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MITIGATING PULSE DISTORTION IN OPTICAL FIBERS USING DIGITAL BACKPROPAGATION AND DISPERSION MANAGEMENT

Sani Halliru Lawan

Department of Electrical Engineering, Bayero University, Kano, Nigeria.

*Corresponding authors' email: shlawan.ele@buk.edu.ng
ORCID iD: https://orcid.org/0000-0003-0790-0573

ABSTRACT

This research investigates the propagation effects of optical pulses traveling through fiber links, focusing on phase modulation, nonlinear phase change, and pulse broadening. We analyze these phenomena to enhance the performance of optical communication systems by evaluating key metrics such as nonlinear phase change (in degrees, o) and pulse broadening ratio over propagation distances. Our findings underscore the significant role of nonlinearities in pulse distortion and assess the effectiveness of Digital Backpropagation (DBP) and optimal dispersion techniques in mitigating these impairments. Simulation results demonstrate that DBP is more effective than optimal dispersion management, reducing nonlinear phase change by maintaining it at 15o up to 80 km, compared to optimal dispersion management, which stabilized it to 34o after the initial peaks before the interaction length, defined as the distance over which nonlinear effects manifest. Similarly, DBP achieves complete suppression of pulse broadening, maintaining the ratio at 1:1 up to 80 km. In contrast, optimal dispersion management only achieves lowering the ratio to 40:1. These findings highlight that DBP has superior capability in mitigating both nonlinear phase change and linear pulse broadening, significantly enhancing signal fidelity over long distances and offering valuable insights for the design and optimization of next-generation optical networks.

Keywords: Nonlinear Schrödinger Equation (NLSE), Digital Backpropagation (DBP), Pulse Broadening, Phase Modulation, Optical Fiber Communication

INTRODUCTION

Optical communication systems serve as the fundamental infrastructure for modern high-speed data transfer networks. Nevertheless, with the growing need for greater bandwidth, it becomes crucial to effectively handle signal distortions that occur throughout the transmission process (Kareem & Murdas, 2023). Optical pulses that travel via fiber networks experience several impairments, including phase modulation and pulse broadening, which degrade the quality of the signal. The impairments are mainly produced by the inherent characteristics of the fiber and the interactions resulting from nonlinearities as the optical pulses travel through the fiber (Ali, Fattah, & Hassib, 2022; Kumar & Kaur, 2021; Lawan & Mohammad, 2018; Varsha, Azeem, Saipriya, Muralidharan, & Nazrin, 2022).

Phase modulation, especially when there are nonlinear variations in phase, results in the presence of phase noise. Pulse broadening, a phenomenon characterized by the linear expansion of the pulse, results in the temporal broadening of the pulse (Lawan & Ajiya, 2013; Lawan, Ajiya, & Shu'aibu, 2012). This reduces the system capability to differentiate between consecutive pulses, hence complicating the detection and processing of signals. Research is essential for understanding and reducing these impacts in order to enhance the efficiency of optical communication systems (Varsha et al., 2022).

This work provides a thorough examination of the impact of propagation effects on optical pulses, specifically investigating the relationship between phase modulation caused by nonlinearities and the broadening of the pulse (Varsha et al., 2022). We analyze the performance of two essential approaches, Digital Backpropagation (DBP) (Yi et al., 2021) and optimal dispersion management in mitigating these impairments. DBP, or digital backpropagation, is an advanced technique for signal processing that can be employed to undo the distortions that occur during signal propagation (Lawan et al., 2020; Yi et al., 2021). At the same time, optimal dispersion management is utilized to modify the dispersion properties of the fiber link in order to minimize pulse distortion (Chou, Rehman, Haider, Muhammad, & Li, 2024; Lawan, Shu'aibu, & Babale, 2012).

To address this research gap, our work involves thorough simulations comparing DBP and dispersion management. The results, are presented in several graphical illustrations, to demonstrate the improvements in signal quality that may be accomplished by DBP and efficient dispersion management. While prior studies address individual mitigation techniques, comparative analyses of DBP and dispersion management remain limited (Lawan et al., 2020). Our work bridges this gap by evaluating both methods under unified conditions. This research gives important understandings for the design and optimization of next generation optical communication systems, seeking to better their robustness and efficiency in the era of increasing data traffic needs.

