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Mitigating Nonlinear Impairments in High-Speed Optical Communication Systems via Volterra Nonlinear Equalizer

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Data Availability Statement

The data supporting the findings of this study are publicly available and are included within this published article.

ORIGINAL ARTICLE

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Abstract

This paper presents an in-depth investigation into applying a frequency domain Volterra series nonlinear equalizer (FD-VNLE) to mitigate nonlinear impairments in optical communication systems operating at high speeds. The study aims to address the issues presented by nonlinear effects, specifically self-phase modulation (SPM), which significantly degrades system performance at higher power levels. A comprehensive mathematical model of the FD-VNLE was developed to provide theoretical insight, while its implementation was carried out using MATLAB co-simulated with OptiSystem. The performance of the 40 Gbps dual-polarization quadrature phase shift keying (DP-QPSK) system was rigorously evaluated, focusing on critical performance metrics like bit error rate (BER) and quality factor (Q-factor). Simulation results indicated that without nonlinear compensation, the system experienced performance degradation beyond an input power of 12 dBm, where the optimum BER was 10^{-77} and the Q-factor was 18. However, deploying FD-VNLE and applying digital signal processing (DSP) successfully reduced the BER to 10^{-300} and improved the Q-factor to 100, maintaining consistent performance up to an input power of 17 dBm. The DSP further diminished residual phase noise and significantly improved the reliability of the system. These findings highlight the promise of FD-VNLE as a powerful tool for enhancing the efficiency and scalability of next-generation high-speed, long-distance optical networks.

Keywords: VNLE, DP-QPSK, Nonlinear impairments, SPM, Optical communication

1. Introduction

Recently, the demand for high-capacity multimedia traffic with extensive transmission range has increased. Optical fiber communication technology is a crucial medium for facilitating high-capacity, extensive traffic, and long-distance transmission. In conventional fiber-optic systems, the Kerr nonlinearity of fiber is an essential factor limiting the enhancement of reach and throughput [1]. The Kerr effect, arising from the dependence of fiber refractive index on the intensity of a signal that will be transmitted, renders the fiber a nonlinear channel; self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM) are nonlinear phenomena resulting from this effect [2].

Among several electrical nonlinearity equalization solutions, the Volterra series nonlinear equalizer (VNLE) has shown favorable performance, processing time, and computational complexity. The frequency domain VNLE utilizes established closed-form solutions from the Volterra series expansions for Schrödinger's nonlinear equation, specifically designed for single-mode fiber. This method employs a higher-order feedforward Volterra filter in conjugation with a linear filter to effectively mitigate in-line dispersion. Notably, only odd-order Volterra filters should be accounted for due to the inherent symmetries of the fiber media [3]. Using higher-order Volterra filters will increase complexity. As a result, just the implantation of a 3rd-order Volterra filter is being accounted [4]. VNLE has been utilized in numerous

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studies for mitigating fiber nonlinearities in optical systems, as noted by Gao et al. [5] Integrated Volterra transfer functions with neural networks, Mhatli et al. [6] Who compared the performance of the third-order Volterra series and least mean square (LMS) algorithms regarding BER over different transmission distances and modulation schemes, Fang et al. [7] Investigated the application of Volterra Expansion-Based Nonlinear Equalization (VENE) to mitigate intra-channel nonlinear effects, and Castro et al. [8] who used the learned Volterra model to mitigate nonlinearity. These studies demonstrate the effectiveness of Volterra-based methodologies, which align with the primary focus of this research. Table 1 illustrates the key improvement of FD-VNLE over traditional nonlinear compensation techniques. FD-VNLE balances between the performance and computational complexity it uses a model-driven approach that allows an analytical understanding of nonlinearities while avoiding the high computational complexity [9].

This study proposes mathematical modeling for mitigating the nonlinearities in single-channel optical fiber systems utilizing the Volterra series transfer function, where SPM is the dominant nonlinearity. A VNLE was developed using MATLAB and co-simulated with OptiSystem to enable effective compensation for SPM. The system is based on Quadrature phase-shift keying (DP-QPSK), combining theoretical modeling with simulated implementation to enhance system performance.

1.1. Fiber nonlinearities

Optical transmission via single-mode fiber (SMF) faces substantial issues, with the nonlinear impacts presenting a considerable constraint during high rates of transmission [10]. This optical link operates as a nonlinear material, primarily due to the Kerr effect. Which it generates several kinds of nonlinearity dependent upon channel separation in multiple-channel networks and the optical signal amplitude. These nonlinear phenomena include SPM, XPM, and FWM [9].

1.2. Self-phase modulation

The SPM results from the interaction between the propagating signal and the fiber, causing a variation in the phase of the signals. Fluctuation in signal amplitude inside the fiber causes variations in the index of refraction, which in turn affects the signal phase. SPM is marked by a self-generated nonlinear phase shift, leading to phenomena referred to as frequency chirping. The frequency chirping interacts with the dispersion in the fiber, resulting in the optical pulse being broadened spectrally. The degree of pulse broadening increases in the transmission systems that have a higher input power [11].

