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Study on the efficiency of Eb/No algorithm for BER estimation over 112-Gb/s PDM CO-OFDM system with QPSK mapping

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ABSTRACT

We research an efficient BER estimation method for 112-Gb/s polarization division multiplexing coherent optical OFDM (PDM CO-OFDM) with QPSK mapping over 800 km SSMF based on Eb/No algorithm in this paper. We first lay out the related formulas' derivation to set up the theoretical basis for the feasibility of Eb/No algorithm and then we implement a series of simulations to illustrate the relationship of BER (and *Q* factor) versus OSNR, launch power of transmitter, chromatic dispersion and nonlinearity in optical fiber link via both Eb/No algorithm and Monte Carlo algorithm. The simulations demonstrate that BER estimated by Eb/No algorithm can achieve a precision up to 10^{-16} just with 10^5 bits while Monte Carlo algorithm needs at least 10^{18} bits to get the same level. Therefore, Eb/No allows a quick and reliable method for BER estimation instead of the time consuming Monte Carlo method, which can be used to support simulations with various conditions.

1. Introduction

Nowadays, orthogonal frequency division multiplexing (OFDM) is extensively investigated to be adopted into optical communication due to its superior performance like high spectral efficiency, robustness against channel impairments. [1,2] Together with coherent detection, coherent optical OFDM (CO-OFDM), which is regarded as an equivalent of RF OFDM used in digital communication, is proposed to combat the chromatic dispersion in fiber media. [1] Synthesizing the benefit of polarization division multiplexing which can easily double the system capacity while keeping the signal bandwidth the same at a moderate complexity level, [3] we adopt PDM CO-OFDM system together with QPSK symbol mapping for each subcarrier in this paper.

Comprehensively considering all the simulation parameters, BER (or *Q* factor) can be the critical indicator to evaluate the system performance. The Conventional BER estimation method that based on Monte Carlo algorithm is widely used in [1,2,4,8] and it can achieve a very high estimation accuracy. However, the guaranteed accuracy is realized at the expense of large amount of simulation data and time. In order to get the accurate BER result, at least 100 error bits should be counted. Meanwhile, the simulation bit number is in inverse proportion to BER, [5] which means that the smaller the BER is, the larger the required simulation bit number will be. Whereas BER in optical communication system is normally small with range of 10^{-12}–10^{-9}, that means the simulation bit number will be ranged from at least 10^{11} to 10^{14}. Contrary to Monte Carlo method, BER estimation method based on the electrical signal Gauss distribution quality [5,7,9] does not require large amount of simulation bits to achieve a pretty good BER accuracy with a wide range.

However, the instinct impairments like chromatic dispersion (CD), fiber nonlinearity, and phase noises etc. in coherent optical OFDM channels are not negligible and the high peak to average power ratio (PAPR) of OFDM is also a limiting factor. Considering all those special conditions in optical link, whether this method is reliable for 112-Gb/s PMD CO-OFDM system has not been conformed yet. Motivated by this, we have taken a series of systematical studies and investigations of BER estimation method based on Gauss distribution quality, Eb/No algorithm, and made a comprehensive comparison of the numerical simulations between MC method and Eb/No method in this paper, including the relationships of BER (*Q* factor) versus OSNR, simulation bit number, launch power, chromatic dispersion, fiber nonlinearity and so on. All of those experimental results demonstrate that accompanying with impairments like OSNR, CD, fiber nonlinearity, and modulator chirp in optical link, BER estimation based on Eb/No method could get a wide range with pretty good accuracy. Therefore, with regard to cost and complexity, Eb/No allows a quick and reliable assessment for PDM CO-OFDM system with QPSK mapping and offers an alternative solution to the time consuming Monte Carlo method.

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2. Theoretical model of Eb/No

BER estimation method based on Gauss distribution quality (Eb/No) is often used in digital communication system. Its presentation is shown in Eq. (1)

$$\text{Eb/No} = \frac{E_b}{N_0/2} \tag{1}$$

Where Eb is the average energy per bit, the ratio of signal power and duration of each bit, and No is the noise power spectral density, the ratio of the noise power and the noise bandwidth.

For CO-OFDM systems with QPSK mapping, the constellation of received digital data of all subcarriers shows four clusters of data points corresponding to four QPSK information symbols and the noise sources that spread each information symbol are mainly amplified spontaneous noise (ASE), phase noise of laser, chromatic dispersion, and fiber nonlinearity etc. in system. [10]. Since the optical OFDM nonlinear distortions are approximate to Gaussian distribution [11], besides, ASE and phase noise of laser can also be regarded as Gaussian noise, therefore, the BER can be derived from the symbol variance. Assuming there is no crosstalk or interference between two orthogonal carriers, the Eb/No can be obtained as Eq. (2)

$$q = \sqrt{\text{Eb/No}} = \sqrt{\frac{E_b}{N_0/2}} = \frac{\mu}{\sigma} = \frac{\mu_y}{\sigma_y} \tag{2}$$

Where μ and σ represent the mean and standard deviation of one constellation point of all OFDM subcarriers data respectively and they can obtained as μ_y and σ_y, where y stands for the considered branch (I or Q) [9]. In order to improve the reliability of estimation, all the symbols will be translated into a single quadrant (all $\{I, Q\} > 0$) in this paper, which is just the sample point. The method takes benefit of central symmetry character of constellation diagram as the in-phase (I) signal and the quadrature (Q) signal are equivalent from the point of system view.