MATERIALS AND METHODS

The methodology of the research includes mathematical modelling of the system presented in section A and the schematic of the system in section B, as follows:

Fiber Channel Model

During propagation of optical signal along the optical fiber transmission system, the propagating signal suffers from fiber impairments, these impairments are grouped into linear and nonlinear propagation impairments. Therefore, in modelling optical fiber channel, both linear and nonlinear impairments need to be presented appropriately. When a slowly-varying electric field envelope is propagating along single-mode optical fiber, the evolution of the electric field can be described by using simplified form of nonlinear Schrödinger Equation (NLSE) (Agrawal, 2012) as

$$\frac{\partial E}{\partial z}+\beta_1\frac{\partial E}{\partial t}+i\frac{\beta_2}{2}\frac{\partial^2 E}{\partial t^2}-\frac{\beta_3}{6}\frac{\partial^3 E}{\partial t^3}+\frac{\alpha}{2}E=i\gamma|E|^2E \quad (1)$$

Description of the terms from the left hand side, E is the slowly varying electric field amplitude, β_1 is the corresponding mode propagation constant, β_2 is the group velocity dispersion (GVD) or simply dispersion, β_3 is the third order dispersion (TOD) and α is the fiber attenuation. For the right hand side of the equation, γ is the nonlinear parameter, which is associated with fiber nonlinearities.

To model the effect of self-phase modulation (SPM), an approximate form of NLSE given in Eq. (1) above is used. The assumption is to neglect the linear effects of the fiber and consider only the terms associated with nonlinearities, and therefore, it yields

$$\frac{\partial E}{\partial z} = i\gamma|E|^2 E \tag{2}$$

The solution of the above Eq. (2), results to

$$E(L,t) = E(0,t)exp(i\varphi_{NL}) \tag{3}$$

where φ_{NL} is the nonlinear phase shift due to the nonlinear effect of SPM, and it is obtained as

$$\varphi_{NL} = \gamma|E(0,t)|^2 L_{eff} = \gamma P L_{eff} \tag{4}$$

The expression for γ is given as

$$\gamma = \frac{\omega_0 n_2}{cA_{eff}} = \frac{2\pi n_2}{\lambda A_{eff}} \tag{5}$$

the L_{eff} represents the effective fiber length, defined as

$$L_{eff} = \frac{1-exp(-\alpha L)}{\alpha} \tag{6}$$

It is clear from the equations above, that the SPM effect caused intensity dependent phase shift to the signal.

$$\omega_{NL} = -\frac{d\varphi_{NL}}{dt} = -\gamma\frac{dP_1}{dt}L_{eff} \tag{7}$$

The propagation distance after which an optical input Gaussian pulse manifests the nonlinear phase effect, is termed the nonlinear length L_{NL} and is given in terms of nonlinear parameter and optical pulse power, as

$$L_{NL} = \frac{1}{\gamma P} \tag{8}$$

The spectral broadening effect of SPM depends on the dispersion regime, in a normal dispersion regime that is operating below the zero dispersion wavelength, the frequency chirping is positive as a function of time, meaning that the frequency increases with time inside the optical pulse. Therefore, in this regime, the pulse experiences broadening due to dispersion, and in the presence of SPM-induced pulse broadening, the pulse will undergo spectral broadening due to dispersion and SPM, which will eventually make worse the broadening of the optical pulse. However, in an anomalous dispersion regime that is operating above the zero dispersion wavelength, the frequency chirping is negative as a function of time, meaning that the frequency decreases with time inside the optical pulse. Therefore, in this regime, the pulse experiences narrowing or chirping due to dispersion, and in the presence of SPM-induced broadening, the pulse will undergo spectral chirping due to dispersion and SPM-induced spectral broadening, which will eventually cancelled or balanced each other in a way that pulse experiences no change in shape.