1.3. Cross-phase modulation

Transmission systems are no longer confined to single-channel configuration. Multiple-channel transmission in wavelength division multiplexing (WDM) systems and subcarrier multiplexing in super-channel techniques for next-generation systems facilitate the type of nonlinear phase modulation termed XPM. The refractive index of fiber is influenced by the intensity of its primary optical signal as well as the intensity of supplementary copropagating signals. XPM transpires when

Table 1. Comparison of FD-VNLE with traditional nonlinear compensation techniques.

Feature	Digital Back Propagation (DBP)	Phase Conjugation (PC)	Perturbation-based NLC	FD-VNLE (Proposed Method)
Nonlinearity Compensation	High (ideal model)	Moderate	Good (first-order approximation)	High (models high-order nonlinear effects)
Computational Complexity	Very High	Low to Moderate	Moderate	Moderate (optimized in frequency domain)
Performance at High Data Rates	Good but limited by the complexity	Moderate	Good	Excellent (balances performance and complexity)
Scalability to Wavelength Division Multiplexing Systems	Difficult due to cross-channel interference	Limited (works best in symmetric setups)	Moderate	Scalable (handles multi-channel systems)
Implementation Feasibility	Challenging (especially for long-haul links)	Easier but limited to symmetric systems	Feasible, but accuracy depends on model order	Practical, especially in real-time digital receivers

multiple optical signals of varying wavelengths propagate simultaneously within the cable. The nonlinear phase shift of a channel with wavelength λ_i is dependent upon its power P_i and the power of other copropagating channels due to XPM [12].

$$Y(\omega) = H_1(\omega)X(\omega) + \sum_{n=2}^{\infty} \int \cdots \int H_n(\omega_1, \cdots, \omega_{n-1}, \omega) \times X(\omega_1)\cdots X(\omega_{n-1}) \times X(\omega - \omega_1, \cdots, \omega_{n-1}) d\omega_1 \cdots d\omega_{n-1} \quad (1)$$

1.4. Four-wave mixing

Unlike XPM and SPM, FWM features an energy exchange process among simultaneously propagating channels, leading to nonlinear phase alteration in the optical field. This transfer results in a decrease in power, leading to diminished performance. Additionally, FWM generates inter-channel crosstalk, where the generated signal interferes with other copropagating channels, significantly decreasing system efficiency due to these crosstalk effects. The dispersion of the fiber and separation between channels influence the effect of FWM. Changes in fiber dispersion with wavelength result in FWM-generated signal traveling at different speeds compared to the original signal. As a result, enhanced fiber dispersion restricts interactions between signals and lessens the power available for newly produced signals. The impact of FWM diminishes with wider channel spacing. When channel spacing is large, the effect of FWM is compatibly reduced due to the quick separation of the two signals. However, FWM becomes more substantial with tighter channel spacing [11].

2. Methodology

The Volterra series is one of the initial methods for systematically characterizing a nonlinear system. It is a strong mathematical tool for the investigation of nonlinear systems. It is fundamentally an expansion of the conventional convolution framework for linear systems to accommodate nonlinear systems [13].

In 1997, Peddanarappagari and Brandt-Pearce used the Volterra series transfer function (VSTF) approach to solve the NLSE. Following that, various modifications of this approach have been applied to reduce fiber nonlinearity [14]. An optical channel is modeled using VSTF, and a pth-order theory is developed to derive the inverse VSTF (IVSTF) kernels. IVSTF kernels are employed to characterize the nonlinear equalizer that reduces the effects of nonlinearity in fiber and CD. The Volterra transfer function is obtained in the frequency domain as the correlation between the Fourier transforms of a system's output $\Upsilon(\omega)$ and its input $X(\omega)$.

H_n (ω_1, ..., ω_{n-1}, ω) represents the nth-order kernel within the frequency domain. The even-order Volterra kernels are null because of symmetries present in the fiber. Additionally, in the study of Kerr effects in the fiber optic links, it has been shown that kernels with n greater than 3 have a minimal impact on the analysis [4].

2.1. Mathematical modelling for nonlinear single channel fiber using FD-VSTF

The process of signal traveling in a Dual-Polarization system can be explained using the Manakov Equation (5):

$$\frac{\partial}{\partial z}A_{x/y} + j\frac{\beta_2}{2}\frac{\partial^2}{\partial y^2}A_{x/y} + \frac{\alpha}{2}A_{x/y} = j\frac{8}{9}\gamma\left(\left|A_{x/y}\right|^2 + \left|A_{y/x}\right|^2\right)A_{x/y} \quad (2)$$

$A_{x/y}$ denotes the abbreviation $A_{x/y}$ (t, z), which signifies the gradually changing complex filed envelopes in the x/y polarization component at the time t and position z. The parameters of the fiber, denoted by β_2, α, and γ, represent group velocity desertion, attenuation, and nonlinear coefficient, respectively [15]. The NLSE can be represented utilizing VSTF kernels of a maximum order of three as:

$$A_{x/y}(\omega, z) = H_1(\omega, z)A_{x/y}(\omega) + \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} H_3 (\omega_1, \omega_2, \omega_1 z) \times \left[A_x(\omega_1)A_x^*(\omega_2) + A_y(\omega_1)A_y^*(w_2)\right] \times A_{x/y}(\omega - \omega_1 + \omega_2)d\omega_1 d\omega_2 \quad (3)$$

