Digital Backpropagation Based on DOPC in Fiber Impairments Mitigation

S H Lawan[1], M Y Mohd Noor[2], M A Farabi[2], A S M Supa'at[2], S A Babale[1], S G Mohammed[1] and L U Daura[1]

[1,2]Lightwave Communications Research Group (LCRG), Faculty of Electrical Engineering, Universiti Teknologi Malaysia (UTM), Skudai, Johor, Malaysia
[1]Department of Electrical Engineering, Bayero University, Kano, Nigeria

shlawan.ele@buk.edu.ng

Abstract. This paper presents the study on the impact of the nonlinear phase shift on the performance of optical transmission systems and its suppression using digital backpropagation (DBP) technique. The proposed DBP employed digital optical phase conjugation (DOPC) at the receiver and a virtual fiber, thereby having the combined benefits of DBP and optical phase conjugation. Optical signal propagation was achieved by solving the nonlinear Schrödinger equation (NLSE) using the split-step Fourier method (SSFM). Implementation of DBP was conducted on 100-Gbps, DP-16QAM systems and it has demonstrated its efficacy in suppressing nonlinear phase shift, by improving the minimum bit error rate (BER) from 1×10^{-2} to 6.1×10^{-5}.

1. Introduction

The immense progress of lightwave communication systems to accommodate unending demands is driven by the huge advantages, ranging from longer transmission reach, which is made possible by optical amplification, to its expansion capabilities due to the advancement in multiplexing techniques. These momentous achievements are limited by the propagation impairments. Amongst the impairments that can be detrimental to the performance of optical communication systems are the linear effects of chromatic dispersion (CD) and polarization-mode dispersion (PMD), their consequential effect results in pulse broadening. The nonlinear impairments that are considered to cause serious limitation to the system are stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), four-wave mixing (FWM), cross-phase modulation (XPM) and self-phase modulation (SPM), and are dependent on channel spacing and the level of input power applied to the system [1-3]. Some of the limitations resulting from nonlinearities are the generation of new frequencies, signal phase-shift, and modulation instability or noise. The effects of fiber propagation impairments limit the performance of the system, which results in a high number of bit errors and low optical signal to noise ratio. Therefore, to overcome the distorting effects of fiber impairments, optical communication systems are planned to have minimal impairments by optimizing system parameters or having some form of mitigation mechanisms that can suppress the effects of the distortions [1, 2, 4].

Fiber impairments mitigation is necessary, to improve the performance of optical nonlinear transmission systems [5-9]. Some of the approaches that are used to reduce the propagation impairments are; by optimizing the dispersion in the system such that the residual dispersion and nonlinearity will cancel out each other [2]. The system PMD can provide significant interaction with nonlinearity and lead to performance improvement [1]. Amongst the many mitigation mechanisms, there are prominent approaches, such as digital backpropagation (DBP) [10-12] and optical phase conjugation (OPC) [13-16] and many of their variants are known to significantly suppress the fiber impairments and yield to outstanding performance improvement.

In this work, the effect of fiber propagation impairment due to SPM and its interactions on the performance of an optical transmission system were analyzed. The nonlinear phase-modulation effect leads to strong phase-change, which further leads to spectral broadening in the optical signal. It shows that the constellation points experience rotation due to induced phase change, and the extent of phase change is directly dependent on the input power. The system with higher launch power experiences higher distortion. This phase effect makes worse the system BER. The proposed DBP based on DOPC was implemented on 100-Gbps, coherent DP-16QAM system, and has shown appreciable improvement in the system BER.

2. System Model

In this work, the technique used in solving the nonlinear Schrödinger equation (NLSE), is the split-step Fourier Method (SSFM), to achieve fiber propagation [2].

2.1. Digital Backpropagation

The aim of the DBP approach is for the transmitted optical signal $E(z,t)$ that is distorted due to fiber propagation impairments, to be transformed back to its original shape that is prior to transmission $E(0,t)$, and it does that by unwinding the propagation impairments. This can be achieved by subjecting the transmitted optical signal to a transfer function that is opposite to that of the nonlinear transmission, in doing so, the transmitted signal appears to have propagated back, such that distorted signal be restored to $E(0,t)$. Here the implementation of the DBP is achieved by digitally phase conjugating the transmitted signal at the receiver using DOPC and pass it through a virtual fiber having the same transfer function as that of the nonlinear transmission link. Therefore, at the end of these modules, the received signal can be restored. Figure 1 below shows the block representation of nonlinear optical transmission systems with DBP based on DOPC implementation at the receiver.

