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A Survey: Optimization of Bit Error Ratio in Fiber Optic Communication System

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***Abstract*—**A key objective of the modeling of Fiber Optic Communication systems is to understand the physics of the system behaviour and the development of computational tools for the design of systems and predict their performance. Data transmission via fiber optical link inevitably leads to bit errors due to various effects, the dominant of which are optical amplifier noise, nonlinearity, polarization effects and non ideal transreceivers. There are numerous studies that provide techniques to characterize and calculate the effects in Bit Error Ratio (BER). In This paper, we optimize the Bit Error Ratio (BER) in fiber optic communication. The calculation of the BER in a system of finding optimum power level requires an accurate model of the nonlinear interactions. Our method of calculation of the BER in the presence of nonlinear distortion and amplified spontaneous emission noise is based on calculations of the full Probability Density Function (PDF) of the amplitude or time jitter induced nonlinear phase. Using knowledge of the PDF of the variation of the amplitude induced by combined noise, noise and nonlinear contributions issue to calculate the BER. The purpose of this paper is to develop a method to accurately account between nonlinear crosstalk and channels in the calculation of BER.

***Keywords*—**Optical Fiber Communication (OFC); Bit Error Ratio (BER); Probability Density Function (PDF); Multiplerxer (MUX); Demultiplexer (Demux); Figure of Merit (FOM)

I. INTRODUCTION

Data transmission via fiber optical link inevitably leads to bit errors due to various effects, the dominant of which are optical amplifier noise, nonlinearity, polarization effects and non ideal transreceivers. There are numerous studies that provide techniques to characterize and calculate the effects in Bit Error Ratio (BER) due to them [1] [3]. However, there are still many unanswered important response and one of them is how to accurately calculation of the BER in the presence of nonlinear distortion and amplified spontaneous emission noise.

All modern systems operating in the linear propagation regime, in which the evolution of the signal is nearly linear [4]. However, there are always small and small nonlinear distortions accumulated nonlinear signal during transmission through hundreds and thousands of miles can lead to increased interactions error rate. Reducing the optical power diminishes the importance of nonlinear interactions, but also decreases the signal to noise ratio (SNR). There is an optimum power level at which the BER is low. Even if the power level is less than optimal power therefore accumulation of nonlinear distortions during transmission throughout hundreds or thousands of miles [5] [6]. The calculation of the BER in a system of this type finding optimum power level requires an accurate model of the nonlinear interactions.

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The main challenge in the characterization of nonlinear penalty is that it is a statistical quantity. The ON-OFF locked systems, a digital “1” is represented by the presence and a digital “0” is represented by absence of an optical pulse. The measure of an optical distortion that depends on the individual pattern of pulses around, which is effectively random pulses as in the original random bits of information, and the sequence of bits of information, is quasi-random. This effect is often referred to as the pattern of nonlinear dependence effects [1], [7].

The aim of this paper is to develop a method to accurately account nonlinear crosstalk between channels in the calculation of BER in WDM-return to zero systems.

Our method of calculation of the BER in the presence of nonlinear distortion and amplified spontaneous emission noise is based on calculations of the full probability density function (PDF) of the amplitude or time jitter induced nonlinear phase. Using knowledge of the Probability Density Function of the variation of the amplitude induced by combined noise, noise and nonlinear contributions to calculate the resulting BER.

II. SYSTEM MODEL

Modern fiber optical communications systems contain a large number of optical components such as lasers, demodulators and modulators, demultiplexers and multiplexers, filters, and amplifiers [1], [2]. Additionally, a large body of electrical equipment in the receiver, such as photodiodes, decision circuits, amplifier circuits and

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electrical filters. By simulating these components, the level of detail of the model should be suitable for the system under study. For example, a model of amplifier is often used for optical amplification in which the optical field is simply multiplied by a factor. We use this model in the simulations in this thesis. More realistic models may include amplified spontaneous emission noise, the gain profile, saturation of the gain, and transient polarization hole burning [8]. The first step in any simulation is to simplify the system and restrict the optical propagation model to the essential effects. The nature of the most important effects depends largely on the type of optical system. In particular, the amount of non-linearity has a major impact on the evolution of the signal and noise.

Figure 1 shows a schematic illustration of a simple model of an optical fiber communications system used in this paper. The optical signal is generated by a transmitter and is inserted in the fiber. It then passes through a transmission line composed mainly consists of fiber and optical amplifiers. At the end of the transmission line, the signal is optically filtered and enters a receiver, where it is converted to an electrical current through a high-speed photodiode. This current is passed through a low pass filter and enters a decision circuit.

