

Optical receiver performance evaluation

An essential parameter in determining the system power budget in an optical transmission system is optical receiver sensitivity, defined as the minimum average optical power for a given bit-error rate (BER). When designing a good optical receiver, it is critical to understand the different parameters that will impair overall receiver sensitivity. This article provides an in-depth analysis of complete receiver optical sensitivity and the potential power penalties related to the accumulation of random noise and intersymbol interference (ISI) in both amplitude and timing. The analysis is based on normal receiver sensitivity, assuming an ideal input signal with negligible impairment from factors like ISI, rise/fall time, jitter, and transmitter relative intensity noise (RIN).

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**.

The received optical signal is first converted into photocurrent and amplified by the transimpedance amplifier (TIA). The limiting amplifier acts 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 ISI, 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 need to be determined. Usually, as a figure of merit, we use signal Q-factor to measure 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:

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

Here V_1, V_0 are the mean values for $v(t)$ amplitude high and low without ISI, while 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 the MAXIM® application note, *HFAN-09.0.2 Optical Signal-to-Noise Ratio and the Q-factor in Fiber-Optic Communications Systems*. (www.maxim-ic.com/AN985)

In a practical receiver implementation, ISI exists due to receiver bandwidth limitation, baseline wander, or nonlinearity 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 separately 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 ($V_0 + V_{ISI}$). It is assumed that V_{ISI} is the vertical eye closure caused by ISI (**Figure 2**).

Under this condition, the signal Q-factor can be obtained by calculating the BER from the worst-case noise distribution. Assuming the decision threshold is optimized for minimum BER, the Q-factor is related to vertical eye closure V_{ISI} as follows:

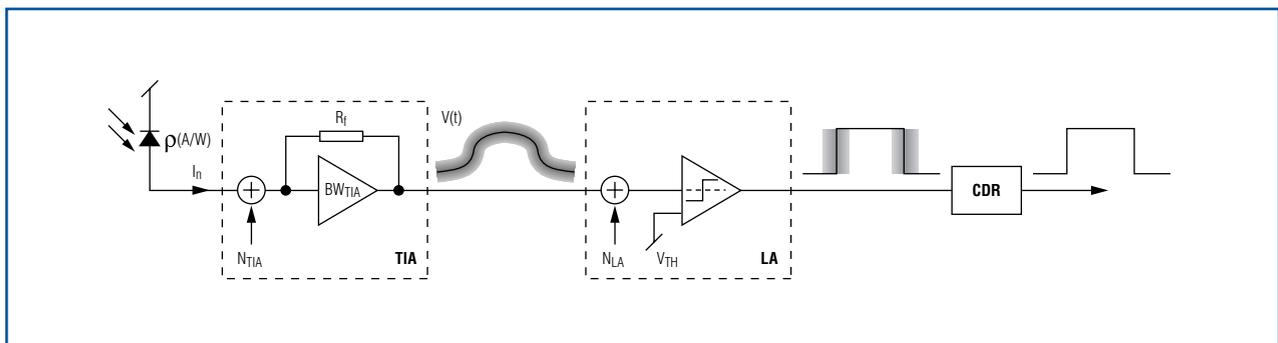


Figure 1. This diagram illustrates a simplified optical receiver model.

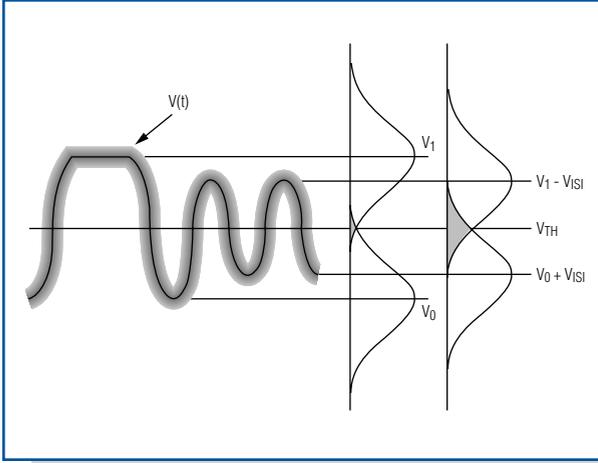


Figure 2. Worst-case amplitude-noise distribution in the presence of ISI facilitates estimation of the ISI penalty on optical sensitivity.

$$Q = \frac{V_1 - V_0 - 2 \times V_{ISI}}{\sigma_1 + \sigma_0} \quad (\text{Eq 2})$$

$$\text{BER} = \frac{1}{2} \text{erfc} \left(\frac{Q_{\text{BER}}}{\sqrt{2}} \right) \quad (\text{Eq 3})$$

Where:

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

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**.