$A(\omega) = A(\omega, 0)$ is the Fourier transform of the input optical signal, the operator (.)* represents the complex conjugate, H_1 is the linear transfer function (first-order kernel), and H_3 is the nonlinear transfer function (third-order kernel) [4]. Described in Eqs. (4) and (5), respectively:

$$H_1(\omega,z)=e^{-\left(\frac{x}{2}-\frac{j\omega^2\beta_2}{2}\right)L} \tag{4}$$

$$H_3(\omega_1,\omega_2,\omega_1 z)=j\frac{8}{9}\frac{\gamma}{u\pi^2}H_1(\omega,z)\frac{e^{-(x-j\beta_2(\omega-\omega_1)(\omega_1-\omega_2))L}}{\alpha+j\beta_2(\omega-\omega_1)(\omega_1-\omega_2)} \tag{5}$$

These are corresponding inverse kernels [16]:

$$\tilde{K}_1=e^{\left(\frac{\alpha}{2}-j\frac{B_2}{2}\omega^2\right)L} \tag{6}$$

$$\tilde{K}_3=-\mathrm{j}\frac{8}{9}\frac{\gamma}{4\pi^2}\tilde{K}_1(\omega,L)\frac{1-e^{(\alpha-i\beta_2(\omega-\omega_1)(\omega_1-\omega_2)L)}}{-\propto+j\beta_2(\omega-\omega_1)(\omega_1-\omega_2)} \tag{7}$$

The input-output inverse nonlinear Volterra filtering, derived from these analyses, is as follows:

$$\widehat{A}(\omega,z_0)=\tilde{K}_1(\omega)A(\omega,z_0+L)+\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\tilde{K}_3(\omega_1,\omega_2,\omega)A^{(z_0+L)}_{(\omega_1,\omega_2,\omega)}\,d\omega_1,d\omega_1 \tag{8}$$

Fig.1 demonstrates a unique phase of digital backward propagation that employs parallel VSTF, the received signal $A_{x/y}$ (t,z_o + L)is transformed to the frequency domain via a DFT. The linear component is compensated using the $\tilde{K}_1$ Kernal, while the nonlinear interaction terms are modeled and compensated through $\acute{G}(\omega)$, The outputs are combined, resulting in an equalized signal in the frequency domain which is then converted back to the time domain via IDFT. The 1st-order Volterra term acts as a linear filter to aid in adjusting chromatic dispersion (CD). This linear filter operates in parallel with the nonlinear filter. $\acute{G}$ (ω) which incorporates the VSTF. The post-equalization signal is represented as a combination of linear and nonlinear components:

$$\widehat{A}(\omega,z_0)=\widehat{A}_{lin,x/y}(\omega,z_0)+\widehat{A}_{nl,x/y}(\omega,z_0) \tag{9}$$

Based on the signals received in both polarization components Ax (ω) and Ay (ω), the equation provided can be used to derive both linear and nonlinear components.

$$\widehat{A}_{lin,x/y}(\omega,z_0)=\tilde{K}_1(\omega)A(\omega,z_0+L) \tag{10}$$

$$\widehat{A}_{nl,x/y}(\omega,z_0)=\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\tilde{K}_3(\omega_1,\omega_2,\omega)A^{(z_0+L)}_{(\omega_1,\omega_2,\omega)}\,d\omega_1,d\omega_1 \tag{11}$$

$$A^{(z_0+L)}_{(\omega_1,\omega_2,\omega)}\triangleq A^*(\omega_2,z_0+L)\times A(\omega,z_0+L)\times A(\omega-\omega_1+\omega_2,z_0+L) \tag{12}$$

By substituting Eq. (11) into Eq. (5), we derived the nonlinear filtering equation for both polarizations:

$$\widehat{A}_{nl,x/y}(\omega,z_0)=\tilde{K}_1(\omega)\acute{G}(\omega) \tag{13}$$

The formulation is expressed here for convenience.

$$\acute{G}(\omega)=\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}-j\frac{8}{9}\frac{\gamma}{4\pi^2}\frac{-e^{(\propto-i\beta_2(\omega-\omega_1)(\omega_1-\omega_2)L)}}{-\propto+j\beta_2(\omega-\omega_1)(\omega_1-\omega_2)}A^{(z_0+L)}_{(\omega_1,\omega_2,\omega)}\,d\omega_1,d\omega_1 \tag{14}$$

2.2. Simulation setup

As illustrated in Figs. 2–4. A 40 Gbit/s DP-QPSK signal was generated with a symbol rate of 10 G symbol/s. An optical signal was introduced into a nonlinear optical fiber measuring 100.2 km in length which is based on a practical case study between Shoresh/Erbil and Chama Denaran, 0.2 dB/km attenuation erbium-doped fiber amplifier (EDFA) for adjusting power levels, and an optical filter known as the Gaussian optical filter (GOPF), featuring a bandwidth of 60 GHz, is utilized to block

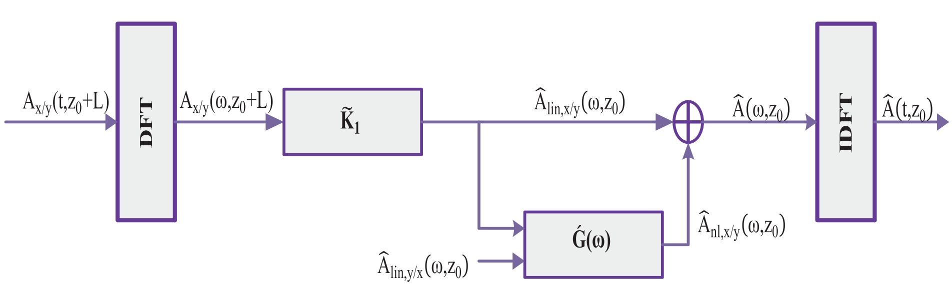


Fig. 1. Block diagram of VSTF structure.

