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Accuracy of EGN Model in Ultra-Wideband Optical Fiber Communication Systems

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ABSTRACT

The efficient and accurate evaluation of the transmission performance of high-capacity optical communication systems has always attracted significant research attentions. The enhanced Gaussian noise (EGN) model is considered as an excellent solution to predict the system performance taking into account linear and nonlinear transmission impairments. Since the conventional form of the EGN model is complicated and intractable for a fast computation, the closed-form simplification has been regarded as a direction to significantly reduce the computational complexity. However, the accuracy of such a closed-form EGN model becomes a main concern in the application of ultra-wideband optical communication systems. In this work, we have investigated the accuracy of the closed-form EGN model for ultra-wideband optical fiber communication systems, where the performance of the system using electronic dispersion compensation, multi-channel nonlinearity compensation and full-field nonlinearity compensation has been evaluated in terms of symbol rate, number of channels and signal power. Our work will provide an insight on the application of the EGN model in next-generation ultra-wideband long-haul optical fiber communication networks.

Keywords: Optical fiber communicaiton, EGN model, Ultra-wideband system, Fiber nonlinearities, Digital nonlinearity compensation

1. INTRODUCTION

Currently, over 95% of digital data traffic is carried over optical fiber networks. With the development of technology, people put forward higher requirements on the amount data transmission. To transmit more data at the same time, the symbol transmission rate and communicaiton bandwidth are constantly increasing. As a result, higher and higher spectrum efficiency leads to more serious nonlinearity interference. It is particularly important to accurately and quickly evaluate the signal-to-noise ratio (SNR) of high-speed and ultra-wideband optical fiber communication systems.[1] The process of optical signal transmission in fiber is complex and unresolvable, but fortunately, the Enhanced GN-model (EGN model),[2–11] arising from the Gaussian noise perturbation analysis, can evaluate the system SNR accurately. To simplify the calculation, a closed-form formula is proposed using some mathematical approximation.[12] In this paper, EGN model will be applied in the closed-form manner. The system will be operated at high symbol rate and larg bandwidth to verify the accuracy of EGN model. The transceiver noise has been added to better judge the actual situation, and EGN model has also been adjusted accordingly.[13–16] At the end of the work, nonlinear compensation using digital back-propagation (DBP)[8,17–23] algorithm was also employed to verify EGN model comprehensively.

This paper is arranged as follows. The transmission system and its parameter settings as well as the structure of EGN model are shown in Section 2. Section 3 details the simulation results and analyses. Conclusions will be summarized in Section 4.

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2. TRANSMISSION SETUP AND EGN MODEL

2.1 Optical transmission system

Figure 1 illustrates the structure of the Nyquist-spaced optical fiber communicaiton simulation system. Data are loaded on optical carriers using quadrature amplitude modulation (QAM) format. The combination of wavelength division multiplexing (WDM) and polarisation division multiplexing (PDM) allows the simultaneous transmission of multiple channels. The signal transmission process in fibers is simulated by numerically solving Manakov equation using split-step Fourier transform method (SSFM), and the step length is set small enough to maintain the simulation accuracy. The erbium-doped fiber amplifier (EDFA) is applied to compensate for the power loss of the optical signal. A coherent receiver is employed to detect the signal at the end of system. Digital signal processing is implemented to perform the electronic dispersion compensation (EDC), DBP, matched filtering and the SNR calculation.

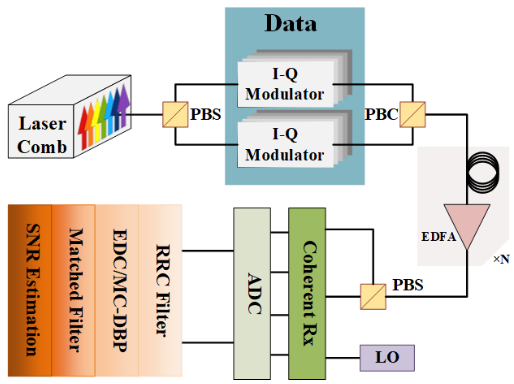

Figure 1. Schematic of the Nyquist-spaced optical fiber communication simulation system using EDC or MC-DBP. PBS: polarisation beam splitter, PBC: polarisation beam combiner, LO: local oscillator, Rx: receiver, ADC: analogue-to-digital convertor

Detailed parameters of the simulation system is listed in Table 1, and the signal is operated at optical launch power unless it is specified.

