receiver is composed of an optical photo detector, a transimpedance amplifier, a limiting amplifier, and a clock data recovery block. The simplified optical receiver model is shown in Figure 1.

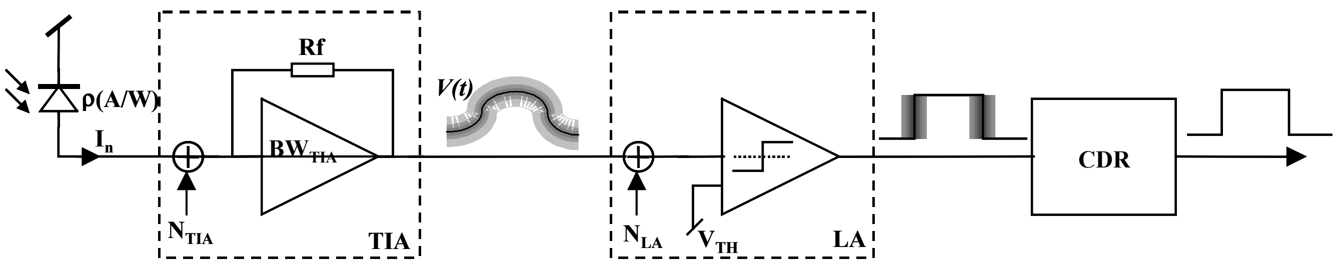

Figure 1. Optical Receiver Model

The received optical signal is first converted into photocurrent and amplified by the transimpedance amplifier (TIA). The limiting amplifier performs as a decision circuit where the sampled voltage $v(t)$ is compared with the decision threshold V_{TH}. At this data decision point, the signal is significantly degraded by the accumulation of random noise and inter-symbol interference, resulting in erroneous decisions due to eye closure.

To know the relationship between BER and eye opening at data decision, the statistical characteristics of the amplitude noise needs to be determined. Usually, as a figure of merit, we use signal Q-factor as a way of measuring the signal quality for determining the BER. If the ISI distortion does not exist, and the dominant amplitude noise has Gaussian distribution, the signal Q-factor is defined as:

$$Q = \frac{V_1 - V_0}{\sigma_1 + \sigma_0} \qquad (1)$$

Here V_1, V_0 are the mean values for $v(t)$ amplitude high and low without ISI, and σ_1, σ_0 are the root-mean-square(rms) of the additive white noise for each Gaussian distribution. For a detailed description please refer to Maxim application note, *HFAN-09.0.2-Optical Signal-to-Noise Ratio and the Q-factor in Fiber-Optic Communications Systems.*

In a practical receiver implementation, ISI exists due to the receiver bandwidth limitation, baseline wander, or non-linearity of the active components. If we monitor the signal eye diagram before the data decision, we find that, in addition to random noise, the signal has a certain amount of bounded amplitude fluctuation caused by ISI, which exhibits strong pattern dependence. To estimate the ISI penalty on optical sensitivity, a simple solution is to consider a worst case amplitude noise distribution. This is done by shifting the mean value of the Gaussian distribution from V_1 and V_0 to the lower amplitude boundary (V_1-V_{ISI}) and (V_0+V_{ISI}) separately, assuming V_{ISI} is the vertical eye closure caused by ISI (refer to Figure 2).

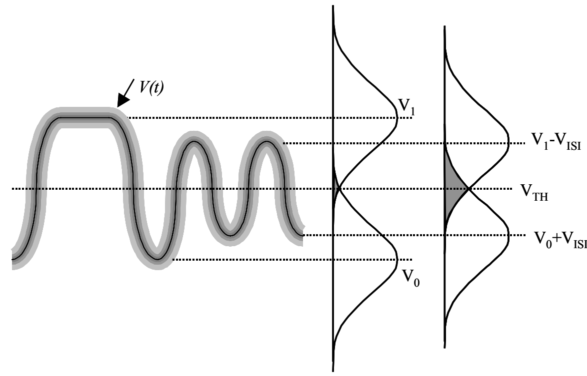

Figure 2. Worst case amplitude noise distribution in the presence of ISI

Under this condition, the signal Q-factor can be obtained by calculating the BER from the worst case noise distribution. The detailed calculation is described in the appendix at the end of this application note. Assuming the decision threshold is optimized for minimum BER, the Q-factor is related to vertical eye closure V_{ISI} as given below:

$$Q = \frac{V_1 - V_o - 2 \times V_{ISI}}{\sigma_0 + \sigma_1} \qquad (2)$$

and $$BER = \frac{1}{2} erfc(\frac{Q_{BER}}{\sqrt{2}}) \qquad (3)$$

Where $$erfc(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-v^2} dv$$

Q_{BER} is the minimum required Q-factor for a given BER. Based on equation (3), the relationship between Q_{BER} and BER is plotted in Figure 3.