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

$$Q = \frac{V_{P-P} - 2 \times V_{ISI}}{2 \times N_{\text{RMS}}} \quad (\text{Eq 4})$$

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 causes optical power penalty or error floor in an optical receiver design.

Optical sensitivity estimation

To achieve the best optical sensitivity, it is important to maximize the signal Q-factor before data decision. The following 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.

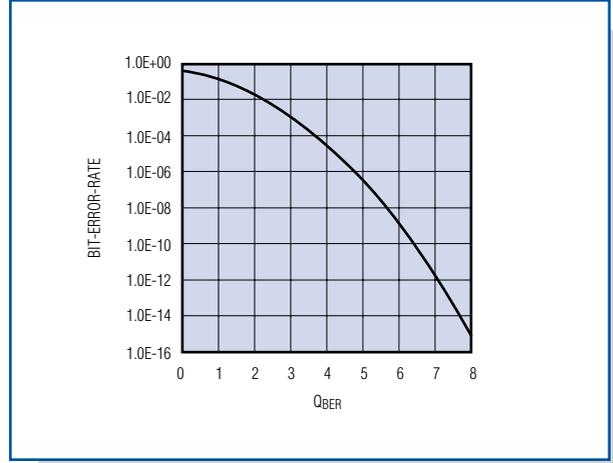


Figure 3. BER vs. Q_{BER} is plotted based on equation 3.

Overall receiver RMS noise penalty

To estimate the receiver total RMS noise impact on optical sensitivity, we must 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 $V_{\text{ISI}} = 0$, and I_{P-P} can be obtained by substituting $V_{P-P} = I_{P-P} \times R_f$ and $N_{\text{RMS}} = N_{\text{TOTAL}} \times R_f$ in equation 4, resulting in:

$$I_{P-P} = 2 \times Q_{\text{BER}} \times N_{\text{TOTAL}} (\mu\text{A}_{\text{RMS}}) \quad (\text{Eq 5})$$

N_{TOTAL} is the total equivalent RMS noise at TIA input, which is determined by the TIA input-referred noise N_{TIA} (μA_{RMS}), the limiting-amplifier input-referred noise N_{LA} (mV_{RMS}), and the TIA small-signal transimpedance gain R_f ($\text{k}\Omega$). The relationship is shown as:

$$N_{\text{TOTAL}} = \sqrt{N_{\text{TIA}}^2 + \left(\frac{N_{\text{LA}}}{R_f} \right)^2} \quad (\text{Eq 6})$$

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} , 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 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:

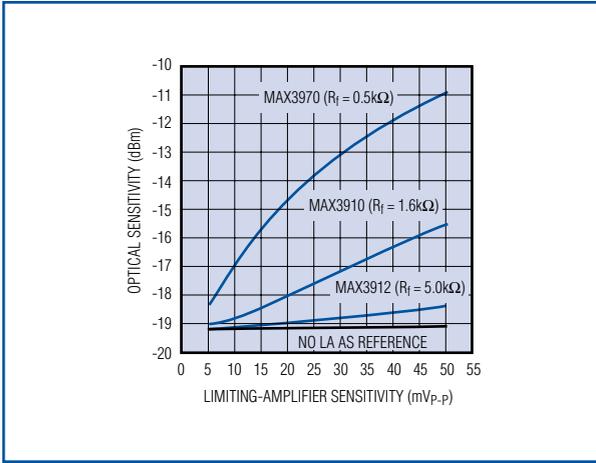


Figure 4. Receiver optical sensitivity is shown for 10Gbps TIA ICs, assuming the SONET minimum extinction-ratio requirement.

$$N_{LA} = \frac{V_{LA}}{2 \times Q_{BER}} \quad (\text{Eq 7})$$

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

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

Optical sensitivity is given by:

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

The MAX3970, MAX3910, and MAX3912, for example, 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 a limiting amplifier of different sensitivities, the achieved optical sensitivity of the complete receiver differs. Assuming $\rho = 0.85 A/W$ and $r_e = 6.6$ (SONET minimum extinction-ratio requirement), the calculated optical sensitivity is shown in **Figure 4**.

