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Optimisation of low frequency characteristics of digital optical links

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In the paper, an analysis of the influence of low frequency characteristics of digital optical links on bit error rate performance is undertaken. Effects caused by both baseline wander and flicker noise are investigated. Links with one and two poles in the low frequency range are taken into account. Also some practical conclusions emerging from the analysis are pointed out.

Keywords: baseline wander, bit error rate, optical links.

1. Introduction

Almost all practical optical transmission systems present some low frequency (LF) cut-off in their transfer function taken from LED or laser driver in the transmitter to the decision circuit in the receiver. The LF cut-off in the optical transmitter may be introduced by the laser mean-power controlling loop [1]. In the receiver, AC coupling (with resulting LF cut-off) is typically used to eliminate DC offset and its thermal drift occurring at the output of the optoelectric (O/E) converter (i.e., photodiode with its front-end). However, the exact value of the LF cut-off frequency is not rigorous from the above point of view and so, it would be desirable to know some guidelines how to choose its value. It may be expected that increasing the LF cut-off frequency results in higher baseline wander, but on the other hand decreasing the LF cut-off frequency leads to higher noise, especially when the 1/f noise component is significant. In this paper the bit error rate (BER) optimisation taking into account the baseline wander and LF noise shaping effects is presented.

2. Transmission system modelling for BER calculation

The block diagram of optical link considered in the paper is shown in Fig. 1. Frequency characteristics of the link are modelled only in the LF range and it is assumed that the HF cut-off frequency is properly chosen to the transmission bit rate. In practice, the AC coupling network is realised simply by a series capacitor in the signal path thus $H_R(f)$ is of high-pass type. The noise source in Fig. 1 represents the total noise occurring at the output terminal of O/E converter. The noise power spectral density (PSD) is assumed to have a flat ("white") component extending up to *1/2T* frequency (what is equal to the minimum bandwidth accordingly to the Nyquist theorem), caused by thermal and shot noise, and some 1/f component in LF region caused by flicker noise. Usually the flicker noise significance is limited to relatively low frequencies (some tens of kilohertz), but sometimes it is dominant in a total noise PSD up to tens of megahertz, especially in PIN-FET receivers [2].

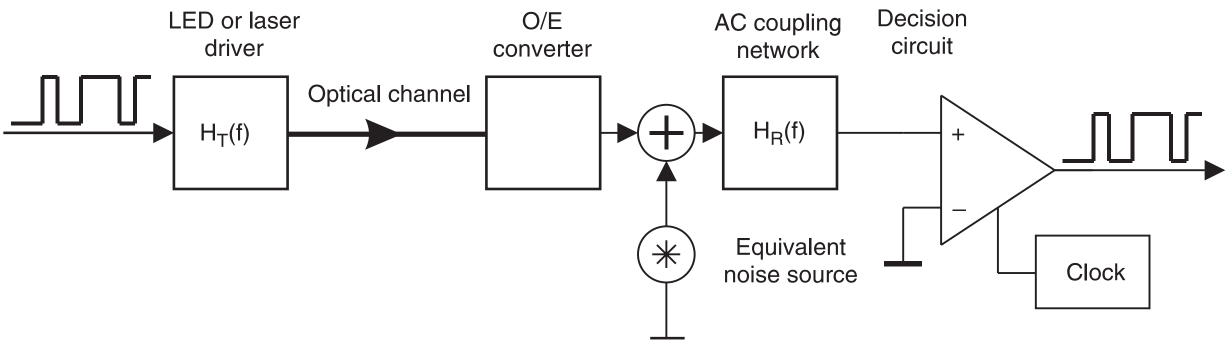

Fig. 1. Block diagram of optical link considered in the paper.

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In general, the baseline wander is caused by removal of the part of signal spectral power density located below the link LF cut-off. If the LF cut-off was caused only by the AC coupling network, the baseline wander would be equal simply to voltage fluctuations across the series capacitor. Baseline wander manifests the most when the long unbalanced data sequences (i.e. having not equal count of "zeros" and "ones") are transmitted. This process itself usually does not cause the errors in data detection but leads to decrease in link noise immunity, consequently increasing its BER.

In the past, the influence of baseline wander on BER was investigated, however, the very simple Gaussian probability density function (PDF) was used for baseline wander modelling [3], what appears to be highly inaccurate [4]. Assuming that the consecutive non-return-to-zero (NRZ) data symbols are uncorrelated[1], it may be shown that the baseline wander is stochastic signal and its PDF may be approximated by beta PDF [4], defined as[2]

$$f(w) = \frac{(w - w_{\min})^{\gamma-1}(w_{\max} - w)^{\gamma-1}}{\int\limits_{w_{\min}}^{w_{\max}}(w - w_{\min})^{\gamma-1}(w_{\max} - w)^{\gamma-1}dw} \qquad (1)$$

for $w \in (w_{\min}, w_{\max})$ and $f(w)=0$ elsewhere. In Eq. (1), $w_{\min}$ and $w_{\max}$ are the minimum and maximum values of baseline wander and γ is determined by the baseline wander variance σ_w^2

$$\gamma = \frac{1}{2}\left(\frac{(w_{\max} - w_{\min})^2}{4\sigma_w^2} - 1\right) \qquad (2)$$