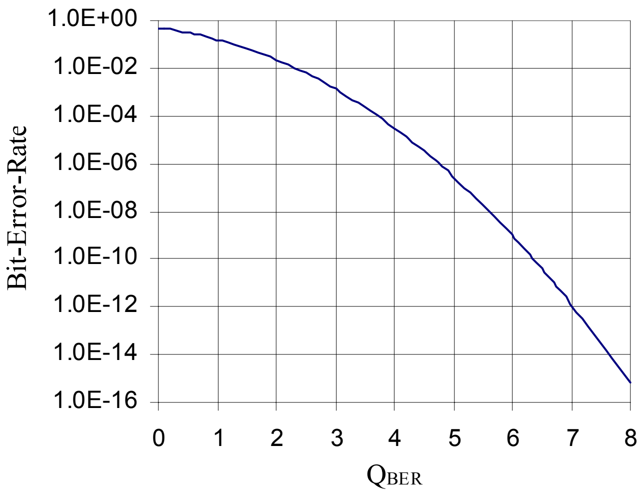

Figure 3. Bit-Error-Rate versus Q_{BER}

Usually we measure the signal peak-to-peak differential swing ($V_{p-p} = V_1 - V_0$) in the lab, and assume $\sigma_1 = \sigma_0 = N_{rms}$, the Q-factor becomes:

$$Q = \frac{V_{p-p} - 2\times V_{ISI}}{2\times N_{rms}} \tag{4}$$

Here N_{rms} is the equivalent rms noise at the input of the limiting amplifier. Equation 4 demonstrates that Q-factor is a measure of the vertical eye opening to rms noise ratio in the presence of ISI. The Q-factor reduction due to ISI will cause optical power penalty or error floor in an optical receiver design.

3 Optical Sensitivity Estimation

To achieve the best optical sensitivity, it is important to maximize the signal Q-factor before data decision. This section demonstrates how to accurately estimate the receiver optical sensitivity with practical device implementations, when overall receiver random noise, ISI, and CDR jitter tolerance are taken into account. Examples are given for both a 10Gbps receiver and a 2.5Gbps receiver using Maxim devices.

3.1 Overall Receiver rms Noise Penalty

To estimate the receiver total rms noise impact on the optical sensitivity, we need to know the minimum required peak-to-peak current at the TIA input (noted as I_{p-p}) that will result in a specified BER. For this random noise analysis it is assumed V_{ISI}=0, and I_{p-p} can be obtained by substituting $V_{p-p} = I_{p-p} \times R_f$ and $N_{rms} = N_{total} \times R_f$ in equation (4):

$$I_{p-p} = 2\times Q_{BER} \times N_{total}\,(\mu A_{rms}) \tag{5}$$

N_{total} is the total equivalent rms noise at TIA input, which is determined by the TIA input referred noise N_{TIA}(uA_{rms}), the limiting amplifier input referred noise N_{LA} (mV_{rms}), and the TIA small signal transimpedance gain R_f (kΩ). The relationship is shown as follows:

$$N_{total} = \sqrt{N_{TIA}{}^2 + (\frac{N_{LA}}{R_f})^2} \tag{6}$$

In practice, the limiting amplifier (LA) input referred noise may not be given, but N_{LA} can be estimated from the limiting amplifier input sensitivity V_{LA}, which is a measure of the minimum differential peak-to-peak signal swing to achieve a given BER. In general, the limiting amplifier sensitivity could result from the input referred noise N_{LA}, DC-offset, or ISI due to bandwidth limitation. However, since most limiting amplifiers will implement a DC-offset cancellation loop for high sensitivity, and the small signal bandwidth is usually much higher than that of the TIA, we can assume that the random noise is the dominant factor for limiting amplifier sensitivity. Under this condition N_{LA} can be estimated from the following equation:

$$N_{LA} = \frac{V_{LA}}{2\times Q_{BER}} \tag{7}$$

According to Figure 3, Q_{BER}=7 for BER=10^{-12}. Assuming ρ is the photo detector responsivity (A/W), r_e is the extinction ratio of the received optical signal, the optical modulation amplitude (OMA) is obtained as:

$$OMA = \frac{I_{p-p}}{\rho}(\mu W) \quad (8)$$

Optical sensitivity is given by:

$$P_{ave}(dBm) = 10\log\left(\frac{OMA}{2\times 1000}\times\frac{r_e+1}{r_e-1}\right) \quad (9)$$

