Optical Receiver Sensitivity Evaluation in Presence of Noise in Digital Communication System

Krasen Angelov[1], Stanimir Sadinov[2], Nataliya Varbanova[3]

Abstract – **The performance of an optical receiver in a digital optical communication link is studied. In the design of an optical receiver, it is vital that the module is capable of converting and shaping the optical signal while meeting or surpassing the maximum BER. Ultimately, the noise influence on the signal will determine the system sensitivity. The challenge is to find a way to determine the QoS of an optical transmission channel independent of data format and bit rate within a short time frame. The *Q*-factor itself significantly reduces measurement time and is thus more cost-effective. The analysis is based, assuming an input signal with impairment from factors like inter-symbol interference, jitter, and transmitter relative intensity noise.**

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

I. Introduction

Most applications of optical signals in digital communications require the detection and subsequent conversion of the light to an electrical signal. In this process, the useful signal will be corrupted by noise and the ultimate sensitivity and performance of the system is limited by the noise characteristics. Optical receiver adds noise; usually thermal noise and shot noise. In communication systems, where electrical, radio or optical signals are transmitted; noise can be viewed as an impairment resulting in the degradation of the information contained in the signal [1,7]. Optical amplifiers can be used to improve the effective receiver sensitivity in optical systems. The optical amplifier works on the principle of stimulated emission [5]. The optical amplifiers add noise to the amplified signal, and at some point, this noise becomes the dominant noise source. The basic manifestation of noise in optical amplifier is in the form of amplified spontaneous emission (ASE). So, the bit error probability (*BER*) is also affected by the ASE noise added by the optical amplifier [2,3,7].

A typical optical receiver is composed of an optical photo detector, a transimpedance amplifier (TIA) [9], 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 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 [3,4].

II. Characteristics of Performance Analysis

A. Eye diagram

The eye diagram represents a superposition of all bits in the signal on top of each other [8]. Fig. 2 shows the eye diagram of a NRZ signal. There are two basic types of adverse effects visible in the eye diagram: Fist, the effect of intersymbol interference (ISI) and, second, the effect of jitter. The ISI is caused by overlap of individual modulation pulses and it leads to the amplitude errors at the sampling instances. The jitter is defined as short-time deviations of a digital signal from its ideal position in time [8]. A larger “eye opening” signifies less noise or distortion and therefore a higher quality of signal.

B. Bit Error Ratio (BER)

In digital communication systems, the decision when to sample and whether the sampled value represents a binary 1 or 0 is affected by noise and signal distortion in the real system and there is nonzero probability of an erroneous decision. Therefore, the received signal quality is directly related to the bit error rate (BER), which is a major indicator of the quality of the overall system [8]. Eq. (1) explains a calculation bit error rate if the *Q*-value is known [4,6]:

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{\exp\left(\frac{-Q^2}{2}\right)}{Q\sqrt{2\pi}}. \qquad (1)$$

C. Q-factor

The *Q*-factor expresses the quality of an optical signal with respect to its signal-to-noise ratio (SNR). It includes all physical impairments of the signal, such as noise, non-linear effects, dispersion (chromatic and polarization). These impairments degrade the signal and cause bit errors. Consequently, a higher value of the *Q*-factor means a better *SNR* and therefore

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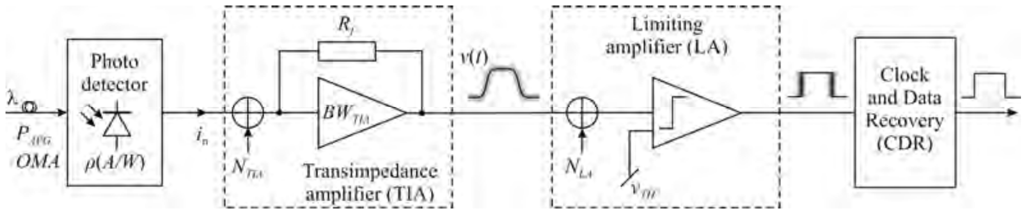

Fig. 1. Simplified block diagram of the optical receiver module

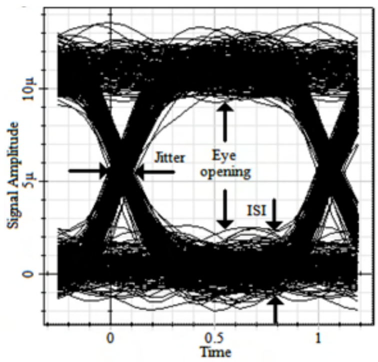

Fig. 2. An example of an eye-diagram and its interpretation

a lower *BER*. Eq. (2) gives the Q-factor of an optical signal [4,6]:

$$Q = \frac{V_1 - V_0}{\sigma_1 + \sigma_0}, \tag{2}$$

where V_1 is the value of the binary 1, V_0 is the value of the binary 0, σ_1 is the standard deviation of the binary 1 and σ_0 is the standard deviation of the binary 0.

III. Optical Receiver Sensitivity Evaluation

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.

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 [3,4,6].

