Estimation of Optical Receiver Sensitivity in HFC Network

Krasen Angelov[1], Stanimir Sadinov[2], Kiril Koitchev[3]

Abstract – **An essential parameter in determining the system power budget in an optical part of the hybrid fiber coaxial (HFC) network 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 analysis of receiver optical sensitivity. The analysis is based on normal receiver sensitivity, assuming an ideal input signal with negligible impairment from factors like inter-symbol interference (ISI), rise/fall time, jitter, and transmitter relative intensity noise (*RIN*).**

Keywords – **optical receiver sensitivity, bit error rate, inter-symbol interference, transimpedance and limiting amplifier.**

I. Introduction

In optical communication systems, sensitivity is a measure of how weak an input signal can get before the bit-error ratio (*BER*) exceeds some specified number. The standards body governing the application sets this specified *BER* [4,6]. For example, Gigabit Ethernet and Fibre Channel specifications require a *BER* of 10^{-12} or better. This BER is the foundation for determining a receiver's sensitivity.

In the design of an optical receiver, such as a HFC optical node, it is vital that the module be capable of converting and shaping the optical signal while meeting or surpassing the maximum *BER*. Ultimately, the influence of noise on the signal will determine the sensitivity of the system [1-3,9-12]. The portion of the receiver that contributes the most noise is the optical-to-electrical conversion provided by the photodetector and the transimpedance amplifier (TIA) [5,8,11].

Sensitivity can be expressed as average power (P_{AVG}) in *dBm* or as optical modulation amplitude (*OMA*) in W_{P-P} (peek-to-peek). Each gives a figure of merit for the receiver. The sensitivity is the minimum *OMA* or P_{AVG} at which the maximum (worst tolerable) *BER* can be maintained [1,2,14]. Optical transmission system designers use sensitivity to determine the maximum distance or link margin available in their system. Expressing the sensitivity in terms of average power is useful, because the average power of a laser is more easily measured than peak-to-peak power. Measuring the peak-to-peak power of a laser at high data rates requires expensive equipment that is error-prone due to the amount of operator intervention. Average optical power can be measured easily and reliably with a relatively inexpensive optical power meter.

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II. Determining the Q-factor

A typical optical receiver is composed of an optical photo detector, a transimpedance amplifier (TIA), a limiting amplifier (LA), and a clock-data recovery (CDR) block. Fig. 1 shows a simple block diagram of the front end of an optical receiver module.

The dominant noise sources in this section are the linear components that provide the optical-to-electrical conversion, namely, the photodiode and the TIA [10,11]. Transimpedance amplifiers are used to amplify and convert the photodiode current into a voltage.

The received optical signal is first converted into photocurrent and amplified by the TIA. The limiting amplifier (LA) 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 inter-symbol interference (ISI), resulting in erroneous decisions due to eye closure [11,12].

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, it can be used signal Q-factor to measure the signal quality for determining the BER [12]. If the ISI distortion does not exist and the dominant amplitude noise has Gaussian distribution, the signal Q-factor is defined as:

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

In a practical receiver implementation, ISI exists due to receiver bandwidth limitation, baseline wander, or non-linearity of the active components. If the signal eye diagram is monitored before the data decision, it is evident 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

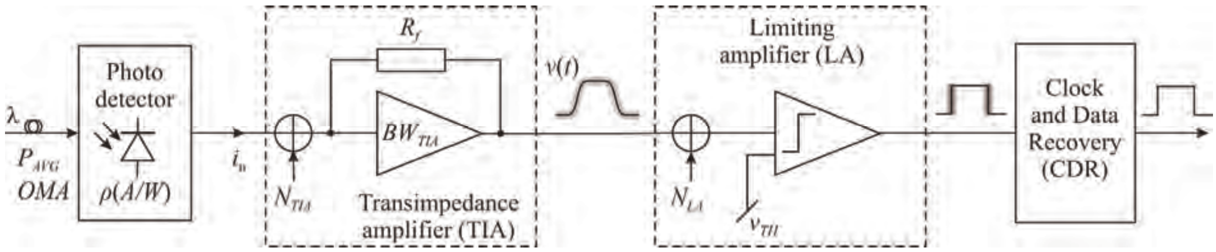

Fig. 1. Simplified block diagram of the optical receiver module

and V_0 to the lower amplitude boundary ($V_1 - V_{ISI}$) and ($V_0 + V_{ISI}$) – Fig. 2. It is assumed that V_{ISI} is the vertical eye closure caused by ISI.

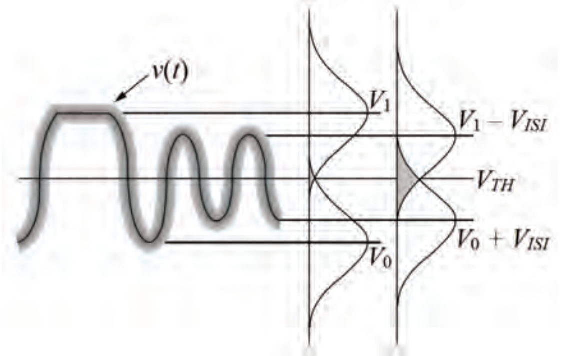

Fig. 2. Worst-case amplitude-noise distribution in the presence of ISI

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

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

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

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 Eq. (3), the relationship between Q_{BER} and BER is plotted in Fig. 3 [12,13].

