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Mitigation of nonlinear impairments using DSP for 2×1 100 Gbps PDM-QPSK

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Abstract - High speed data transmission in optical fiber limited by the linear and nonlinear impairments. Here, we have demonstrated the simulation of coherent 100 Gbps PDM-QPSK. Nonlinearity is more dominant factor to limit the performance of the high speed optical communication. Nonlinearity of system introduce in propagation due to nonlinear behavior of the optical signal because it always follow the Non linear Schrödinger equation in fiber during propagation. It is possible to compensate the linear and nonlinear impairments by DSP (Digital Signal Processing) algorithm.. In this paper we analyze the effect of the nonlinearity based on DSP module. Here we measure the performance of 2×1 100 Gbps PDM-QPSK systems with Nonlinear compensator (NLC) and without NLC. The performance of system is approximately same for with and without NLC at shorter distance. But, for long distance performance of system is degraded without NLC. Nonlinear behavior of optical signal combat by split step Fourier method which is part of Back propagation.

Index Terms – PDM- QPSK (Polarization Division Multiplexed Quadrature Phase Shift Keying), DSP (Digital Signal Processing), NLC(Nonlinear compensator).

I. Introduction

An important goal of a long-haul optical fiber system is to transmit the highest data throughput over the longest distance without signal regeneration. Given constraints on the bandwidth imposed by optical amplifiers and ultimately by the fiber itself, it is important to maximize spectral efficiency, measured in bit/s/Hz Polarization Division Multiplexed Quadrature Phase Shift Keying (PDM-QPSK) is high spectral efficient modulation format that capable to provide high data rate. 100 Gbps PDM-QPSK systems with coherent detection is an attractive solution for long-haul transmission. Its good compromise between transmitter and receiver complexity, and noise tolerance. Moreover, its high symbol rate design is a challenging but realistic speed to implement with DSP (Digital Signal Processing) circuits available today to perform several algorithms to provide correct information at user end. For the algorithm we go later on.DSP key element in high speed optical design for enhancing the performance and the entire algorithm performed in electrical domain. Linear and Nonlinear impairments compensate using DSP algorithm.

In High symbol rate PM-QPSK effect of CD (Chromatic Dispersion) and PMD (Polarization Mode Dispersion) is more dominant for long distance communication system. These impairments can be combat using the several approaches in order to enhancing the performance. However, By using of amplifier along with span adds ASE (Amplifier Spontaneous Emission) noise that accumulated at every amplifier stage due to that the performance of system is degraded. The OSNR level can be kept high by increasing the amplifiers launch power, but this will increase the impact of non-linear effects (intra- and cross-channel [5]). So viable solution to increase range of 100Gbaud PDM-QPSK we use the low noise figure amplifier such as EDFA(Erbium Doped Fiber Amplifier).Optical sources are not purely monochromatic so due to that CD and PMD introduce in propagation. Back propagation algorithm that available in DSP can mitigate effect of CD and Nonlinear distortion. Moreover, Split Step Fourier method used in Back propagation algorithm. In that method span of fiber splitted in two section (i) linear section (ii) nonlinear section. CD considered in linear section and Nonlinear distortion considered in nonlinear section respectively. Nonlinear distortion includes the effect of self phase modulation (SPM) and cross phase modulation (XPM).In this paper we simulated the 2×1 100 Gbaud PDM-QPSK WDM systems. Effective nature of nonlinearity on system has been evaluated. System Performance measure in presence of NLC (Non Linear

Compensator) and without NLC at offline DSP stage.

II. COHERENT DETECTION WITH DSP-BASED LINEAR EQUALIZATION

Optical systems using a direct detection receiver remained the widely used technique for the last four decades. This receiver, simple to operate, makes decisions based only on the intensity of the received signal. Therefore, it allows only amplitude based modulation formats such as the OOK .For High spectral efficient modulation such as M-PSK and M-QAM system, direct detection exhibits the very poor performance. Enhanced performance obtains by paying price in complexity of receiver design based on the coherent detection.

The basic idea behind coherent detection is depicted in Fig 1. It consists of combining the optical signal coherently with continuous-wave (CW) optical field before it falls on the photo detector.