2.2. DBP Implementation on DP-16QAM

In this section, the description of the system set-up used for the study on the effect of nonlinear phase change due to fiber nonlinearity on high-speed optical transmission systems, and its mitigation using DBP approach, is presented. The set-up as shown in Figure 1 is made of 100-Gbps coherent dual polarization or polarization multiplex 16-level quadrature amplitude modulation (DP-16QAM) system. The 16QAM optical signals are generated using DP-16QAM transmitter (TX). The technique of polarization multiplexing is used to accomplish transmission using the X and Y polarizations, by splitting the output laser having 0.1 MHz linewidth from a local oscillator (LO) into two, with the aid of polarization beam splitter (PBS), the two orthogonal polarizations were then modulated using separate 16QAM modulators, and combined afterward with the aid of polarization beam combiner (PBC). For the nonlinear transmission system, each span is made of 80 km length of SSMF having an attenuation coefficient of 0.2 dB/km, dispersion of 16 ps/nm-km, nonlinearity coefficient of 1.3 W^{-1}/km and gain compensating EDFA, 10 number of fiber spans were used. At the end of the transmission link, DBP was implemented on the signal, and then the signal was filtered using a Gaussian optical filter (GOF) with 3 dB bandwidth of 50 GHz. The coherent DP-16QAM receiver (RX) is based on homodyne detection design, it has a LO whose laser linewidth is 0.1 MHz. Signal demodulation was achieved using two separate 16QAM receivers, for each of the two split continuous wave (CW) lasers from the LO component. The signals after coherent detection were passed to the digital signal processing (DSP) component where several functionalities were carried out apart from nonlinearity compensation in order to recover the transmitted channels. The decision component was used to perform soft decision on the received symbols based on threshold boundaries. The BER was calculated with differential coding over 65536 bits. The reference wavelength is 1550 nm.

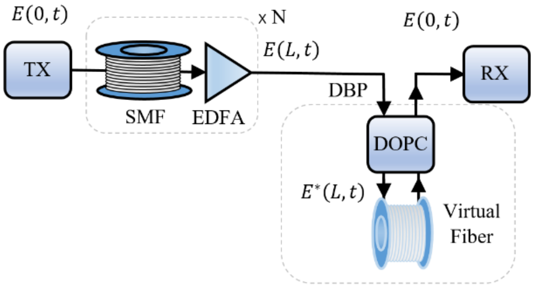

Figure 1. Block diagram of the nonlinear optical transmission system with DOPC based DBP for mitigation of transmission impairments.

3. Results and Analysis

This section presents the results and analysis obtained by the implementation of DBP on 100-Gbps DP-16QAM system, using OptiSystem design. The results of the study on the effect of nonlinear phase change on the performance of the 100-Gbps, coherent DP-16QAM system is presented in this section. The system was subjected to fiber nonlinearity and the nonlinear phase changing effects on the performance were noted in terms of BER and corresponding OSNR. Figure 6 shows the effects of nonlinear phase distortion because of phase modulation, on the signal constellations as launch power increases. It shows that the severity of phase distortions due to nonlinearity increases with an increase in the launch power. Figures 2 (a) – (d) were obtained at the launch power of 3 to 6 dBm respectively.

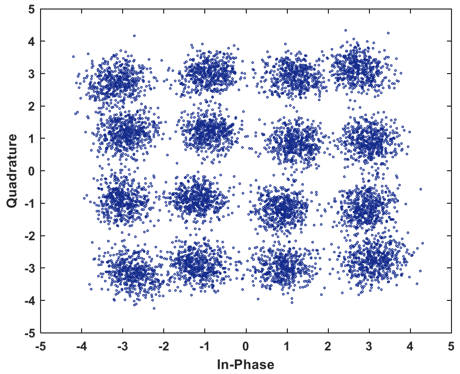

Figure 2a. Distortion on signal constellations at 3 dBm.

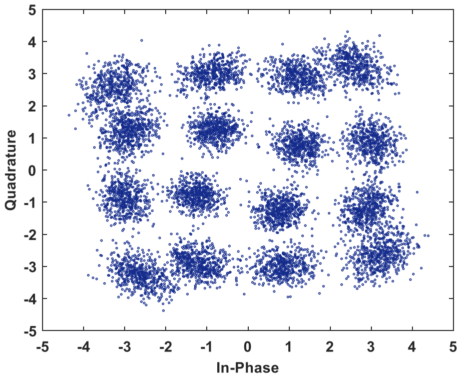

Figure 2b. Distortion on signal constellations at 4 dBm.

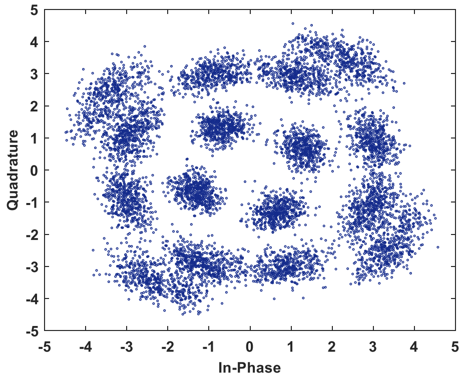

Figure 2c. Distortion on signal constellations at 5 dBm.