To achieve the best optical sensitivity, it is important to maximize the signal *Q*-factor before data decision. The equation for calculating sensitivity is as follows [4,6]:

$$P_{AVG} = 10\log\left(\frac{i_n SNR(r_e+1)}{2\rho(r_e-1)}1000\right),\quad dBm, \tag{3}$$

where 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) [4,7].

The process in estimating the minimum peak-to-peak swing of the optical signal begins with the choice of the maximum *BER*. 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:

$$OMA_{\min} = \frac{i_n SNR}{\rho}. \tag{4}$$

In communication systems noise can be viewed as an impairment resulting in the degradation of the information contained in the signal [7]. The optical receiver adds two types of noise namely thermal noise and shot noise. Since optical amplifiers are based on the principle of stimulated emission, its main contribution to noise is ASE noise.

A. Thermal noise

The thermal noise of a receiver arises from the fact that electrons in a receiver circuit have some probability of generating a current even in the absence of an optical signal. This noise (referred to as Johnson noise), can be represented by the variance of thermal current per unit frequency [5]:

$$\sigma_{th}^2 = 4kT/R, \tag{5}$$

where T is the absolute temperature, k is Boltzmann's constant and R is the detector load resistance.

B. Shot noise

The shot noise arises from the Poisson distribution of the electron-hole generation by the photon stream. The latter is a stochastic process having random arrival times. On average, the number of electron-hole pairs created will be proportional to the number of photons, with a given constant of proportionality.

During a given time interval, with a certain number of photons incident upon the detector, the number of electron–hole pairs generated will have fluctuations as determined by Poisson statistics [5]. A dc photocurrent of I_{pd} will generate a shot noise power density of:

$$\sigma_{sh}^2 = 2eI_{pd}. \tag{6}$$

D. ASE Noise

ASE is produced by spontaneous emission that has been optically amplified by the process of stimulated emission in gain medium. Noise associated with ASE is the limiting factor in determining the ultimate signal-to-noise ratio in any system using optical amplifiers [3,4,5]. The output ASE power can be calculated using classical derivation in:

$$P_{ASE} = n_{sp}(G-1)h\nu B_o, \tag{7}$$

where h is Plank's constant, v is the optical frequency of transition, B_o is the optical bandwidth and n_{sp} is the inversion parameter, given by

$$n_{sp} = \frac{\sigma_e(\lambda)N_2}{\sigma_e(\lambda)N_2 - \sigma_a(\lambda)N_1}, \quad (8)$$

where $\sigma_a(\lambda)$ and $\sigma_e(\lambda)$ are the absorption and emission cross sections, respectively; N_1 and N_2 are the population density in lower and upper states; G is the overall gain of the amplifier.

Eq. (7) gives the ASE power for one polarization mode. So, for single mode fiber, the right hand side of Eq. (7) must be multiplied by a factor of 2.

When an amplified optical signal and accompanying spontaneous emission are detected in a photodetector, the noise is transformed into the electrical domain and appears along with the induced photocurrent as a noise current. Photodetection is a nonlinear square-law process [5]. The photocurrent is therefore composed of a number of beat signals between the signal and noise optical fields E_S and E_N, respectively, in addition to the squares of the signal field and spontaneous emission field. The photocurrent I_{pd} is found as:

$$I_{pd} \propto (\overrightarrow{E_{tot}})^2 = (\overrightarrow{E_S} + \overrightarrow{E_N})^2 = E_S^2 + E_N^2 + 2\overrightarrow{E_S}.\overrightarrow{E_N}. \quad (9)$$

In Eq. (9), one can identify the first term as pure signal, the second term as pure noise and it is referred to as spontaneous-spontaneous (sp-sp) beat noise, and the third term as mixing component between signal and noise and it is referred to as signal-spontaneous (s-sp) beat noise [3,6].

The power spectrum of current corresponding to s-sp beat noise is uniform in the frequency interval ($-B_o/2$) to ($B_o/2$) and has an equivalent one-sided power density of

$$N_{s-sp} = \frac{4e^2}{hv} P_{in} n_{sp} (G-1)G. \quad (10)$$

The power spectrum of current corresponding to spontaneous-spontaneous beat noise extends from 0 to B_o with a triangular shape and a single-sided power density near dc of

$$N_{sp-sp} = 2n_{sp}^2 (G-1)^2 e^2 B_o. \quad (11)$$

E. SNR calculation

The Q-factor can be also expressed in terms of the optical signal-to-noise ratio ($OSNR$) as:

$$Q = \sqrt{\frac{B_o}{B_e}} \frac{2OSNR}{4\sqrt{OSNR+1}+1}, \quad (12)$$

with B_o and B_e the optical and electrical bandwidths, respectively. Eq. (12) seems nonlinear and can be used to derive the $OSNR$ needed to obtain a given BER, for an ideal system with only amplifier noise and without nonlinearities or inter-symbol interference.