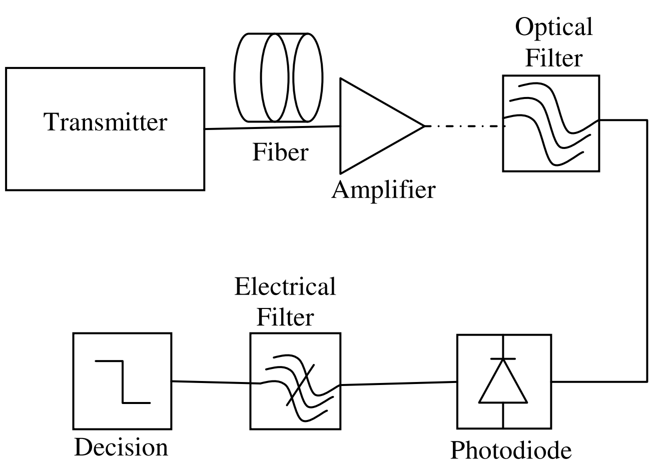

Figure 1. Optical Fiber Communication System

In a digital transmission system, typical fiber optic pulses are directly created by an optical laser, or the output of a laser is modulated continuous wave by an external modulator. In RZ transmission, the marks are represented by isolated optical pulses, while in NRZ signaling a sequence is represented by a constant continuous light intensity. We assume that the amplitude modulation is produced by a Mach-Zehnder interferometer. The functional form of the RZ is used in this paper

$$Y(t) = \sqrt{\frac{1}{2}\left[1+\cos\left(\pi \sin\frac{\pi t}{T}\right)\right]}\, exp^{iC\pi \cos\frac{2\pi t}{T}} \quad (1)$$

Where T is the bit period and C is the chirp parameter.

III. CALCULATION OF THE PULSE AMPLITUDE DISTORTION AND THE BIT ERROR RATIO

We use the different method for calculating the Probability Density Function of the collision induced time shift to obtain the Probability Density Function of the current received, and we validate the result with a full statistical model based on IS simulations. When we have any available single press in the target channel, the agreement between the reduced deterministic method and the full statistical method is excellent. With multiple pulses in the target channel, it is also important to account for the amplitude jitter due to inter- and intra-channel interactions. We introduce a method for calculating the Probability Density Function of the nonlinearly induced that is not current variation due to the timing jitter. Accounting for Both timing and amplitude jitter, we can Achieve a very good agreement with the IS simulations. In order to calculate the BER, we combine in Original deterministic techniques for calculating the nonlinear penalty with a model for noise-induced signal distortion That Assumes That the noise is additive, white, and Gaussian. We calculate the Probability Density Functions of the current in the marks and spaces from that determine the BER using an approach described by Forestieri [9].

A. *Probabilistic characterization of the nonlinear induced pulse distortion*

1) Reduced Time Shift Method: For the calculation of the distortion of the current received signal is due to the time jitter, we use a simplified method, in which pulse shape $i(t)$ is calculated in the receiver using a propagation model complete and a model of receiver including an optical filter a quadratic ideal photo-detector and an electric filter. They use this form of pulse to determine the value of the sampled current I got a time change ∂T using the expression

$$I(\partial T) = i(T_0 - \partial T) \quad (2)$$

Where T_0 is the central time of the pulse, then we obtain the pdf of the current using the cumulative distribution function of time change

$$F_{\partial T}(t) = \int_{-\infty}^{t} p(\tau)\, d\tau \quad (3)$$

Where $p(\tau)$ is the time shift of pdf.

$$F_I(x) = \Pr[i(t) < x] = \Pr(\partial T < T_1 \cup \partial T > T_2) = F_{\partial T}(T_1) + 1 - F_{\partial T}(T_2) \quad (4)$$

The solution of this equation is

$$i(t - T_0) = x \quad (5)$$

The received current $p_I(x)$ of the pdf is given by

$$p_I(x) = \frac{dF_I(x)}{dx} \quad (6)$$

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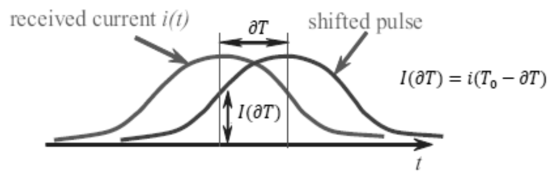

Figure 2. Conversion of time shift to the current distortion

2) Multipulse interactions and the nonlinear induced amplitude jitter: Pulses treated of the same frequency channel or they do not overlap. Indeed, in the system under study, each pulse overlaps with up to four of its neighbors due to the dispersive spreading. This interaction pulse combined with intra-channel nonlinear crosstalk between channels leads to an increase in jitter amplitude to be taken into account in the destination channel, besides the timing jitter, to obtain results accurate. Therefore we treat the electric field in the destination channel as the sum of electric fields of single pulses rather than simply adding powers so that

$$|u_0|^2 = |\sum_i \alpha_{0l} u_{0l}|^2 \neq \sum_i \alpha_{0l} |u_{0l}|^2 \quad (7)$$