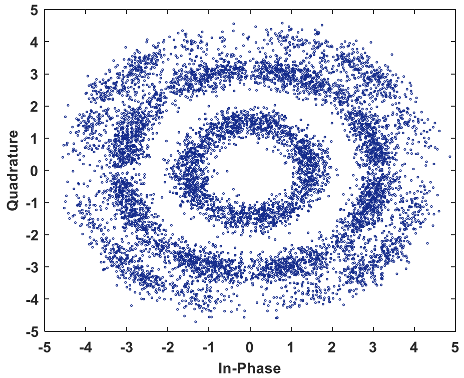

Figure 2d. Distortion on signal constellations at 6 dBm.

It shows that the constellation points experience rotation due to induced phase change, and the extent of phase change is directly dependent on the input power. The system with higher launch power will experience higher distortion. This phase effect makes worse the system BER and OSNR.

Figure 3 (a) depicts the nonlinear transmission system performance at various propagation distance of 400, 800, 1200, and 1600 km, in which all the four performance curves demonstrate typical nonlinear behavior due to an increase in launch power from -6 to 6 dBm. It shows that the BER deteriorated with the accumulation of nonlinearity. Figure 3 (b) shows performance curves in terms of BER vs corresponding OSNR at 800 km, for the situations before and after the implementation of DBP. The results show that without the DBP the system BER deteriorates when the launch power is high enough for the nonlinearity to occur. In this case, it occurs at launch power of between 3 to 6 dBm, within this range the BER deterioration worsens with an increase in the launch power, limiting the minimum BER of 1 x 10^{-2} to occur at 13 dB OSNR point. With the implementation of DBP, the nonlinear phase distortion was effectively suppressed, thereby, allowing the BER to continue to improve with an increase in the launch power, with minimum BER of 6.1 x 10^{-5} occurring at OSNR of 16.3 dB point. This shows significant improvement in the system BER with the use of DBP. The corresponding constellation diagram is shown in Figure 3 (c), it is distortion free in comparison to the distorted signal constellations shown above.

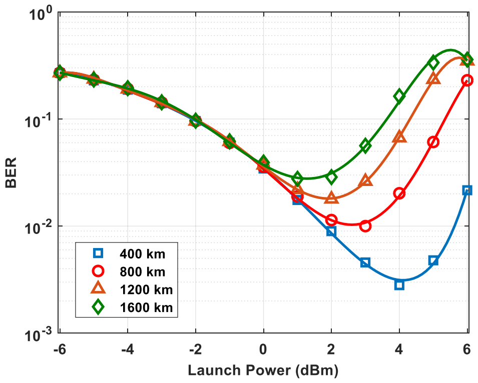

Figure 3a. BER vs Launch Power at various propagation distances.

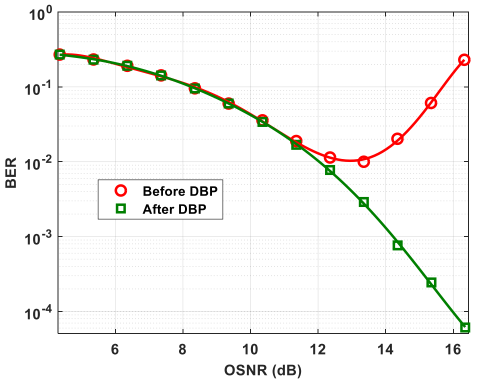

Figure 3b. BER vs OSNR of the System.

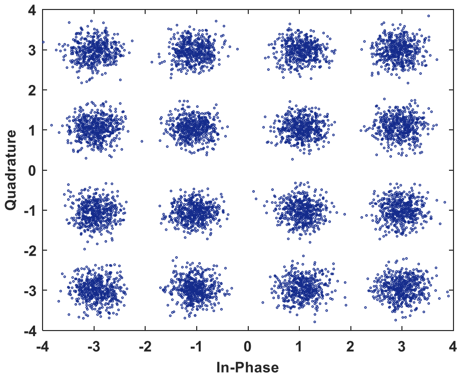

Figure 3c. The corresponding constellation diagram with the DBP implemented.

During the propagation of optical signals along the length of the nonlinear optical transmission links, the impairments accumulate and distort the optical signal. On reaching the receiver side of the link, these accumulated impairments affect the quality of the reception, sometimes the received signal is detected incorrectly and or even makes the detection system unable to detect the signal. Therefore, there is a need for the mitigation of such impairments. Mitigation techniques such as backpropagation may increase computational complexity, but they can substantially suppress transmission impairments.

4. Conclusion

Optical fiber propagation impairments affect the performance of the system. Optical pulse experiences nonlinear phase modulating effects with the increase in fiber length. These impairments can lead to signal phase change and variation in the optical intensity. The resulting effects cause modulation instability. It is considered here, for mitigation of these effects, the proposed DBP based on DOPC.

The DBP approach was implemented on 100-Gbps, coherent DP-16QAM system, which is a complex system with high bitrate, it has achieved improvement in minimum BER of the system from 1×10^{-2} to 6.1×10^{-5}. The DBP demonstrated its effectiveness in nonlinearity suppression by substantially mitigating the nonlinear phase modulation.

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