For example, the MAX3970, MAX3910, and MAX3912 are 10Gbps TIA ICs, with typical input-referred noise of $1.1\mu A_{rms}$, but with different transimpedance gain. When each of these devices is used in conjunction with the limiting amplifier with different sensitivity, the achieved optical sensitivity of the complete receiver will be different. Assuming ρ=0.85A/W and r_e=6.6 (SONET minimum extinction ratio requirement), the calculated optical sensitivity is shown in Figure 4.

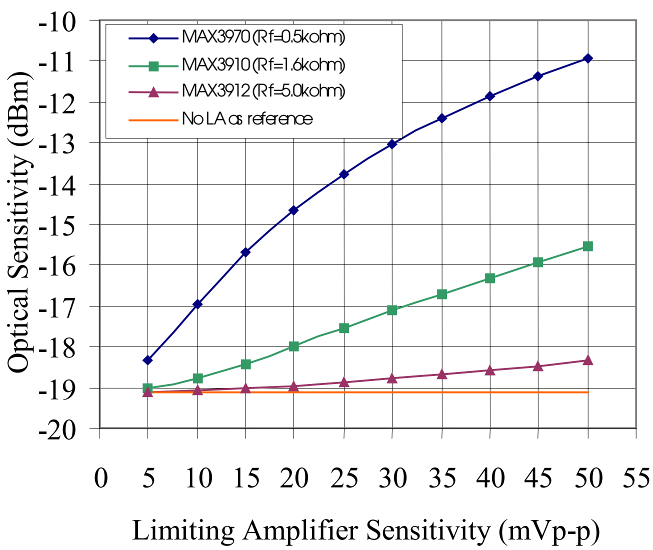

Figure 4. 10Gbps Receiver Optical Sensitivity

If we use the optical sensitivity obtained from the TIA input referred noise as a reference without a LA, the optical power penalty caused by total receiver random noise is the difference between the reference and the combination of TIA with limiting amplifier. For example, the MAX3971 is a 10Gbps limiting amplifier with input sensitivity of 9.5mVp-p for BER≤10^{-12}. When the MAX3970 TIA is used together with MAX3971, the optical power penalty is about 2.1dB. However, when MAX3912 TIA is used with MAX3971, the optical penalty is only 0.03dB.

Another example is the 2.5Gbps SFP receiver module, which consists of an optical photo detector, a 2.5Gbps TIA followed by a limiting amplifier. For this application, Maxim provides a series of TIA ICs such as MAX3267, MAX3271, MAX3275, MAX3277, and MAX3864. Figure 5 shows the optical sensitivity for MAX3267 (N_{TIA}=0.495µArms, R_f=1.9kΩ), MAX3864 (N_{TIA}=0.49µArms, R_f=2.75kΩ) and MAX3277 (N_{TIA}=0.3µArms, R_f=3.3kΩ), when each of these devices is used together with a limiting amplifier with different sensitivity.

Choices for 2.5Gbps limiting amplifiers are MAX3265, MAX3269, MAX3272, MAX3765, MAX3861 and MAX3748. The user can choose different TIA and limiting amplifier combinations for use in different SFP modules, depending on performance, cost or package.