The effect of dispersion can be modelled based on NLSE, by considering only the second order term, which represents the effect of CD [6, 7, 11]. Therefore, Eq. (1) reduces to

$$\frac{\partial E}{\partial z} = -i\frac{\beta_2}{2}\frac{\partial^2 E}{\partial t^2} \tag{9}$$

Solution of Eq. (9) in frequency domain is results in

$$E(L,\omega) = E(0,\omega)\, exp(-i\frac{\beta_2}{2}\omega^2 L) \tag{10}$$

From Eq. (10), the signal is a function of the phase and initial input power. Dispersion affects the phase of the signal spectrum without changing the spectral power distribution and thereby causing the propagated pulse to be broadened. For any optical fiber, the manufacturer normally gives the dispersion coefficient D in ps/nm-km, it is directly related to β_2 as

$$\beta_2 = -\frac{\lambda^2}{2\pi c}D \tag{11}$$

where λ is the wavelength and c is the speed of light. The propagation distance after which an optical input Gaussian pulse manifests the broadening effect, is termed the dispersion length L_D and is given in terms of pulse width t_0 as

$$L_D = \frac{t_0^2}{|\beta_2|} \tag{12}$$

At the end of propagation length or fiber span the transmitted pulse experiences the effect of dispersion, the pulse is broadened, to overcome the effect of dispersion, the transmitted signal or pulse is compensated. The Gaussian pulse shape used in the study takes the form of

$$E(0,t) = \sqrt{P}\, exp\left[-\frac{1}{2}\left(\frac{1+iC}{2}\right)\left(\frac{t}{t_0}\right)^2\right] \tag{13}$$

where P is the pulse power, C is the chirping parameter and t_0 is the pulse width at half maximum.

System Schematic

The schematic of the optical communication system illustrates the key stages involved in the propagation and compensation of optical pulses. It begins with the Pulse Source, which generates an initial Gaussian optical pulse with a full-width at half-maximum (FWHM) of 20 ps, used as the input for the system. The pulse is then transmitted through the Fiber Link, representing an 80 km optical fiber that imparts linear and nonlinear distortions. The Gaussian pulse width (20 ps FWHM) was selected to reflect standard pulse durations in high-speed optical systems (Agrawal, 2012), balancing simulation accuracy and computational efficiency. The 80 km fiber length aligns with industry-standard single-span deployments (Yi et al., 2021). These distortions are shown as nonlinear effects due to self-phase modulation (SPM), where the pulse undergoes intensity-dependent phase shifts, and dispersion effects, leading to pulse broadening as it travels through the fiber. To counter these effects, the system employs a Digital Backpropagation (DBP) module, which applies inverse modeling transformations to mitigate the combined effects of dispersion and nonlinearities observed after propagation. The output pulse is the resulting signal after DBP and dispersion management, ideally restored to its original shape or significantly improving it. The schematic in Figure. 1 visualizes the flow of the system.

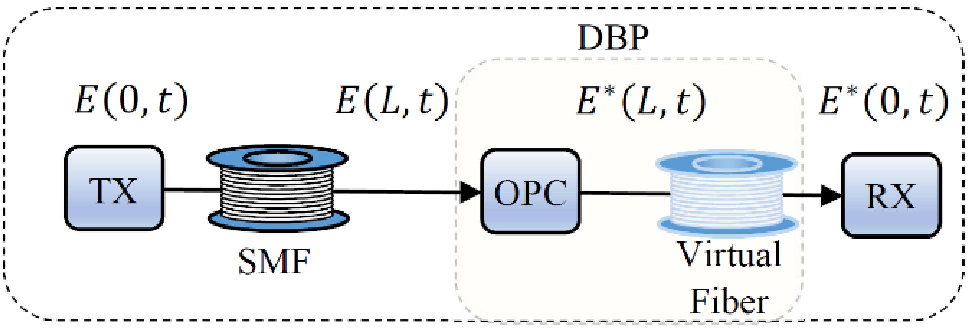

Figure 1: Schematic of the Optical Communication System with Digital Backpropagation (DBP) and Dispersion Management

The system comprises the initial pulse generation E(0, t), propagation through an optical fiber E(L, t), and compensation using DBP to mitigate dispersion and nonlinear effects.