The values of σ_w^2, $w_{\min}$ and $w_{\max}$ depend on the bit duration T and the link frequency characteristics in LF range. Limiting further considerations to the cases when the link LF transfer function poses only one pole (with the time constant τ_{LF}) or is of the second order type (with equal time constants)[3], the following approximations may be obtained [4]

$$\begin{aligned} \sigma_w^2 &\approx 0.125T/\tau_{LF}, \\ w_{\min} &= 0, \\ w_{\max} &= 1, \end{aligned} \qquad (3)$$

for the first order and

$$\begin{aligned} \sigma_w^2 &\approx 0.313T/\tau_{LF} + 0.125(T/\tau_{LF})^2, \\ w_{\min} &\approx -(0.14 + 0.14\,T/\tau_{LF}), \\ w_{\max} &\approx 1.14 + 0.14\,T/\tau_{LF}, \end{aligned} \qquad (4)$$

for the second order transfer functions (although exact expressions for σ_w^2, $w_{\min}$ and $w_{\max}$ are possible they are very complex and approximated Eqs. (3) and (4) are enough accurate for all practical purposes).

Taking commonly accepted Gaussian PDF for noise modelling it is necessary to know the noise power (i.e., its variance σ_n^2) for BER calculation. In the further computation, the total noise PSD in the frequency range (0,1/2T) is assumed to obey the equation $S_n(f) = N_F(1 + f_C/f)$, where the parameters N_F (noise floor) and f_C (the flicker noise corner) are defined accordingly to Fig. 2. Because the $H_R(f)$ is of the first order, taking into account the relation

$$\sigma_n^2 = \int\limits_0^{1/2T} S_n(f)\left|H_R(f)\right|^2 df,$$

the noise variance at the input of the decision circuit can be obtained as

$$\sigma_n^2 = \frac{N_F}{2T}\left(1 - \frac{\mathrm{arctg}(\pi\tau_{LF}/T)}{\pi\tau_{LF}/T} + f_C T \ln(1 + 4\pi^2\tau_{LF}^2/T)\right). \qquad (5)$$

Having determined baseline wander and noise PDFs, BER can be calculated as follows [4]

$$BER = \frac{1}{2}\int\limits_{w_{\min}}^{w_{\max}} \mathrm{erfc}\left(\frac{\sqrt{2}}{4}\frac{1/2 + w}{\sigma_n}\right)f(w)dw \qquad (6)$$

where $f(w)$ and σ_n are given by Eqs. (1) and (5), respectively.

3. Obtained results

Exploiting Eqs. (1)–(6), the calculations of link BER were performed and their results are drawn in Fig. 3, where BER is plotted versus the LF time constant normalised to the bit

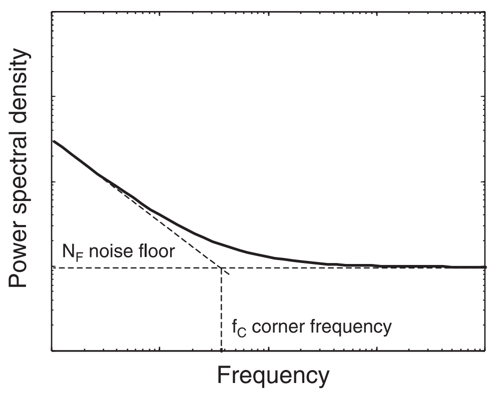

Fig. 2. Power spectral density of equivalent noise source.

[1] Assumption of uncorrelatedness is usually valid for optical links, when no redundant coding is applied to data prior transmission. Application of redundant coding modifies transmitted signal PSD, especially in LF region, thus modifies baseline wander effects.

[2] The unity signal amplitude is taken in all equations.

[3] For the performance analysis purposes the link transfer function in the LF range may be considered to be dominated by one pole in the receiver or having two poles with comparable time constants (located either in the receiver or in the receiver and the transmitter).