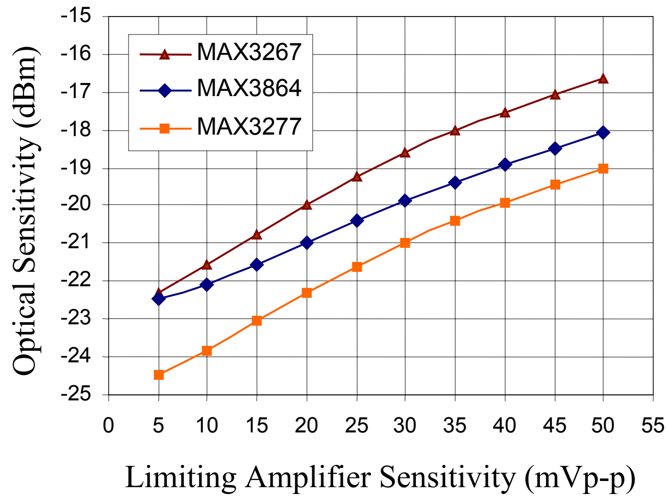

Figure 5. 2.5Gbps Receiver Optical Sensitivity

3.2 Inter-Symbol Interference Penalty

In an optical receiver, ISI can result from the following sources: high frequency bandwidth limitation, insufficient low frequency cutoff caused by AC-coupling or DC-offset cancellation loop, in-band gain flatness, or multiple reflection between the interconnection of TIA and limiting amplifier. Depending on the nature of the data pattern being received (e.g. PRBS 2^{31}-1, K28.5, 8B/10B encoding), the ISI distortion could be different. ISI will result in eye closure in both amplitude and timing.

If we define the ISI due to vertical eye closure as:

$$ISI = \frac{2 \times V_{ISI}}{V_{p-p}} \tag{10}$$

The minimum required TIA input current is related to ISI according to:

$$I_{p-p} = \frac{2 \times Q_{BER} \times N_{total}}{(1 - ISI)} \tag{11}$$

The ISI penalty is defined as the difference in optical sensitivity in the presence of ISI, as compared to an ideal case when ISI=0. The calculation result is shown in Figure 6. The optical power penalty is 0.46dB for 10% ISI distortion.

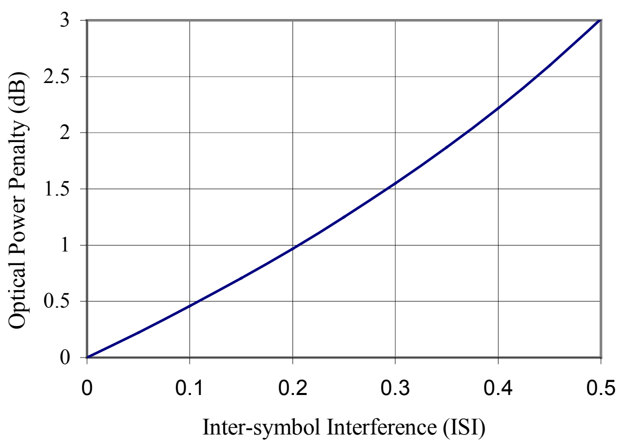

Figure 6. Optical power penalty caused by ISI

Finally, the total optical power penalty in dB is the sum of the ISI penalty and the overall random noise penalty.

3.3 CDR Jitter Tolerance Penalty

As the signal goes through the receiver amplifier chain to the limiting stage, the amplitude noise is converted into timing jitter at the data midpoint crossing. Random jitter and deterministic jitter are generated due to the existence of random noise, limited bandwidth, pass-band ripple, group delay variation, AC-coupling, and non-symmetrical rise/fall times. The combination of these jitter components decreases the eye opening available for error-free data recovery. Therefore, the CDR jitter tolerance capability is another critical factor for determining the optical sensitivity.

The CDR jitter tolerance is a measure of how much peak-to-peak jitter can be added to the incoming data before causing errors due to misalignment of the data and recovered clock. For a PLL based CDR design, a minimum data eye opening is required, which is determined by the clock to data sampling position, the retiming Flip-Flop setup/hold times and the phase detector characteristics. Assuming the random jitter is RJ_{rms}, the total deterministic jitter is DJ_{p-p}, and the CDR minimum required eye opening is T_{OPEN} at a specified BER, then the timing Q-factor is defined as:

$$Q = \frac{T_b - T_{open} - DJ_{p-p}}{2 \times RJ_{rms}} \tag{12}$$

$$RJ_{p-p} = 2Q_{BER} \text{ x } RJ_{rms} \tag{13}$$

See HFAN-04.0.2 Converting between RMS and Peak-to-Peak Jitter at a Specified BER.

The relationship between the CDR minimum eye opening requirement and the Q-factor is illustrated in Figure 7. To achieve a specified BER, the corresponding minimum Q_{BER} can be found from Figure 3.