RESULTS AND DISCUSSION

This section presents the findings from the propagation of an optical Gaussian pulse along an 80 km optical fiber. The evolution of the pulse during propagation is analyzed to provide insights into propagation impairments, their impact on the shape of the optical signal and their mitigations to improve the integrity of the signal. Figure. 2 presents the nonlinear phase changes experienced by an optical Gaussian pulse during its propagation along an optical fiber. As the pulse evolves, the intensity of the optical signal modulates the refractive index of the nonlinear medium, leading to changes in the phase of the optical signal. These phase changes are dependent on the interaction length and become more pronounced as the propagation distance increases. Figure. 2 illustrates the evolution of a Gaussian pulse in a nonlinear optical medium, where the pulse intensity modulates its own phase, resulting in the phenomenon of Self-Phase Modulation (SPM). The nonlinear effect depicted here is solely attributed to SPM. The propagation distance considered in the analysis extends up to 80 km. As the Gaussian pulse propagates through the fiber, it is subjected to phase modulation due to fiber nonlinearity. This nonlinear phase distortion increases with the length of the fiber.

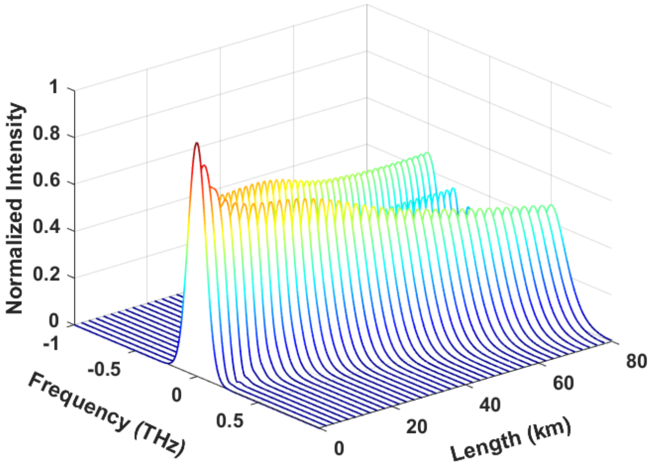

Figure 2: Effects of phase modulation during propagation of optical pulse along the fiber link

The behavior of an optical Gaussian pulse subjected to broadening effects due to second-order dispersion in the fiber is depicted in Figure. 3. As the propagation distance increases, the pulse broadens, resulting in a significant increase in pulse width. Additionally, the intensity of the pulse decreases. By the time the optical signal reaches the end of the link, the pulse width has expanded considerably. This broadening leads to Inter-Symbol Interference (ISI) in multi-channel systems, highlighting the effects of dispersion on pulse integrity over long distances.

Figure. 4 illustrates the combined effects of nonlinear phase changes with the right vertical axis and linear pulse broadening with left vertical axis due to fiber nonlinearity and dispersion, respectively. The nonlinear behavior of the pulse within an optical medium is influenced by its intensity. As the optical pulse propagates, the varying intensity alters the refractive index of the medium, leading to changes in the phase of the signal. Initially, the phase change increases almost uniformly to 37°, then decreases to 36°. It subsequently increases again, reaching a peak value of 40° at approximately 14 km of fiber length. After this peak, the phase change exhibits significant fluctuations, dropping to as low as 27° around 36 km. As the signal continues to propagate along the optical link, the phase change eventually stabilizes at 32° by the 80 km mark.

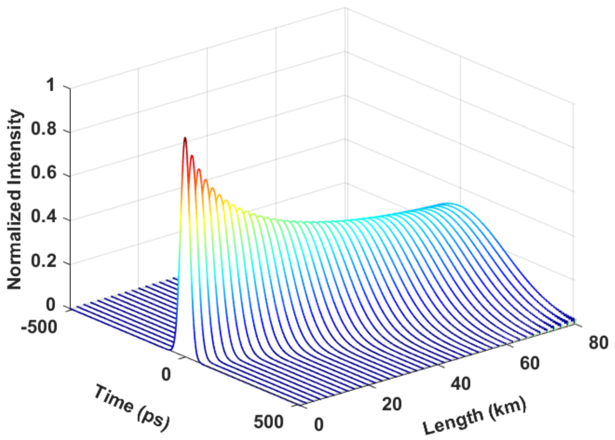

Figure 3: Signal spectrum after transmission, showing the formation of FWM products