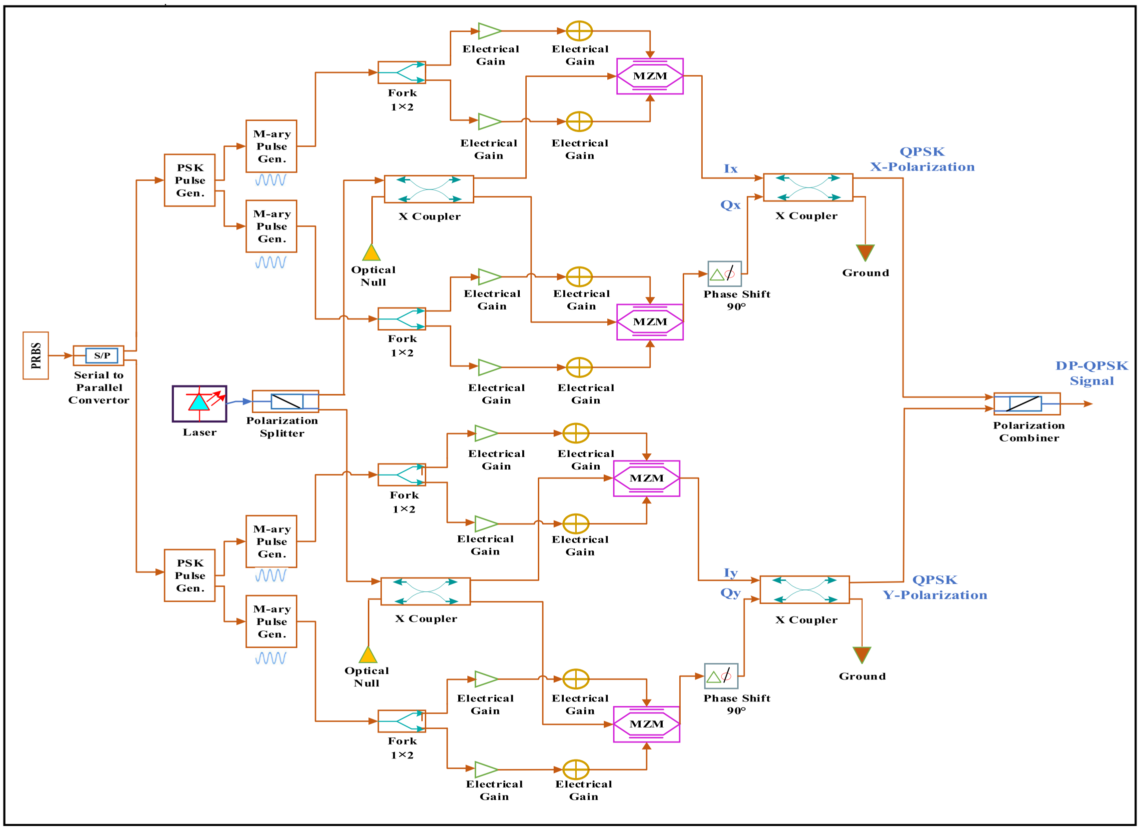


Fig. 2. DP-QPSK Transmitter.

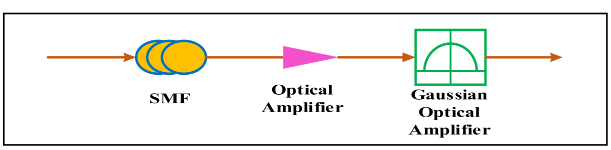


Fig. 3. Optical Fiber Communication Channel.

the noise that comes from out-of-band amplified spontaneous emission from overwhelming the EDFAs and improve the signal-to-noise-ratio (SNR). It enhances spectral shaping for perfect coherent detection. In a coherent DP-QPSK receiver, four signals detected by balanced photodiodes were processed using VNLE for equalization. The VNLE was implemented by using a MATLAB code and co-simulated with OptiSystem simulator frequency offset recovery and carrier phase recovery performed by using a DSP. The BER analyzer was used to obtain the results, while the constellation visualizer provided the constellation diagram.

3. Results and discussion

The analysis was conducted on the performance of a 40 Gbps DP-QPSK optical communication system, focusing on the influence of input power on critical system parameters, including BER and Q-factor. The system's capability to reduce nonlinear impairments was evaluated utilizing an FD-VNLE and DSP for carrier phase estimation. The results are presented in two scenarios: one without compensation techniques and another with FD-VNLE and DSP applied. Fig. 5 shows the system's behavior without nonlinear compensation. As seen in Fig. 5(A), the BER initially decreases with increasing input power, reaching the lowest value of 10^{-77} at an optimal power level of 9 dBm. However, beyond this point, the BER begins to increase rapidly due to the onset of nonlinear impairments such as SPM, which distort the transmitted signal. This degradation becomes more significant as the input power exceeds 12 dBm. Similarly, Fig. 5(B) illustrates the relationship between input power and Q-factor. Initially, the Q-factor increases with power, peaking at 18 around 9 dBm of input power, where the system performs optimally. However, as input power continues to rise, nonlinear effects dominate, causing a sharp decline in the Q-factor. This decline indicates the system's inability to sustain higher power levels without compensation, limiting the practical operational power range to 12 dBm, beyond which performance drops drastically.