We obtain the current distortion ΔI_{kl} using the expression

$$\Delta I_{kl}(t) = I_{kl}(t) - I_T(t) \quad (8)$$

We assume an arbitrary bit pattern, the total distortion $\Delta I(t)$ can be represented as a sum of individual contributions ΔI_{kl} peer interactions, so that

$$\Delta I(t) = \sum \alpha_{kl} \Delta I_{kl}(t) \quad (9)$$

Where $\alpha_{kl} = 1$ or 0

Then the pdf of the current is simply the inverse Fourier transform of the characteristic function,

$$p_{\Delta I}(I, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} v(\xi, t) e^{-i\xi I} d\xi \quad (10)$$

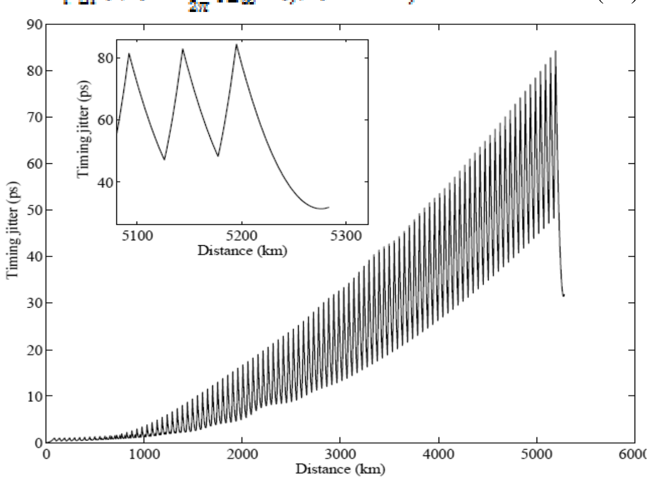

Figure 3. Timing jitter as a function of distance

B. Calculations Bit Error Ratio

We have developed for measuring the nonlinear penalty to calculate the BER in the presence of amplified spontaneous emission (ASE) noise from optical amplification. We will use the assumption that the nonlinear penalty is statistically independent of the ASE noise as greatly simplifies analysis. In principle, these two processes are not independent; as you can imagine the noise affect the signal, and him an effect of how signals interact. However, since the noise is a zero mean process, the resulting noise effect in the reduction or increase in the optical power of a pulse and thus nonlinear interference generated by this pulse. Over a large statistical ensemble tends to extinguish the correlation between nonlinear penalty and noise [10].

The most common model is Additive White Gaussian Noise (AWGN), which takes that the noise is completely independent of the signal and one can simply add noise contributions from all the inline amplifiers are the end of the previous optical transmission filter. Since the optical receiver includes a photo-detector square low, the signal distribution after the photo-detector is no longer Gaussian noise, which is called as radio communications. To calculate the Bit Error Ratio, we will use in combination with the Probability Density Function nonlinear induced current distribution with noise Probability Density Function. Our method for combining noise induced distortion and nonlinearly does not depend on the noise density function. Therefore, for the purpose of simplicity and calculate the Probability Density Function AWGN noise using the technique of Forestieri [9].

1) AWGN Model: Optical field consisting of the information signal and noise in a Fourier transform basis. Then we pass the field through optical filter with a frequency response $H_o(f)$, a square law photo-detector ideal, and an electrical filter with a response $H_e(f)$. Finally, we will evaluate the current of the Probability Density Function and BER at the sampling time t_k.

Assume $x(t)$ be the complex field of optical noise-free signal, which is periodic with a period of NT, where N is the number of bits in the sequence, and T is the bit period. Then, the signal $x(t)$ can be represented into a Fourier series as

$$x(t) = \sum_{l=-\infty}^{\infty} x_l exp\left(\frac{-i2\pi lt}{NT}\right) \quad (11)$$

Whereas

$$x_l = \frac{1}{NT} \int_{t=0}^{NT} x(t) \exp\left(\frac{i2\pi lt}{NT}\right) dt \quad (12)$$

For noise also uses Fourier expansion in the range $t_k - T_f < t < t_k$, where T_f is the time constant related to the time response of the filters:

$$T_f = \mu\left(\frac{1}{B_0} + \frac{1}{B_e}\right) \quad (13)$$

Where B_e and B_0 are bandwidths of electrical and optical filters.

The noise can then be represented by

$$w(t) \sum_{m=-\infty}^{\infty} w_m exp\left[\frac{-i2\pi m(t - t_k - T_f)}{T_f}\right]$$
$$t_k - T_f < t < t_k \quad (14)$$

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Where w_m is the independent complex Gaussian random variables with are zero mean and whose real and imaginary parts have a variance $\sigma^2 = N_0/2T_f$.