Table 1. Simulation system parameters.

Parameter Name	Value
Center wavelength	1550 nm
Attenuation coefficient (α)	0.2 dB/km
Chromatic dispersion coefficient (D)	17 $ps/nm/km$
Nonlinear coefficient (γ)	1.2 $/W/km$
EDFA noise figure	4.5 dB
TRx noise SNR	25 dB
Fiber span length	80 km
Simulation step size	Logarithmic ($\geq$ 1600 steps)
PMD	0

2.2 EGN model

For dual-polarisation multi-span EDFA amplified Nyquist-spaced WDM transmission systems, the amplifier spontaneous radiation (ASE) noise can be considered as additive Gaussian noise in the EGN assumption. As described in Ref 24, ASE nosie power is expressed as follows:

$$\sigma^2_{\mathrm{ASE}} = N_s(G-1)F_n h\mu_0 R_s \tag{1}$$

where G is the EDFA gain, F_n is the EDFA noise figure, N_s is the amount of fiber spans, h is Plank constant and μ_0 is the center lightwave frequency. For nonlinear noise, the following formula is obtained by Ref 5–7,9,10,15,25–27:

$$\sigma^2_{\mathrm{NLI}} = \sigma^2_{\mathrm{s-s}} = N_s^{\epsilon+1}\eta_{\mathrm{EGN}}P^3 \tag{2}$$

$$\eta_{\mathrm{EGN}} \approx \eta_{\mathrm{GN}} - \frac{80}{81}\frac{\kappa\gamma^2 L^2_{\mathrm{eff}}}{\pi|\beta_2|L_{\mathrm{s}}R^2_{\mathrm{s}}}\left[\Phi\left(\frac{N_{\mathrm{ch}}+1}{2}\right)+C+1\right] \tag{3}$$

$$\eta_{\mathrm{GN}} \approx \left(\frac{2}{3}\right)^3 \frac{\alpha\gamma^2 L^2_{\mathrm{eff}}}{\pi|\beta_2|R^2_{\mathrm{s}}} arsinh\left(\frac{\pi^2}{2}|\beta_2|L_{\mathrm{eff}}N^2_{\mathrm{ch}}R^2_s\right) \tag{4}$$

$$\epsilon \approx \frac{3}{10}Log_e\left[1+\frac{6}{L_s}\frac{L_{\mathrm{eff}}}{arsinh\left(\frac{\pi^2}{2}|\beta_2|R^2_{\mathrm{s}}L_{\mathrm{eff}}N^2_{\mathrm{ch}}\right)}\right] \tag{5}$$

where the constant κ is related to the fourth standardised moment (kurtosis) of the input signal constellation. For QPSK (4-QAM), 16-QAM, 64-QAM, and 256-QAM, its values are $[1, 17/25, 13/21, 121/200]$. Function $\Phi(x)$ is digamma function, and $C \approx 0.557$ is Euler-Mascheroni constant, β_2 is group velocity dispersion coefficient, α is fiber attenuation coefficient γ is fiber nonlinear coefficient, L_{eff} is effective fiber span length, N_{ch} is the total number of WDM channels, R_{s} is symbol rate. Considering the combine effect of ASE noise and nonlinear interference, and DBP compensation,[20,28] EGN model can be written as the following form:

$$SNR = \frac{P}{\tilde{\kappa}P + \sigma^2_{\mathrm{ASE}} + 3\eta(\xi_{\mathrm{TRx}}\tilde{\kappa}P + \xi_{\mathrm{ASE}}\sigma^2_{\mathrm{ASE}})P^2} \tag{6}$$

$$\xi_{\mathrm{ASE}} = \sum_{n=1}^{N_{\mathrm{s}}} n^{\epsilon+1} \approx \frac{N_{\mathrm{s}}^{\epsilon+1}}{2} + \frac{N_{\mathrm{s}}^{\epsilon+2}}{\epsilon+2} \tag{7}$$

$$\xi_{\mathrm{TRx}} = N_{\mathrm{s}}^{\epsilon+1} \tag{8}$$

$$\eta = \eta(\text{WDM bandwidth}) - \eta(\text{DBP bandwidth}) \tag{9}$$

where $\tilde{\kappa}$ is a constant related to transceiver noise figure. In this paper, the EGN model results are all derived from Eq. (6).