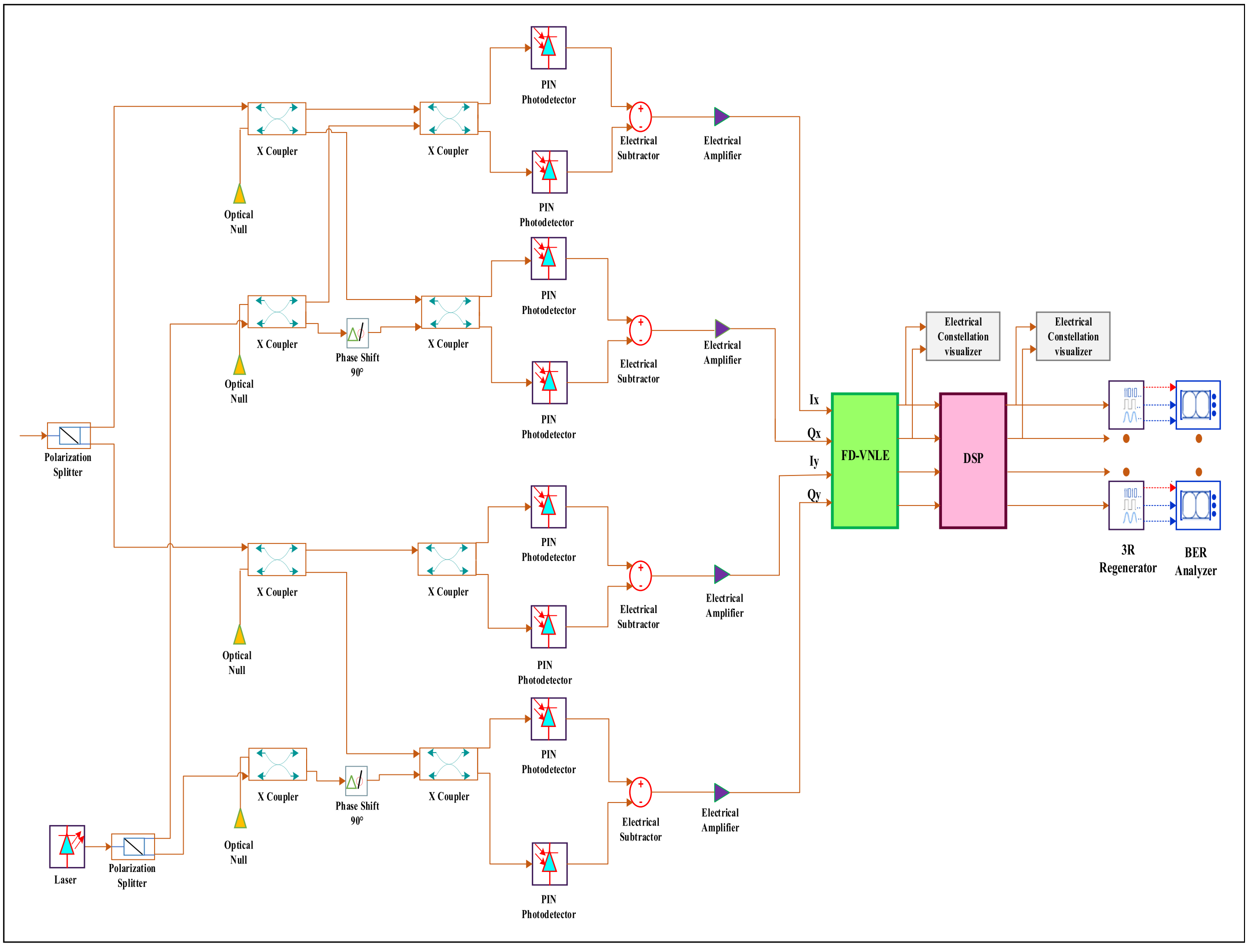


Fig. 4. DP-QPSK Coherent Receiver.