Conversely, the pulse broadening effect due to dispersion increases linearly with the propagation distance along the optical fiber link, from 1:1 at 0 km to about 12:1. This broadening effect is quantified by the ratio of the output pulse width to the input pulse width. This relationship highlights the distinct impact of dispersion, where the pulse width expands proportionally with distance, in contrast to the nonlinear phase shift, which follows a more complex, fluctuating pattern.

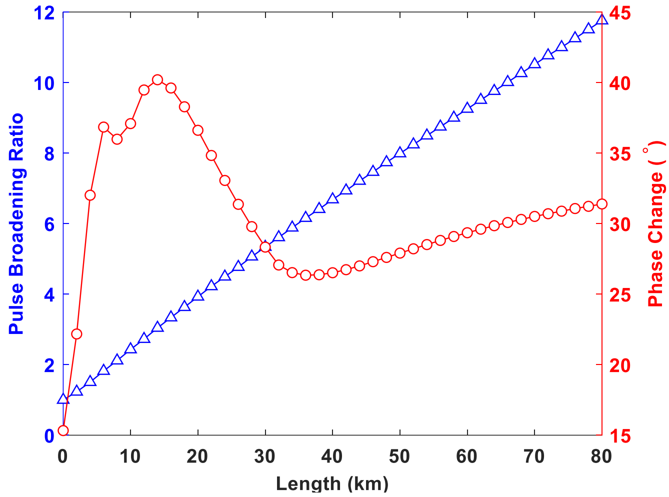

Figure 4: Effects of the nonlinear phase change and linear broadening for a typical 20 ps optical Gaussian pulse propagating in a nonlinear dispersive medium

The comparative performance of DBP and optimal dispersion management in mitigating nonlinear phase changes is illustrated in Figure. 5. The phase change in degrees (°) is plotted against propagation distance (in kilometers). The upper curve labelled as typical, shows the nonlinear phase change when dispersion is 16 ps/nm-km, that is prior to any compensation, the phase changes due to nonlinearity increases with distance of propagation, up to around 40° and then fluctuates. The optimized results were obtained at 4 ps/nm-km to reduce nonlinear effects without excessive pulse broadening. This optimization explores the interaction between dispersion and nonlinearities. An optimal amount of dispersion stabilizes the nonlinear phase changes, maintaining them almost constant at around 34° up to 80 km, with noticeable effects starting at the dispersion length of approximately 20 km. Below this length, the phase change from 15 to 34° significantly impacts system performance. In contrast, the DBP approach, improves system performance considerably, completely suppressing the phase change to maintain it at 15°, as depicted in the lower flat curve in Figure. 5 labelled as DBP. The DBP approach is found to be more efficient than parametric optimization such as optimal dispersion management in overcoming the nonlinear phase changes, thereby maintaining signal quality over longer propagation distances.

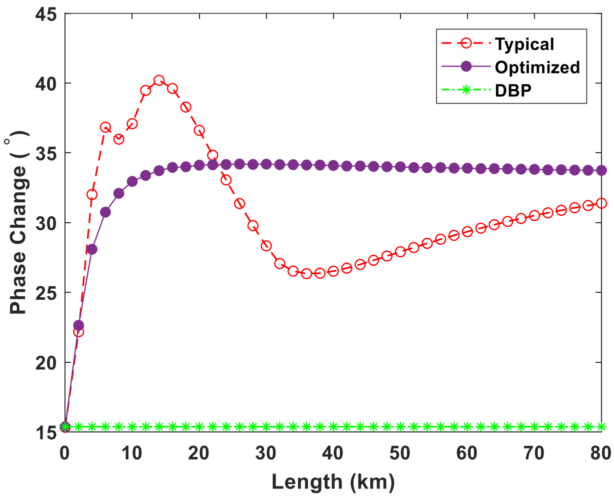

Figure 5: Performance comparison of DBP and use of optimal dispersion at 4 ps/nm-km, in suppression of nonlinear phase change for a 20 ps optical Gaussian pulse propagating in a nonlinear medium