In case of amplifier operating with moderately large optical input signals, the SNR at the amplifier output is dominated by signal spontaneous beat noise. In this limit, the equivalent electrical SNR at the amplifier output is given by [5]

$$SNR = \frac{GP_{in}}{4hvn_{sp}(G-1)B_e}. \quad (13)$$

Provided that G is reasonably high, the SNR is determined only by the input power and the inversion parameter n_{sp}. More specifically, the SNR is independent of the gain. This is an important result that governs the system performance and determining of optical receiver sensitivity using Eq. (3):

F. 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 is 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 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:

$$Q = \frac{T_b - T_{OPEN} - DJ_{P-P}}{2RJ_{RMS}}, \quad (14)$$

$$RJ_{P-P} = 2Q_{BER} RJ_{RMS}. \quad (15)$$

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:

$$JT_{P-P} = T_b - T_{OPEN}. \quad (16)$$

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

$$JT_{P-P} \geq 2Q_{BER} RJ_{RMS} + DJ_{P-P}. \quad (17)$$

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:

$$RJ_{RMS} = \frac{t_r}{I_{P-P} / N_{TOTAL} 0{,}6}, \quad (18)$$

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

$$t_r \approx 0{,}22 / BW_{TOTAL}. \quad (19)$$

The CDR jitter-tolerance penalty on optical sensitivity can be estimated by combining Eqs. 17 and 18, then solving for I_{P-P} as:

$$I_{P-P} = \frac{2Q_{BER}.t_r.N_{TOTAL}}{(JT_{P-P} - DJ_{P-P}).0,6}\,. \quad (20)$$

Substituting the Eq. (20) in Eq. (3) the optical receiver sensitivity in terms of P_{AVG} can be obtained.

IV. Results

Examples are given for optical receiver using MAXIM devices MAX3277 TIA and MAX3272 LA. The datasheet parameters are as follows: N_{TIA} = 0,35μA, R_f = 3,3$k\Omega$, N_{LA} = 0,22mV, the total receiver small-signal bandwidth is 7.0GHz, and ISI = 0. Assuming r_e = 6,6 and ρ = 0,85A/W, the calculated optical sensitivity (P_{AVG}) versus optical signal-to-noise ratio (OSNR) is shown in Fig. 3. The results on Fig. 3 are based on Eqs. (3), (13) and (20). It is shown the minimum required optical sensitivity P_{AVG} for a given SNR. For example, when the SNR = 14,1dB (which is equivalent to BER = 10^{-12} or Q_{BER} = 7,1) the optical sensitivity is –21,78dBm in ideal case, –14,98dB considering optical link with amplifier noise, and –14,59dB considering the jitter-tolerance penalty.

Another useful representation of minimum required optical sensitivity P_{AVG} is the dependence of BER needed. The results are shown in Fig. 4.

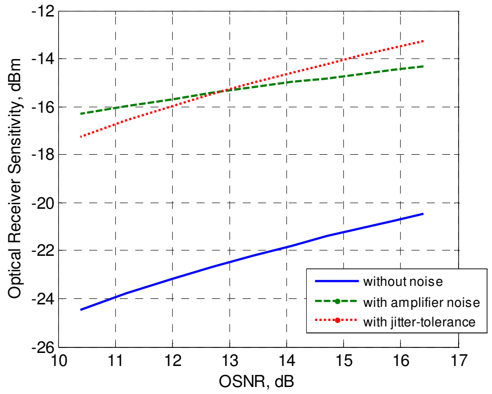

Fig. 3. Optical receiver sensitivity versus optical signal-to-noise ratio

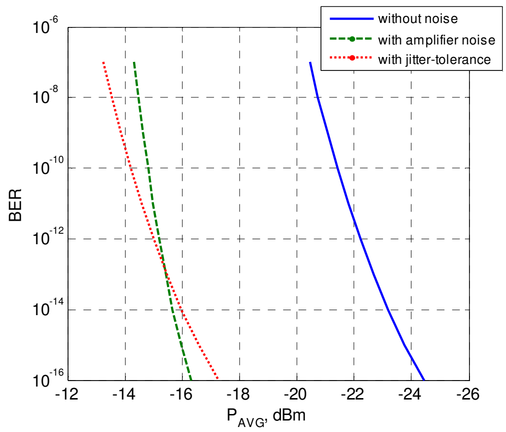

Fig. 4. Bit Error Rate versus minimum required optical receiver sensitivity (P_{AVG})

From Figs.3 and 4 it is evident that for OSNR lower than 12,75dB a dominant factor is the amplifier noise when determining the optical receiver sensitivity. For higher OSNR dominant is the jitter-tolerance penalty. In general, to achieve a specified BER, the minimum TIA input current should satisfy the Q_{BER} in both amplitude and timing.

V. Conclusion

By applying the technique presented in this paper, it is easy to estimate and predict more realistic optical receiver sensitivity. It is necessary to consider error sources in both amplitude and timing. It has been shown how the amplitude and timing-error sources separately affect the overall receiver BER. A general expression of Q-factor can be predicted when shot noise and thermal noise are also considered. Using these guidelines, optical receiver performance can be accurately predicted. 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. The approach presented in this article can be used for estimating the signal Q-factor and, therefore, determining the BER.

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