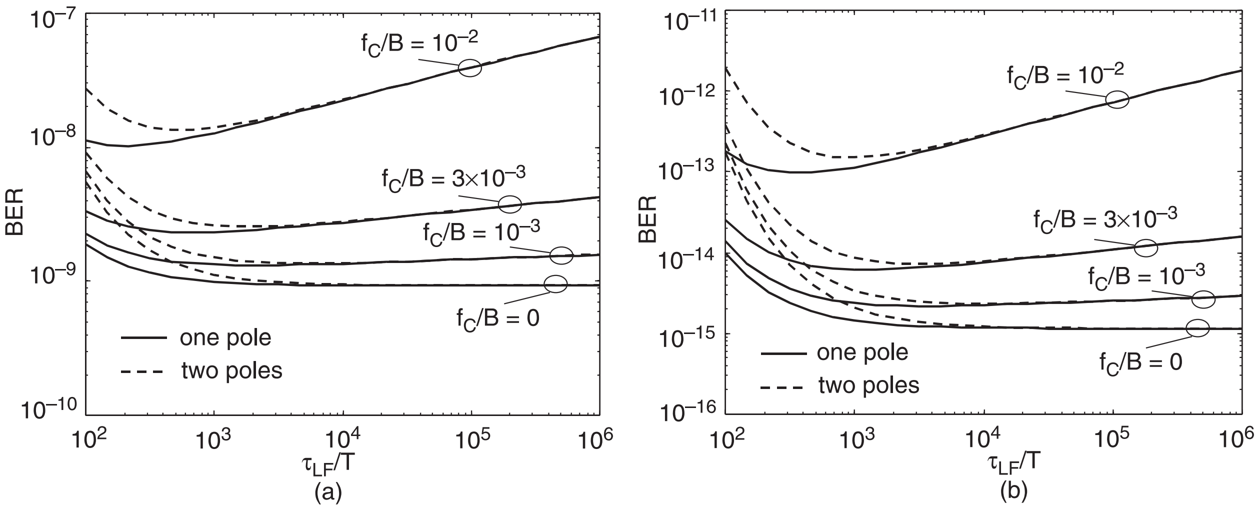

Fig. 3. BER performance of analysed optical links. Description is given in the text.

duration (and this way related to the bit rate $B = 1/T$). The curves are parameterised by the flicker noise corner frequency f_C normalised to the bit rate B. The noise floor N_F is chosen in this way to obtain $BER = 10^{-9}$ [for Fig. 3(a)] and $BER = 10^{-15}$ [for Fig. 3(b)] in the case when $f_C = 0$ and $\tau_{LF} \to \infty$ (what is equivalent to the lack of baseline wander and flicker noise). In each figure, two sets of curves are shown: for the dominant pole introduced by the AC coupling network (drawn with the solid lines) and for two poles with equal time constants (plotted with the dashed lines).

It may be noticed that in all cases, except these with no the flicker noise ($f_C = 0$), some BER minimum can be observed. To understand this behaviour, two facts may be pointed out: the increasing τ_{LF} reduces the baseline wander [see Eqs. (3) and (4)] but from the other hand it causes that greater amount of flicker noise PSD is located in the pass-band of the AC coupling network and so reaches the decision circuit [see Eq. (5)]. The general feature of the presented curves is that the optimum is more visible for links with two poles what is caused by stronger BER degradation in the range of baseline wander domination (additionally a slight shift of the minimum location may be observed).

In principle some BER minimum may be expected even for $f_C = 0$, but in fact it does not occur. It appears that the increasing τ_{LF} takes much more effect on the BER through the baseline wander decrease than through the noise variance increase.

It may be observed from Figs. 3(a) and 3(b) that the optimum location of LF cut-off is quite essential if $f_C T$ is greater than 10^{-3} (what occurs for relatively slow links or high values of f_C). Usually the optimisation process leads to τ_{LF} values in the range ($2\times10^2 T$, $2\times10^3 T$). For $f_C T < 10^{-3}$ determination of the value τ_{LF} is not such rigorous and it is enough to assure that $\tau_{LF} > 10^3 T$. It may be concluded that the value $t_{LF} \approx 10^3 T$ may be recommended in most practical situations, even without detailed knowledge about noise characteristics.

4. Conclusions

In the paper, the optical transmission link LF cut-off influence on the system BER was investigated. It was found that in most cases some minimum of BER is possible to obtain by proper choice of the LF cut-off. The close matching to this optimal value is more rigorous in links with relatively high flicker noise corner frequency and/or with two poles in LF region. Some practical conclusions emerging from the analysis were pointed out.

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Forthcoming conferences

Readers are invited to send the Executive Editor details of conference to be announced

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E-mail: sara.sommerville@iop.org
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8–9 April
Nanotechnology Meets Business
Frankfurt, Germany
The first international conference on investment opportunities in nanotechnology across Europe. New technologies and their commercial potential will also be discussed.
Contact: Caroline Russell
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Fax: +44(0)1786447530
E-mail: caroline@nano.org.uk

21–25 April
2003 Materials Research Society (MRS) Spring Meeting
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DFC7: International Conference on Deformation and Fracture Composites
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URL: http://comp03.aml.gr

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Research, development, applications, and engineering in areas as diverse as electronic materials and resin technology will be covered.
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Fax: +1 6263328929
E-mail: dweaveribo@cs.com
URL: www.sampe.org

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Osaka, Japan
This event incorporates the 13 International PV Science & Engineering Conference, the 30 IEEE PV Specialists Conference, and the 18 European PV Solar Energy Conference. Subjects to be covered include new materials and devices, thin-film cells and technologies. Discussions will also span national programs, policies, and economics.
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Tel/Fax: +81 42 388 7109
E-mail: wcpec3@cc.tuat.ac.jp
URL: www.wcpec3.org

18–23 May
Organic Thin Films
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Topics for discussion will include characterization and modeling of organic thin films, as well as their application in materials science and biomaterials.
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