Figure. 6 illustrates the comparative performance of Digital Back Propagation (DBP) and optimal dispersion management in the suppression of linear broadening for an optical Gaussian pulse propagating through a nonlinear as well as dispersive transmission link. Three cures were presented labelled as typical, optimized and DBP. Typical curve is when no compensation effort applied to the system towards minimizing any propagation impairment, the second curve labelled as optimized in the Figure. 6 represents the pulse broadening ratio under optimized dispersion conditions, achieved at 4 ps/nm-km, this optimization minimizes the pulse broadening effect without inducing excessive nonlinear phase modulation of the optical signal. The interaction between dispersion and nonlinearities is such that at very low dispersion levels, nonlinear effects predominate, whereas at minimized nonlinearity levels, dispersion effects become more pronounced. Optimal dispersion allows for a balance that maintains minimal nonlinear phase changes and stable signal propagation. The third curve labelled DBP, reveals the results of DBP approach implementation, it shows substantial improvement in the system performance, effectively overcoming the pulse broadening and therefore reducing it to negligible levels, clearly demonstrating its superiority over mere parametric optimization such as optimal dispersion management.

This research rigorously compares DBP and optimal dispersion management in mitigating pulse distortion effects, such as nonlinear phase change and linear broadening, in optical communication systems. It quantitatively assesses their performance using metrics like phase change and pulse broadening ratio across propagation distances, revealing DBP has superior ability to maintain signal quality over long distances. The study has practical application to real-world optical communication challenges underscores its relevance to the design of next-generation networks.

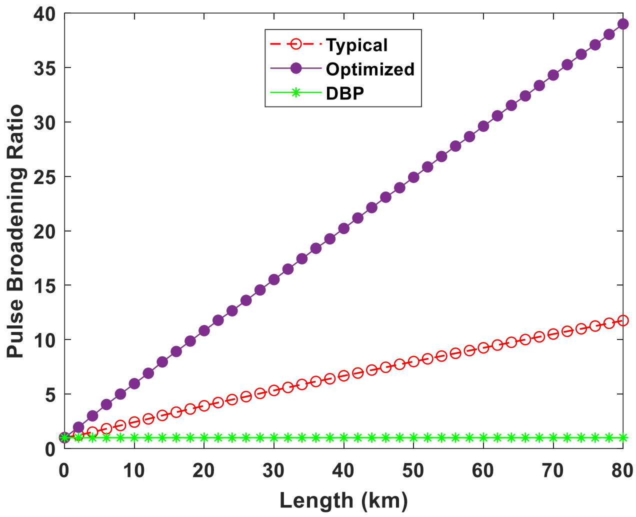

Figure 6: Performance comparison of DBP and use of optimal dispersion at 4 ps/nm-km, in suppression of linear broadening for a 20 ps optical Gaussian pulse propagating in a dispersive medium

Potential error sources include simulation approximations such as omission of higher-order dispersion and polarization-mode dispersion. Our results align with Lawan et al. (2020), who reported excellent phase distortion suppression using DBP, but this study further quantifies DBP superiority in pulse-broadening mitigation as presented in Figure. 6.

CONCLUSION

In conclusion, this study provides the first direct quantitative comparison of DBP and dispersion management, establishing DBP superior efficacy in mitigating pulse distortion. Optical fiber systems suffer from nonlinear phase modulation and linear broadening, impairing signal performance by altering pulse width, signal phase, and optical intensity, thus causing modulation instability and inter-symbol interference (ISI) in multi-channel systems. This study provides first direct comparison of DBP and parametric optimization in dispersion management for mitigating propagation effects, establishing DBP has superior efficacy in reducing pulse distortions. The findings contribute to the advancement of signal processing techniques in optical fibers, suggesting future research avenues including broader condition testing, hybrid method integration, real-time application development, analysis of impacts on system capacity and latency, long-term reliability assessments, and cost-benefit evaluations to enhance practical implementations in optical communication networks.

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