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 $9.5 mV_{P-P}$ for $BER \leq 10^{-12}$. When the MAX3970 TIA is used together with MAX3971, the optical power penalty is about 2.1dB. When the

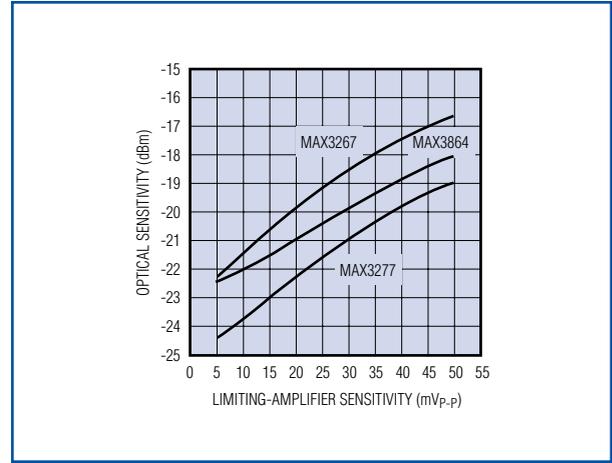


Figure 5. This graph shows the receiver optical sensitivity for 2.5Gbps TIA ICs when each is used with a limiting amplifier of different sensitivity.

MAX3912 TIA is used with MAX3971, however, the optical penalty is only 0.03dB.

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

Choices for 2.5Gbps limiting amplifiers are the 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 needs.

Intersymbol 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 a TIA and a 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 differ. ISI results in eye closure in both amplitude and timing.

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

$$ISI = \frac{2 \times V_{ISI}}{V_{P-P}} \quad (\text{Eq 10})$$

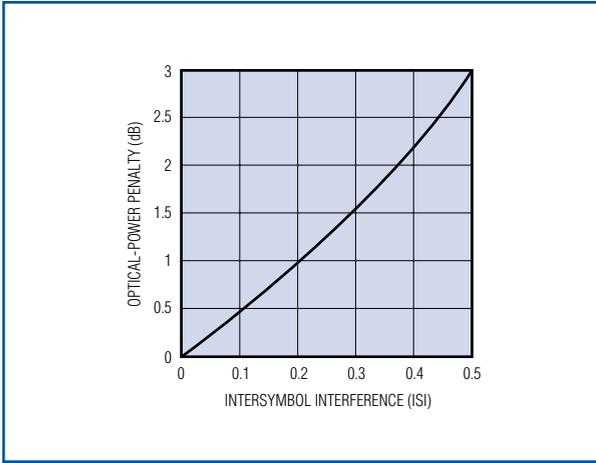


Figure 6. The relationship between ISI and optical power penalty in an ideal case is illustrated.

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

$$I_{P-P} = \frac{2 \times Q_{BER} \times N_{TOTAL}}{(1 - ISI)} \quad (\text{Eq 11})$$

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 calculated result is shown in **Figure 6**. The optical power penalty is 0.46dB for 10% ISI distortion.

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

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 and deterministic jitter are generated due to the existence of random noise, limited bandwidth, passband ripple, group-delay variation, AC-coupling, and nonsymmetrical rise/fall times. The combination of these jitter components decreases the eye opening available for error-free data recovery. Consequently, CDR jitter-tolerance capability is another critical factor for determining optical sensitivity.

CDR jitter tolerance is a measure of how much peak-to-peak jitter can be added to the incoming data before errors occur 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 that the random jitter

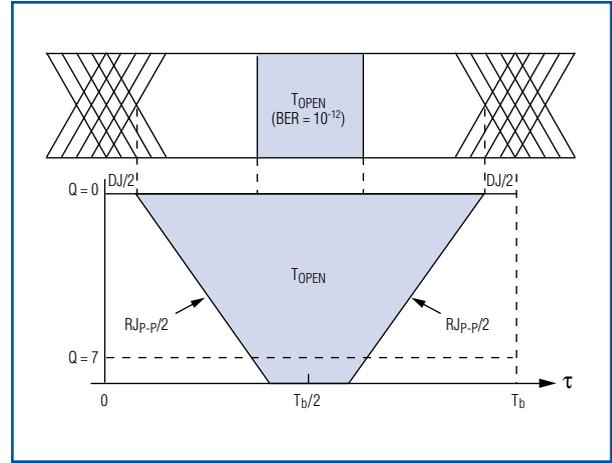


Figure 7. This illustrates the relationship between CDR minimum eye opening and the Q-factor.

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:

$$Q = \frac{T_b - T_{OPEN} - DJ_{P-P}}{2 \times RJ_{RMS}} \quad (\text{Eq 12})$$

$$RJ_{P-P} = 2Q_{BER} \times RJ_{RMS} \quad (\text{Eq 13})$$

For more information, refer to application note *HFAN-04.0.2 Converting between RMS and Peak-to-Peak Jitter at a Specified BER*. (www.maxim-ic.com/AN337)

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.