The Probability Density Function can be evaluated as

$$pdf_{nk}(\gamma) = \frac{1}{\pi}\int_{-\infty}^{\infty} Re\left\{exp\left[\varphi\left(u_s + \frac{1}{2}kv^2 + iv\right)\right](1 - ikv)\right\}dv \quad (15)$$

The Probability Density Function (equ. 15) can be calculated numerically using the trapezoidal rule and the integration intervals divide by two steps $(-\infty, 0]$ and $[0, \infty)$. The integration starts from $v = 0$ and stops when the sum contributions become negligible.

2) Combining nonlinear effects and noise: Assume that the nonlinear distortions induced signal-induced noise is statistically independent to calculate the BER. The Probability Density Function of collision induced time shift is given by the Probability Density Function of nonlinear distortion amplitude induced by $p_{\Delta I}(I,t)$ (equ. 10) is given by and Probability Density Function noise induced distortion is obtained from (equ. 15),

$$p_{noise} = pdf_{nk}(I - d_k - v_k) \quad (16)$$

In order to calculate the Probability Density Function $P(I,t)$ of the current I received at the sampling time t due to both signal distortion and nonlinear noise, the convolution of the Probability Density Function p_T time change or Gaussian Probability Density Function with noise Probability Density Function $p_{noise}(I,t)$ of the received current that is obtained by propagating a signal of one channel carrying a PRBS of length 32 through the system amplitude and distribution of jitter (equ. 9):

$$p(I,t) = \int_{\xi=-\infty}^{\infty}\left|\int_{\tau=-\infty}^{\infty} p_{noise}(\xi, t-\tau)\,p_T(\tau)\,d\tau\right| p_{\Delta I}(I-\xi, t)\,d\xi \quad (17)$$

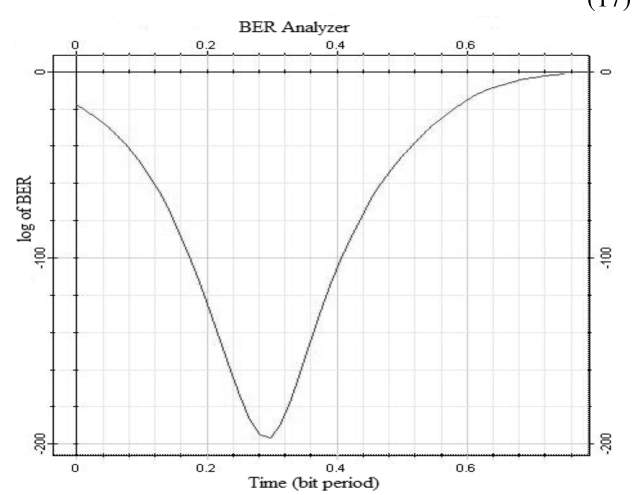

Figure 4. BER Analysis

As a result, the BER values obtained with the two methods are much closer to the two Probability Density Functions time shift. However, in the case of 25 GHz spaced channels, the jitter time leads to a very large error rate. At this point, the relative distance in the BER estimates obtained with the two methods becomes significant. As the calculation of the exact Probability Density Function collision induced change of time using the method of the characteristic function is not computationally expensive, we believe that you should always be used instead of the Gaussian approximation.

Comparison of results of different techniques

Input Bits	Signal Generator	Modulation Techniques	Optical Power (dB)	Min BER
10101100	RZ	MZ	20	$7.94587\times e^{-122}$
10101100	RZ	EAM	20	0
10101100	NRZ	MZ	20	$3.09973\times e^{-28}$
10101100	NRZ	EAM	20	$3.84761\times e^{-28}$
10101100	RZ	MZ	15	$1.86539\times e^{-59}$
10101100	RZ	EAM	15	$7.99419\times e^{-132}$
10101100	NRZ	MZ	15	$1.06647\times e^{-37}$
10101100	NRZ	EAM	15	$4.50779\times e^{-53}$

IV. CONCLUSION

The BER is the key figure of merit in an optical fiber communications and must be calculated accurately systems design. In this paper, we have addressed an important aspect of the evaluation of Bit Error Ratio (BER), the effect of nonlinearity in optical signal transmission and its contribution to the BER with optical amplifier noise.

In this paper, we have presented a new approach, whose essence is to characterize worth nonlinearly induced with a full Probability Density Function. One can use biased Monte Carlo simulations to estimate the Probability Density Function with the required accuracy. In this comprehensive statistical approach, we use the full propagation equation, which cannot be solved analytically for modeling the system and solve numerically by randomly changing the conditions of entry into each new simulation run.

The method for measuring BER proposed here is based on calculating the time shift Probability Density Function collision induced which is the main nonlinear effect and induced nonlinear fluctuation amplitude. This paper presents and validates the tools that allow one to characterize accurately and inter and intra-channel nonlinear effects in calculating the BER.

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