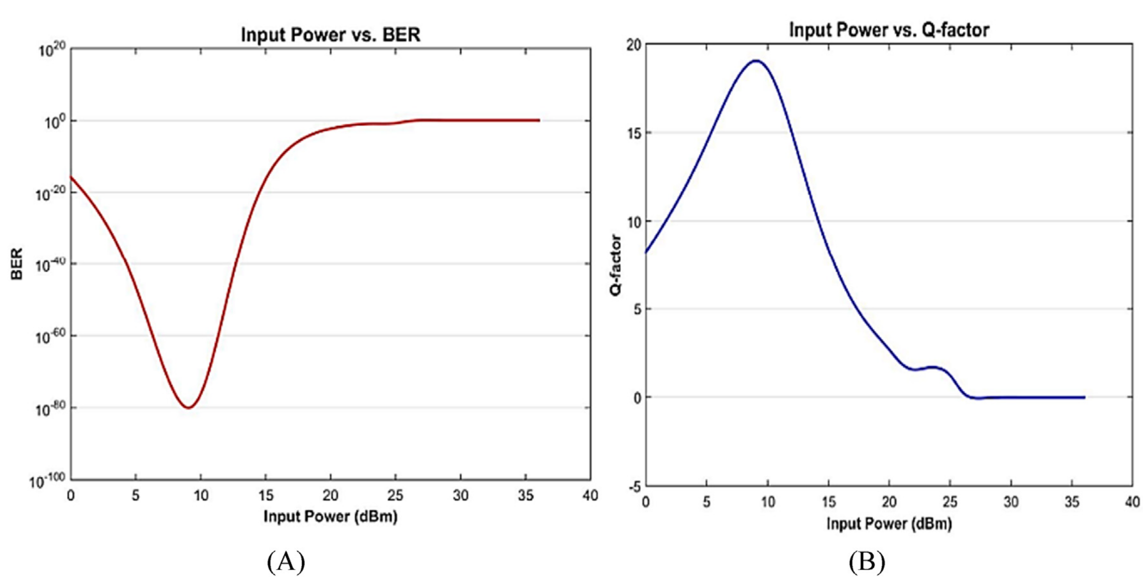
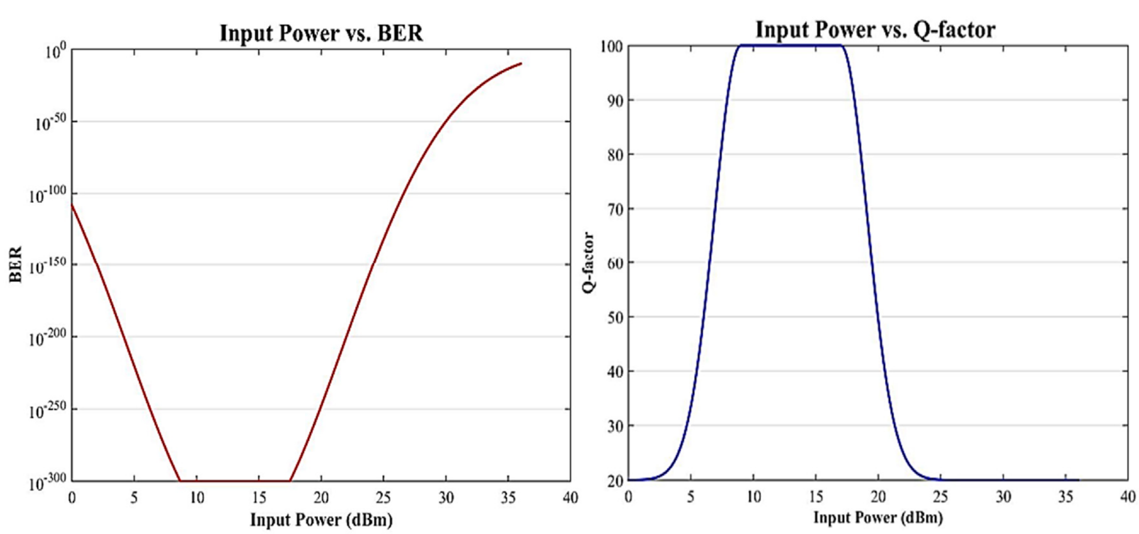


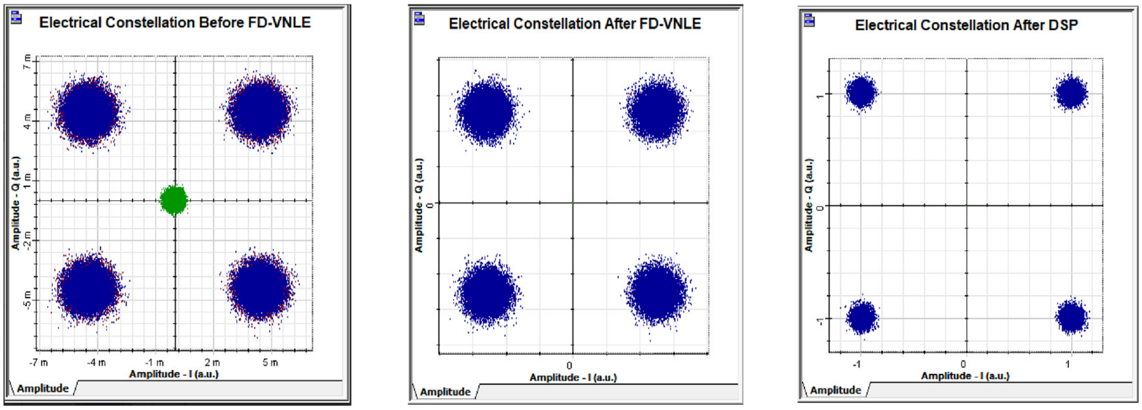
Fig. 5. (A) BER vs. Input Power and (B) Q-factor vs. Input Power without applying FD-VNLE and DSP.