3. RESULTS AND DISCUSSIONS

To investigate the impact of transmission bandwidth, the transmission distance is set as 800 km (10 spans), and the results are shown in Fig. 2. It can be seen from Fig. 2(a) that the SNR curves of 16QAM, 64QAM and 256QAM are highly coincident, slightly lower than that of QPSK modulation format. A good agreement has been achieved between the numerical simulations and the EGN model. Therefore, to simply the analysis, only 16QAM results are plotted in Fig. 2(b) and 2(c). Observing the distance between EGN model curves and corresponding color markers in Fig. 2(b), the EGN model under ultra-large bandwidth is highly credible. The fitting curves in Fig. 2(c) is plotted to illustrate the accuracy of EGN model in detail. The closed-form EGN model is inaccurate in estimating self-channel interaction (SCI)[7] effect, since the calculation of estimating SCI effect can not be simplified. Therefore, the performance of EGN model in a small bandwidth is not as accurate as in a large bandwidth, as shown in the shaded area in Fig. 2(c). However, the deviation of EGN model is always within 0.2 dB, which is small enough to be considered as an accurate representation. At a large bandwidth, such as 0.6 THz to 3.3 THz, EGN model shows a good accuracy. In summary, in high-speed ultra-wideband optical communication systems, EGN model has sufficient accuracy as a tool to estimate SNR quickly.

The system using multi-channel digital back-propagation (MC-DBP) for compensating nonlinear interaction is also investigated. EGN model results are obtained by solving Eq. (6), where η(DBP bandwidth) is calculated

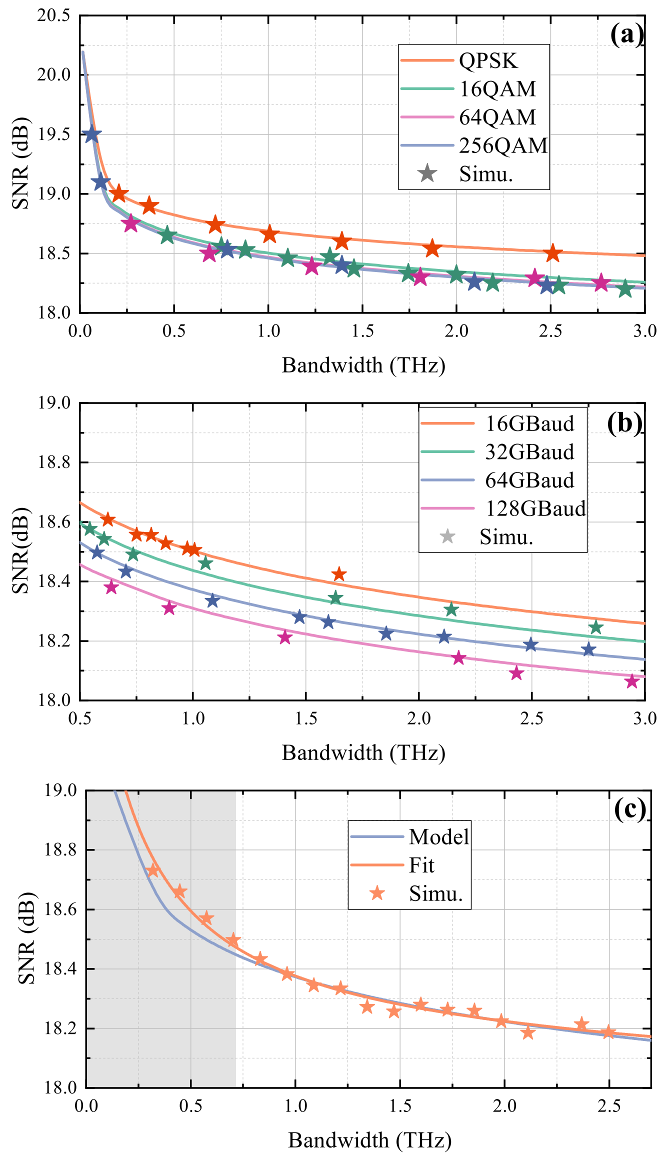

Figure 2. (a): Model v.s. simulation in different modulation formats at 16 GBaud. (b): The accuracy of EGN Model at different symbol rate using 16QAM. (c): Details of Simulation results and EGN model results at 64 GBaud in 16QAM. The blue line is fitted by simulation results.