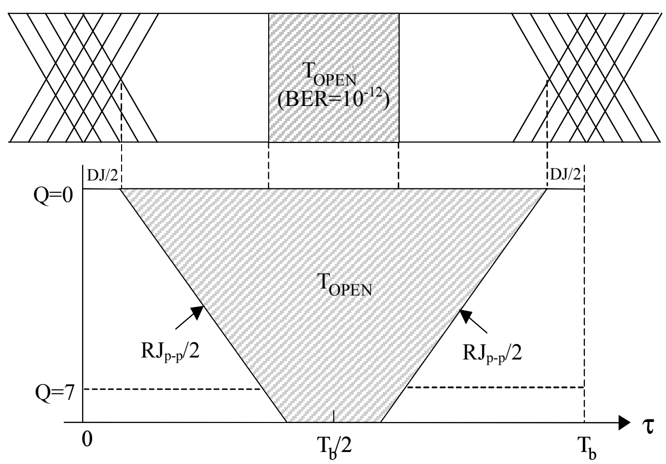

Figure 7. CDR minimum eye opening and Q-factor

When the jitter frequency at the CDR input is higher than the PLL bandwidth, the CDR jitter tolerance (noted as JT_{p-p}) is related to T_{OPEN} as:

$$JT_{p-p} = (T_b - T_{OPEN}) \tag{13}$$

To avoid degrading the optical sensitivity, the CDR high frequency jitter tolerance should satisfy:

$$JT_{p-p} \geq 2 \times Q_{BER} \times RJ_{rms} + DJ_{p-p} \quad (14)$$

The random jitter RJ_{rms} is generated from the additive white noise at signal transitions, depending on the slope of the edge transition. Assuming the signal rise/fall time (20% to 80%) before limiting is symmetrical and equal to t_r, the random jitter can be estimated by:

$$RJ_{rms} = \frac{t_r}{(V_{p-p} / N_{rms}) \times 0.6} \quad (15)$$

Here t_r is dependent on the overall receiver small signal bandwidth BW_{total}. Assuming a first order low pass filter:

$$t_r \approx \frac{0.22}{BW_{total}} \quad (16)$$

At the optical receiver input, it is assumed that the TIA is linear before the limiting amplifier. Therefore the random jitter can be expressed as a function of the peak-to-peak current to the total rms noise ratio at TIA input:

$$RJ_{rms} = \frac{t_r}{(I_{p-p} / N_{total}) \times 0.6} \quad (17)$$

Using Equation 17, the random jitter at the limiting amplifier output is plotted in Figure 8 as a function of TIA input current to noise ratio.

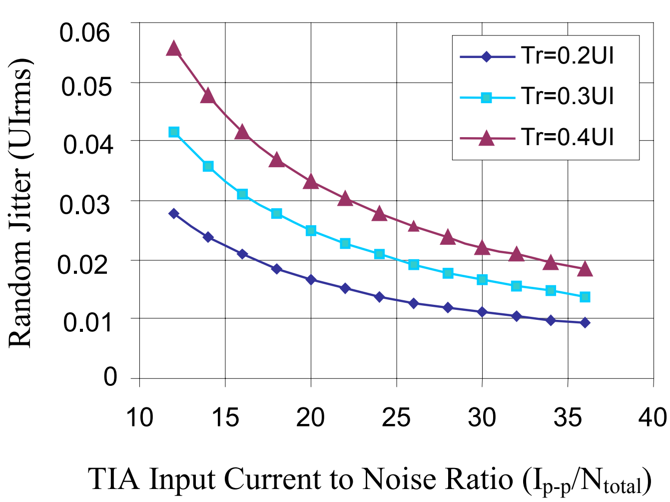

Figure 8. Random jitter for different input current to noise ratio

The CDR jitter tolerance penalty on optical sensitivity can be estimated by combining Equations 14 and 17, then solving for I_{p-p} as follows:

$$I_{p-p} = \frac{2 \times Q_{BER} \times t_r}{(JT_{p-p} - DJ_{p-p}) \times 0.6 / N_{total}} \quad (18)$$

Again we take the OC-192 receiver as an example: assuming ρ=0.85A/W, r_e=6.6, the total receiver small signal bandwidth is 7.0GHz, N_{total}=1.1uA$_{rms}$, and ISI=0. Figure 9 shows the achievable optical sensitivity with different CDR jitter tolerance (BER=10^{-12}).