Usually it is measured the signal peak-to-peak differential swing ($V_{P-P} = V_1 - V_0$) and assuming $\sigma_1 = \sigma_0 = N_{RMS}$, so the Q-factor becomes:

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

where N_{RMS} is the equivalent RMS noise at the input of the limiting amplifier.

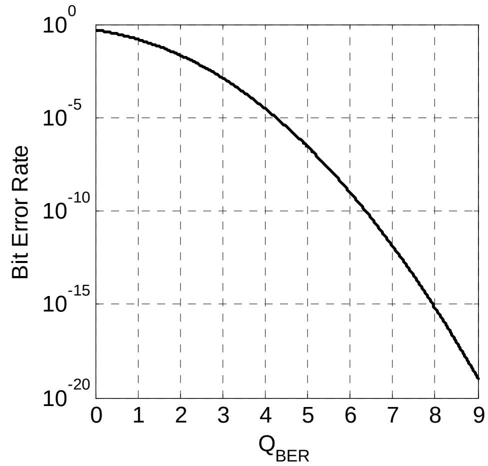

Fig. 3. $BER = f(Q_{BER})$

III. Optical receiver sensitivity estimation

To achieve the best optical sensitivity, it is important to maximize the signal Q-factor before data decision. Here is demonstrated an estimation of the optical receiver sensitivity with practical device implementations, when overall receiver random noise and ISI are taken into account.

The equation for calculating sensitivity is as follows [13,14]:

$$P_{AVG} = 10 \log\left(\frac{i_n SNR(r_e + 1)}{2\rho(r_e - 1)} 1000\right), \quad dBm. \quad (5)$$

i_n is the noise of TIA; ρ – responsivity flux (conversion efficiency) of the photodetector, in A/W; r_e – the ratio of a logic-one power level (P_1) relative to a logic-zero power level (P_0) and it can be expressed as $r_e = P_1 / P_0$ or $r_e = 10\log(P_1 / P_0)$, dB.

Eq. (5) assumes that all of the noise in the system is due to the TIA. It also assumes that the LA following the TIA has a decision threshold of zero ($V_{TH} = 0$).

The noise of the TIA, i_n, is expressed as "input referred noise" in RMS current (A_{RMS}) or "input referred noise density" in ($A_{RMS} / \sqrt{Hz}$). This is the inherent noise of the amplifier. Input referred noise is directly proportional to the value of the photodiode capacitance and bandwidth of the TIA [10].

The process in estimating the minimum peak-to-peak swing of the optical signal begins with the choice of the maximum *BER* [13]. This determines the signal-to-noise ratio (*SNR*). Next, the RMS input referred noise (i_n) of the TIA and the responsivity (ρ) of the photodetector must be found from the vendor's data sheets. These are related by:

$$OMA_{\min} = \frac{i_n SNR}{\rho} . \tag{6}$$

This relationship assumes that the noise is Gaussian.

A. Overall receiver penalty

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

$$I_{P-P} = 2Q_{BER} N_{TOTAL} , \quad \mu A_{RMS} , \tag{7}$$

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

$$N_{TOTAL} = \sqrt{N_{TIA}^2 + \left(\frac{N_{LA}}{R_f}\right)^2} . \tag{8}$$

In practice, the input-referred noise N_{LA} may not be given, but it 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 [10,14]. The random noise is the dominant factor for limiting amplifier sensitivity. Under this condition, N_{LA} can be estimated from the following equation:

$$N_{LA} = \frac{V_{LA}}{2Q_{BER}} . \tag{9}$$

Substituting the Eq. (7) in Eq. (6) and assuming $Q_{BER} = 7{,}1$ for $BER = 10^{-12}$ (Fig. 3), the $OMA_{(N)}$ is obtained as:

$$OMA_{(N)} = \frac{I_{P-P} SNR}{\rho} , \quad \mu W . \tag{10}$$

B. 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 reflections between the interconnection of a TIA and a LA [10,14]. ISI results in eye closure in both amplitude and timing.

The *ISI* due to vertical eye closure is defined as:

$$ISI = \frac{2V_{ISI}}{V_{P-P}} . \tag{11}$$

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

$$I_{P-P(ISI)} = \frac{2Q_{BER} N_{TOTAL}}{(1 - ISI)} , \quad \mu A_{RMS} . \tag{12}$$

Substituting the Eq. (12) in Eq. (6) and assuming $Q_{BER} = 7{,}1$ for $BER = 10^{-12}$ (Fig. 3), the OMA_{ISI} is obtained as:

$$OMA_{(ISI)} = \frac{I_{P-P(ISI)} SNR}{\rho} , \quad \mu W . \tag{13}$$

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 Fig. 4.