by substituting the amount of MC-DBP channels for N_{ch} in Eq. (3) and Eq. (4). The results are shown in Fig. 3. It can be seen that EGN model matches the simulation results well. In addition, the relationship between SNR and MC-DBP bandwidth is not linear, but close to "S" shape. This is more obvious at high symbol rate (comparing the orange curve and blue curve in Fig. 3). Therefore, the compensation bandwidth should be appropriately selected to obtain the maximum performance-to-cost ratio.

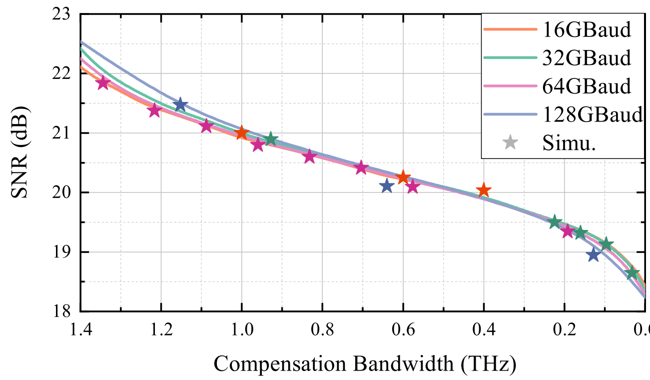

Figure 3. Model v.s. simulation at different nonlinear compensation bandwidth. 0 Hz means chromatic dispersion compensation only. The simulation system was launched at around 1.5 THz (Round up the decimal part).

The accuracy at different powers of EGN model has been studied using a system with a bandwidth of 1.5 THz to transmit 800 km (80 km x 10) in 16-QAM at 16 GBaud and 64 GBaud. Due to the nonlinearity, the system will have an optimal power that maximizes the SNR. For EGN model, the premise is Gaussian noise assumption, which requires nonlinear effect cannot be too strong. So when the power gets larger and larger, the accuracy of the EGN model will decrease. However from a practical engineering perspective, the system will be launched near the optimal power, so it is not of high significance to study the accuracy of the model under strong nonlinearity. As shown in Fig. 4, EGN model is accurate enough near the optimal power.

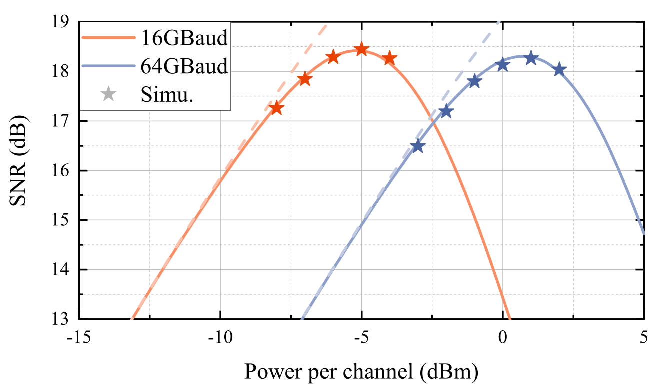

Figure 4. Model v.s. simulation at different launched power. Dotted lines is plotted when only ASE noise exists.

4. CONCLUSIONS

In this paper, we have investigated the accuracy of the closed-form EGN model under different transmission scenarios. As a result, the EGN model shows extremely high accuracy at ultra-large bandwidth to estimate optical communication system's SNR quickly. For systems with nonlinear compensation methods (MC-DBP), the EGN model still has a high credibility. We extended the conclusions in the original paper[2,7] at larger bandwidth and higher symbol rate, and proved the accuracy of the EGN model in more extreme cases. In summary, the closed-form EGN model can quickly and accurately evaluate the high-speed ultra-wideband optical communication system's SNR, near the optimal power with and without the use of MC-DBP to compensate for nonlinear interference.

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