Fig. 6 highlights the significant performance improvements achieved by applying FD-VNLE and DSP. In Fig. 6(A), the BER remains low and stable across a higher power range compared to the uncompensated system. The minimum BER achieved is 10^{-300} an optimal power level of 9 dBm, showing a substantial enhancement in error reduction. Furthermore, the system maintains an acceptable BER power level of up to 17 dBm, beyond which a gradual increase is observed. However, even at higher power levels, the rate of BER increase is considerably lower than in the uncompensated case. Fig. 6(B) further illustrates the influence of FD-VNLE and DSP on the Q-factor. Upon applying the compensators, the Q-factor attains a remarkable maximum of 100 at 9 dBm, representing a substantial enhancement compared to the uncompensated condition. The system demonstrates improved power tolerance, sustaining efficient performance up to 17 dBm, hence broadening the working range and enhancing overall signal integrity. A direct comparison of the results in Figs. 5 and 6 highlights the significant enhancement achieved by DS-VNLE and DSP. In the uncompensated case, the system attains minimum BER 10^{-77} and maximum Q-factor, exhibiting significant performance degradation beyond 12 dBm. Conversely, by the implementation of FD-VNLE and DSP, the system attained a markedly reduced BER to 10^{-300} and a substantially elevated maximum, Q-factor of 100, so successfully broadening the operational power range to 17 dBm. The results demonstrate that the compensated system exhibits significantly greater resilience to nonlinear distortions, facilitating higher input power without substantial degradation. The uncompensated system begins to exhibit nonlinear distortions beyond 12 dBm, whereas the adjusted system effectively alleviates these issues, allowing for enhanced data rates with diminished error rates and superior signal quality. The combination of FD-VNLE and DSP not only enhances the system's reliability but also makes it a feasible solution for long-haul optical communication applications, where sustaining good performance over a considerable distance. Fig. 7 illustrates constellation diagrams. Before the implementation of FD-VNLE Fig. 7(A), the constellation points are significantly scattered due to substantial nonlinear distortions and phase noise. This distortion is mostly caused by nonlinear phenomena, such as SPM, which modifies the transmitted signal. Upon the implementation of the FD-VNLE in Fig. 7(B), the constellation points demonstrate improved alignment with their ideal positions, indicating a significant reduction in nonlinear distortions. These results demonstrate the power of the FD-VNLE in reducing nonlinear distortions. Further enhancement was observed after applying the DSP for carrier phase estimation, as shown in Fig. 7(C). The constellation points are clustered around their ideal positions, satisfying more reduction in residual phase noise. The improvements in the constellation diagram led to increased BER. Applying the FD-VNLE allows the system to maintain performance at high input power levels. The integration of DSP enhances the signal quality, resulting in improved BER and Q-factor. These findings validate incorporating the FD-VNLE and DSP functions as an efficient approach



(A) (B)

Fig. 6. (A) BER vs. Input Power and (B) Q-factor vs. Input Power after applying FD-VNLE and DSP.



(A) (B) (C)

Fig. 7. Constellation Diagram (A) before the FD-VNLE (B) after the FD-VNLE and (C) after the DSP.

Table 2. Comparison between current study with previous studies.

Parameters	Mhatli et al. [6]	Fang et al. [7]	Current Study
Transmission Channel	SMF	SMF	SMF
Data Rate	20 Gb/s	31.06 Gb/s	40 Gb/s
Distance	100 km	300 km	100.2 Km
Modulation Type	16-QAM/CO-OFDM	16-QAM	DP-QPSK
Technique	Volterra-based NLE,	Volterra Nonlinear Equalizer (VNLE)	Volterra Nonlinear Equalizer (VNLE)
Channel Spacing	N/S	N/S	50 GHz
Q-Factor	9.5 dB	N/S	18 dB 100 dB
BER	Below 10^{-3}	2.5×10^{-4}	10^{-77} 10^{-300}
Simulation Type	N/S	Monte Carlo simulations using VPI TransmissionMaker 10.1	MATLAB co-simulated with OptiSystem

for reducing nonlinearities and improving performance in next-generation high-speed optical networks. This method enables the system to operate reliably at high data rates across long distances. The comparison between this study with previous studies is shown in Table 2.

4. Conclusion

This paper demonstrated the development and implementation of a mathematical representation for the FD-VNLE that reduced nonlinear distortion in a very high-speed optical communication network. The mathematical model for nonlinear single-channel fiber has been built using the FD-VSTF, which offered a theoretical insight into the influence of nonlinear effects. This emphasized the issues presented by nonlinear effects and their impact on system performance by focusing on SPM only. The incorporation of the suggested VNLE model, executed in MATLAB and co-simulated with OptiSytem, resulted in substantial enhancements in critical performance measures, including BER and Q-factor. The results indicated that in the absence of compensation, system performance degrades beyond an input power of 12 dBm, where the BER reaches 10^{-77} and the Q-factor peaks at 18. However, the application of FD-VNLE and DSP decreased the BER to $10^{-300,}$ and the Q-factor was markedly enhanced to 100, maintaining steady operation up to 17 dBm. Moreover, the incorporation of DSP improved the system's capacity to manage residual impairments, underscoring the need to integrate nonlinear equalization with sophisticated signal processing methodologies. These enhancements validated that VNLE is a viable method for guaranteeing dependable transmission in high-speed DP-QPSK systems, broadening the operational power range, and improving overall system performance. These findings facilitated additional investigation into the application of VNLE to alternative modulation formats and the optimization of its implementation for future energy-efficient, high-capacity optical networks.