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:

$$JT_{P-P} = (T_b - T_{OPEN}) \quad (\text{Eq 14})$$

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

$$JT_{P-P} \geq 2 \times Q_{BER} \times RJ_{RMS} + DJ_{P-P} \quad (\text{Eq 15})$$

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

$$RJ_{RMS} = \frac{t_r}{(V_{P-P}/N_{RMS}) \times 0.6} \quad (\text{Eq 16})$$

Here t_r is dependent on the overall receiver small-signal bandwidth BW_{TOTAL} . Assuming a first-order lowpass filter:

$$t_r \approx \frac{0.22}{BW_{TOTAL}} \quad (\text{Eq 17})$$

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

$$RJ_{RMS} = \frac{t_r}{(I_{P-P}/N_{TOTAL}) \times 0.6} \quad (\text{Eq 18})$$

Using Equation 18, the random jitter at the limiting-amplifier output is plotted in **Figure 8** as a function of TIA input current to noise ratio.

The CDR jitter-tolerance penalty on optical sensitivity can be estimated by combining equations 15 and 18, then solving for I_{P-P} as:

$$I_{P-P} = \frac{2 \times Q_{BER} \times t_r}{(JT_{P-P} - DJ_{P-P}) \times 0.6/N_{TOTAL}} \quad (\text{Eq 19})$$

Again we take the OC-192 receiver as an example. Assuming $\rho = 0.85A/W$ and $r_e = 6.6$, the total receiver small-signal bandwidth is 7.0GHz, $N_{TOTAL} = 1.1\mu A_{RMS}$, and ISI = 0. **Figure 9** shows the optical sensitivity achievable with different CDR jitter tolerance ($BER = 10^{-12}$).

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

Conclusion

To estimate optical-receiver sensitivity, it is necessary to consider error sources in both amplitude and timing. This article shows how the amplitude and timing-error sources separately affect the overall receiver BER with practical device implementations. Using these guidelines, optical receiver performance can now be accurately predicted to choose the proper TIA, limiting amplifier, and CDR. In reality, the optical input is not an ideal signal, because it suffers random noise from the transmitter as well as ISI from fiber dispersion. When a stressed optical signal is received, the same approach presented in this article can be used for estimating the signal Q-factor and, therefore, determining the BER.

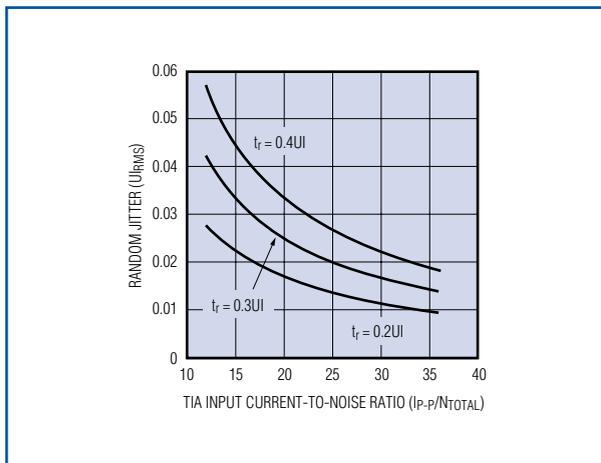


Figure 8. Random jitter and input-current-to-noise ratios are shown for rise times of 0.2UI, 0.3UI, and 0.4UI.

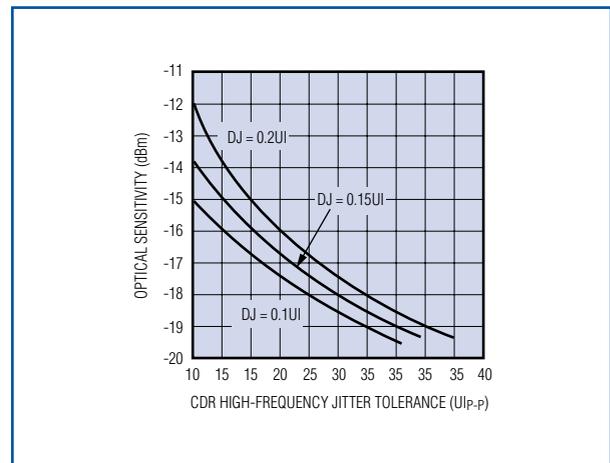


Figure 9. The relationship between optical sensitivity and CDR jitter tolerance is illustrated for deterministic jitter tolerances of 0.1UI, 0.15UI, and 0.2UI.