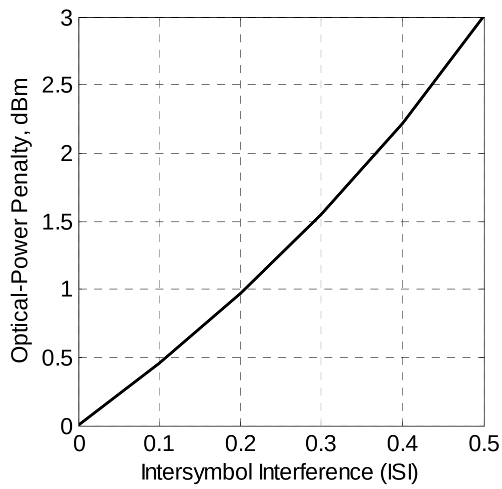

Fig. 4. Optical-power penalty versus ISI for an ideal case

C. Optical receiver sensitivity

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

For estimation of optical receiver sensitivity limited by the receiver noise impact and ISI impact, Eqs. (10) and (13) are substituted in Eq. (5).

Examples are given for optical receiver using MAXIM devices MAX3277 TIA and MAX3272 LA for HFC fiber channel applications. The datasheet parameters are as follows: $N_{TIA} = 0{,}35\mu A$, $R_f = 3{,}3k\Omega$, $N_{LA} = 0{,}22mV$ [15,16]. Assuming $r_e = 6{,}6$ and two values of $\rho = 0{,}85A/W$ and $0{,}65A/W$, the calculated optical sensitivity (P_{AVG}) versus Signal-to-Noise Ratio (*SNR*) is shown in Fig. 5.

The results on Fig. 5 are based on Eqs. (5), (10) and (13). It is shown the minimum required optical sensitivity P_{AVG} for a given *SNR*. For example, when the *SNR* = 14,1*dB* (which is equivalent to *BER* = 10^{-12} or Q_{BER} = 7,1 [12]) the optical sensitivity is –21,78*dBm* when *ρ* = 0,85*A/W* and –19.45*dBm* when *ρ* = 0,65*A/W*. For the receiver with higher responsivity of the photodetector the optical sensitivity will be lower.

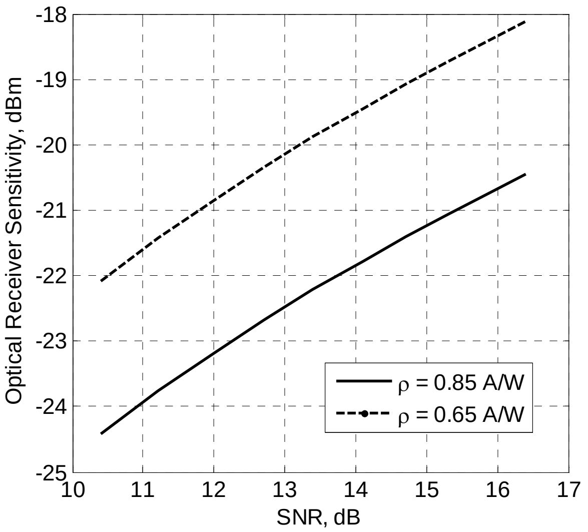

Fig. 5. Minimum required optical receiver sensitivity versus signal-to-noise ratio

Another useful representation of minimum required optical sensitivity P_{AVG} is the dependence of *BER* needed. The results are shown in Fig. 6.

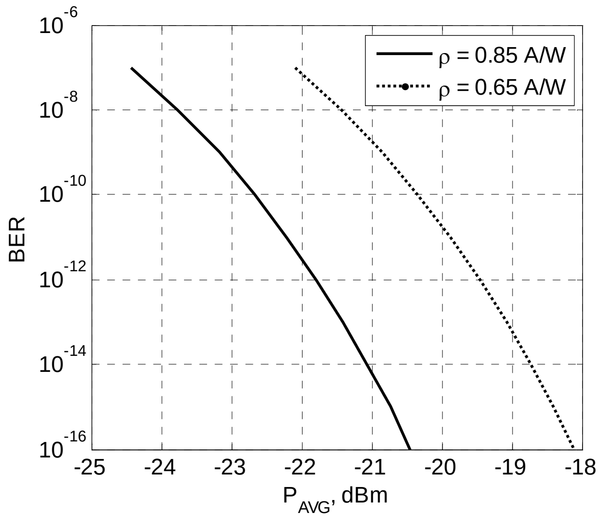

Fig. 6. Minimum required optical receiver sensitivity (P_{AVG}) versus Bit Error Rate

IV. CONCLUSION

By applying the technique presented in this paper, it is easy to estimate and predict optical receiver sensitivity. Relying on a vendor specifications accurate estimate of optical sensitivity can be made.

To estimate optical-receiver sensitivity, it is necessary to consider error sources in amplitude. It is shown how the amplitude error sources separately affect the overall receiver BER with practical device implementations. 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*.

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