Author's contribution

Safa Jabbar Mohammed: Developed the mathematical model, performed the simulations, analyzed the results, and prepared the manuscript.

Assistant Professor Dr. Jalil A. Hamadamin: Provided supervision, technical guidance, and critical feedback on the manuscript.

Ethics information

Ethical approval was not required for this research.

AI usage declaration

The authors declare that the content of this work was not generated using AI.

Funding information

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Conflict of interest

The authors state no conflict of interest in doing this research.

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References

[1] He Z, Mirani A, Karlsson M, Schröder J. Perturbation-based joint SPM and XPM compensation for superchannel system. IEEE Photonics Technol Lett 2024 Dec 1;36(23):1349−52. https://doi.org/10.1109/LPT.2024.3474479 [Internet].

[2] Ali RS, Fattah AY, Hassib MD. The effects of optical fiber impairments on communication systems. Indones J Electr Eng Comput Sci 2022 Oct 1;28(1):241. https://doi.org/10.1109/COMST.2017.2719958 [Internet].

[3] Bakhshali A, Chan WY, Cartledge JC, O'Sullivan M, Laperle C, Borowiec A, et al. Frequency-domain Volterra-based equalization structures for efficient mitigation of intrachannel kerr nonlinearities. J Lightwave Technol 2016 Apr 15;34(8):1770−7. https://doi.org/10.1109/JLT.2015.2510607 [Internet].

[4] Peddanarappagari KV, Mäõté Brandt-Pearce M. Volterra series transfer function of single-mode fibers. J Lightwave Technol 1997;15:2232. https://doi.org/10.1109/50.643545 [Internet].

[5] Gao C, Xi L, Li D, Ge P, Zhang W. A neural networks nonlinear equalizer based on Volterra series tranfer function. In: 2023 21st International Conference on Optical Communications and Networks (ICOCN). IEEE; 2023. p. 1−3. https://doi.org/10.1109/ICOCN59242.2023.10236108 [Internet].

[6] Mhatli S, Mrabet H, Amari A. Extensive simulation of fibre non-linearity mitigation in a CO-OFDM-WDM long-haul communication system. IET Optoelectron 2018 Oct 21;12(5):258−62. https://doi.org/10.1049/iet-opt.2018.5041 [Internet].

[7] Fang X, Fu Y, Wu Q, Zhang L, Zhang F. Volterra expansion based intra channel nonlinear effect equalization method for optical OFDM/OQAM systems. IEEE Access 2020;8:205657−68. https://doi.org/10.1109/ACCESS.2020.3036861 [Internet].

[8] Castro N, Boscolo S, Ellis AD, Sygletos S. Learned Volterra models for nonlinearity equalization in wavelength-division multiplexed systems. Opt Express 2025 Apr 21;33(8):16717 [Internet], https://opg.optica.org/abstract.cfm?URI=oe-33-8-16717.

[9] Kasmi M, Mhatli S, Bahloul F, Dayoub I, Oh K. Performance analysis of UFMC waveform in graded index fiber for 5G communications and beyond. Opt Commun 2020 Jan 1;454:124360. https://doi.org/10.1016/j.optcom.2019.124360 [Internet].

[10] Amari A, Dobre OA, Venkatesan R, Kumar OSS, Ciblat P, Jaouen Y. A survey on fiber nonlinearity compensation for 400 Gb/s and beyond optical communication systems. IEEE Commun Surv Tutorials 2017;19(4):3097−113. https://doi.org/10.1109/COMST.2017.2719958 [Internet].

[11] Fang X, Xu Y, Zuo S, Zhou H, Li L. A novel sparse Volterra model based fiber nonlinear equalization method for polarization-division-multiplexed CO-OFDM systems. Opt Fiber Technol 2024 Dec 1;88:103889. https://doi.org/10.1016/j.yofte.2024.103889 [Internet].

[12] Amari A. Nonlinear effects compensation for long-haul superchannel transmission system. Doctoral dissertation (Ph. D), Télécom ParisTech. 2016 [Internet]. Available from: https://pastel.hal.science/tel-01668545.

[13] Cheng CM, Peng ZK, Zhang WM, Meng G. Volterra-series-based nonlinear system modeling and its engineering applications: A state-of-the-art review. Mech Syst Signal Process 2017 Mar 15;87:340−64. https://doi.org/10.1016/j.ymssp.2016.10.029 [Internet].

[14] Bakhshali A. Nonlinearity compensation for next generation coherent optical fiber communication systems Doctoral dissertation (Ph. D). Queen's University (Canada); 2017 (September). Available from: https://qspace.library.queensu.ca/bitstream/handle/1974/22822/Bakhshali_Ali_201709_PhD.pdf.

[15] Guiomar FP, Pinto AN. J Lightwave Technol 2013 Dec 1; 31(23):3879−91. https://doi.org/10.1109/JLT.2013.2288781 [Internet].

[16] Guiomar FP, Reis JD, Teixeira AL. Pinto AN. digital post-compensation using Volterra series transfer function. IEEE Photonics Technol Lett 2011 Oct;23(19):1412−4. https://doi.org/10.1109/LPT.2011.2162229 [Internet].