Then BER can be expressed as [9]

$$\text{BER} = Q\left(\sqrt{\frac{E_b}{N_0/2}}\right) = \frac{1}{2}\text{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right) = \frac{1}{2}\text{erfc}\left(\frac{q}{\sqrt{2}}\right) \tag{3}$$

And the Q factor is

$$Q = 10\log_{10}(q^2) \tag{4}$$

Here we can see, as long as we find out the mean μ and the standard deviation σ of one branch (I or Q) in one constellation quadrant, we will be able to calculate the value of q and then BER and Q factor can be obtained according to Eqs. (3) and (4). Notice that the theoretical foundation of this method is that all impairments in CO-OFDM system are regarded as Gaussian noise.

As signal-to-noise ratio (SNR) is a measure of signal strength relative to background noise that used in analog and digital system, OSNR which represents the ratio of signal power to the noise power in "a given bandwidth" is proposed to be used in optical communication system. Since optical signal has a carrier frequency which is much higher than the modulation frequency, therefore, the bandwidth that the noise covers is far wider than that of signal itself, however, noise that actually influences the resulting signal is the filtering one. That is just what we say about "a given bandwidth", normally with a reference of 0.1 nm (12.5 GHz).

Since in digital communication system, the time length for sending and receiving symbol is represented by the symbol interval, the average power per symbol is equal to 0 therefore instead of power, symbol energy, which is the integral of power within symbol interval, is commonly used in digital system. Based on this, we will discuss the relationship between OSNR in optical domain and Eb/No (Q factor and BER) in digital domain.

Assume that the energy of one bit equal is to E_b, and the energy of one symbol is E_s. Then we have Eq. (5) where M is the modulation level.

$$E_s = \log_2 M \times E_b \tag{5}$$

Zero padding (ZP) is some kind of guard band for original signal, and it is actually part of the subcarriers, typically at both ends of band. Therefore, the Eq. (5) can be rewritten as Eq. (6),

$$E_s = \log_2 M \times (1 - \eta_{zp}) \times E_b \tag{6}$$

where $\eta_{zp} = N_{zp}/N_{IFFT}$ is the ratio of ZP. N_{zp} is the subcarrier number for ZP and N_{IFFT} is all subcarrier number for IFFT operation.

Cyclic prefix (CP) insertion is realized after IFFT operation, so the symbol energy within the time length of one OFDM symbol block T_d will be distributed into a time period of $T_d + T_{cp}$, where T_{cp} is the time length of CP, and the ratio of CP will be $\eta_{cp} = T/(T_d + T_{cp})$, therefore

$$E_s = \log_2 M \times \eta_{cp} \times (1 - \eta_{zp}) \times E_b \tag{7}$$

Assuming that the time length of one symbol is equal to T_S, the signal power in channel will be

$$\begin{aligned} P_s &= \frac{E_s}{T_s} = E_s \times R_s \\ &= [\log_2 M \times \eta_{cp} \times (1 - \eta_{zp}) \times E_b] \times \frac{R_b}{\log_2 M \times \eta_{cp} \times (1 - \eta_{zp})} \\ &= E_b \times R_b \end{aligned} \tag{8}$$

Where R_s is the symbol rate and R_b is the bit rate.

In optical domain, the noise power for OSNR with 0.1 nm (12.5 GHz) bandwidth is represented as

$$P_n = \frac{N_0}{2} \times 2 \times B_N = N_0 \times B_N \tag{9}$$

Therefore, the OSNR can be express as Eq. (10)

$$\text{OSNR} = \frac{P_s}{P_N} = \frac{E_b R_b}{N_0 B_N} = \frac{E_b}{N_0} \times \frac{R_b}{B_N} \tag{10}$$

Because our system is a dual polarization system, then we can rewrite Eq. (10) as

$$\frac{E_b}{N_0/2} = \frac{B_N}{R_b} \times \text{OSNR} \tag{11}$$

Since

$$\begin{aligned} \text{BER} &= \frac{1}{2}\text{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right) \\ Q &= 20 \times \log 10\left\{\sqrt{2} \times \text{erfcinv}\,[2 \times \text{BER}]\right\} \end{aligned} \tag{12}$$

And OSNR can be translated into decibel form with $\text{OSNR} = 10^{\text{OSNR}_{dB}/10}$

Then combining Eqs. (11) and (12), we have the Eq. (13) as

$$\begin{aligned} \text{BER} &= \frac{1}{2}\text{erfc}\left(\sqrt{10^{\text{OSNR}_{dB}/10} \times \frac{2B_N}{R_b}}\right) \\ Q &= 10\log_{10}\left(2 \times 10^{\text{OSNR}_{dB}/10} \times \frac{2B_N}{R_b}\right) \end{aligned} \tag{13}$$

Eq. (13) is exactly the formula we use to calculate our theory value of BER and Q factor.

3. Illustration of simulation system

In this paper, all of our simulations are implemented based on 112-Gb/s PDM CO-OFDM system. Its schematic model is shown in Fig. 1.