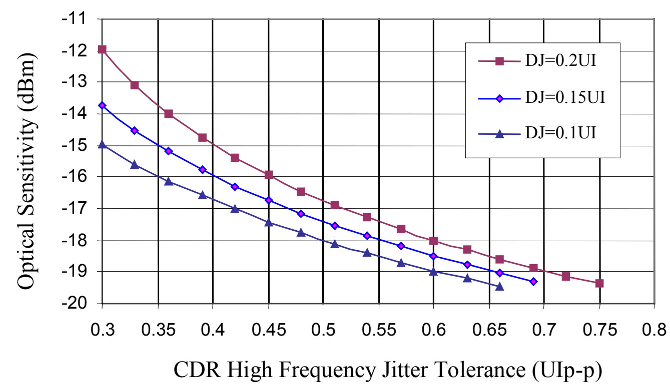

Figure 9. Optical sensitivity versus CDR jitter tolerance

In general, to achieve a specified BER, the minimum TIA input current should satisfy the Q_{BER} in both amplitude and timing.

4 Conclusion

In order to estimate optical receiver sensitivity, it is necessary to consider error sources in both amplitude and timing. This application note shows how the amplitude and timing error sources separately affect the overall receiver BER with practical device implementations. Optical Receiver performance can now be accurately predicted using these guidelines to choose the proper TIA, Limiting Amplifier and CDR. In reality, the optical input will not be an ideal signal since it suffers the random noise from transmitter, as well as ISI from fiber dispersion. When a stressed optical signal is received, the same approach presented in this paper can be used for estimating the signal Q-factor and therefore determine the bit-error-rate.

A Appendix

In Figure 2, assuming the amplitude noise for making an erroneous decision is additive white noise, the probability density function for *v(t)* can be mathematically described as:

$$P(v) = \frac{1}{\sqrt{2\pi}} \cdot \frac{1}{\sigma_1} \cdot e^{-\left[\frac{(v-V_1)^2}{2\sigma_1^2}\right]} \quad \text{(A1)}$$

$$P(v) = \frac{1}{\sqrt{2\pi}} \cdot \frac{1}{\sigma_0} \cdot e^{-\left[\frac{(v-V_0)^2}{2\sigma_0^2}\right]} \quad \text{(A2)}$$

Here V_1, V_0 are the mean value for *v(t)* amplitude high and low, and σ_1, σ_0 are the root-mean-square (rms) of the white noise for each Gaussian distribution.

In the presence of ISI, it is assumed that the amplitude noise distribution is a superposition of the Gaussian distribution. For simple analysis, a worst case noise distribution is considered: If V_{ISI} represents the amplitude reduction due to ISI, then the mean value of the amplitude noise distribution is shifted at $(V_1\text{-}V_{ISI})$ and (V_0+V_{ISI}) respectively:

$$P(v) = \frac{1}{\sqrt{2\pi}} \cdot \frac{1}{\sigma_1} \cdot e^{-\left[\frac{[(v-(V_1-V_{ISI})]^2}{2\sigma_1^2}\right]} \quad \text{(A3)}$$

$$P(v) = \frac{1}{\sqrt{2\pi}} \cdot \frac{1}{\sigma_0} \cdot e^{-\left[\frac{(v-(V_0+V_{ISI}))^2}{2\sigma_0^2}\right]} \quad \text{(A4)}$$

BER is obtained by integrating the area of the tails of the noise distribution in Figure 2, assuming the probability of transmitting 1's and 0's are equal.

Let: $$erfc(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-x^2} dx$$

$$BER = \frac{1}{4}\left[erfc\left(\frac{(V_1 - V_{ISI}) - V_{TH}}{\sqrt{2}\sigma_1}\right) + erfc\left(\frac{V_{TH} - (V_0 + V_{ISI})}{\sqrt{2}\sigma_0}\right)\right]$$

(A5)

Assuming the decision threshold V_{TH} is optimized to minimize the BER, which gives:

$$\frac{(V_1 - V_{ISI}) - V_{TH}}{\sigma_1} = \frac{V_{TH} - (V_0 + V_{ISI})}{\sigma_0} \quad \text{(A6)}$$

Where:

$$V_{TH} = \frac{(V_1 - V_{ISI}) \times \sigma_0 + (V_0 + V_{ISI}) \times \sigma_1}{\sigma_1 + \sigma_0} \quad \text{(A7)}$$

When substituting equation (A7) into equation (A5), BER becomes:

$$BER = \frac{1}{2} erfc(\frac{V_1 - V_0 - 2\times V_{ISI}}{\sqrt{2}(\sigma_1 + \sigma_0)}) \quad \text{(A8)}$$

Signal Q-factor is defined as:

$$Q = \frac{V_1 - V_o - 2\times V_{ISI}}{\sigma_0 + \sigma_1} \quad \text{(A9)}$$