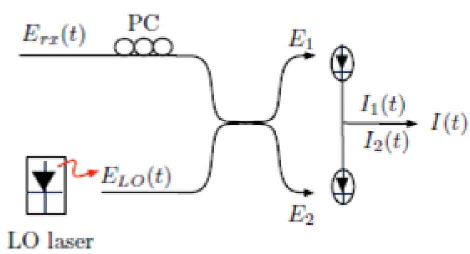


Fig 1: Coherent detection [4]

PHASE AND POLARIZATION DIVERSITY RECEIVER

In order to increase the spectral efficiency of the coherent systems, and utilize the polarization degree of freedom, multiplexing independent modulated data streams in the two orthogonal polarizations is used for the coherent 100Gbit/s. Those systems are denoted by Polarization Multiplexing (POLMUX). For POLMUX coherent system, a phase and polarization diversity receiver is used to map the phase and in-quadrature components of the incident signal contained in both polarizations. The block diagram of such a receiver in depicted in Fig 2.

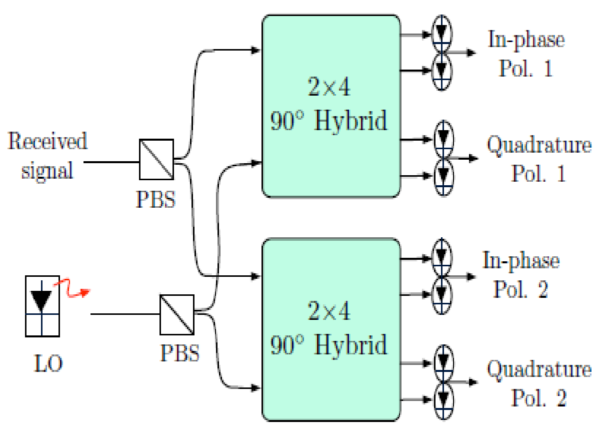


Fig 2: Block diagram of a phase and polarization diversity optical coherent receiver (POLMUX), LO and PSB stand for Local oscillator and Polarization Beam Splitter respectively [4]

DSP-BASED LINEAR EQUALIZATION [1]

Light signal propagates in to fiber then linear and nonlinear impairments introduce among of that linear impairments compensate by linear equalization which depicted in to Fig 3.*H(ω)* is transfer function of the fiber link that describes the first order linear impairments such as CD and PMD. By using the inverse transfer function of fiber link i.e. $H^{-1}(\omega)$ after receiver side that can be compensate the CD and PMD either in time domain or frequency domain. Above discussed process is not compensating the nonlinear impairments .This process is part of offline DSP which mitigate the linear impairments.

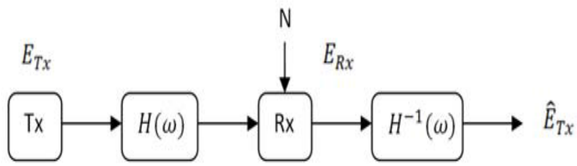


Fig 3: Linear electronic equalization at the receiver

I. NON-LINEAR EFFECTS AND DIGITAL BACK PROPAGATION

Propagation of a light signal in an optical fiber is described by the nonlinear Schr̈odinger equation (NLSE) [2], which taking into account the effect of polarization on the nonlinear interactions takes the following form:

$$\frac{\partial A_x}{\partial z} = \frac{j\beta_2}{2}\frac{\partial^2 A_x}{\partial t^2} - \frac{\alpha}{2}A_x + j\gamma\left(|A_x|^2 + \frac{2}{3}|A_y|^2\right)A_x$$
$$\frac{\partial A_y}{\partial z} = \frac{j\beta_2}{2}\frac{\partial^2 A_y}{\partial t^2} - \frac{\alpha}{2}A_y + j\gamma\left(|A_y|^2 + \frac{2}{3}|A_x|^2\right)A_y \quad (1)$$

where, A_x and A_y are the complex envelope of two orthogonal polarization components of the electric field, α is the attenuation coefficient, β_2 is the dispersion parameter, γ is the nonlinear coefficient, z and t are the propagation direction and time, respectively. In typical fiber birefringence affect on modes very small amount. Random scattering of polarization of electric field over small length
(typically around 100 m [2]) than the nonlinear interaction length (typically above 10 km) so that the resulting nonlinearity is averaged over the entire Poincar´e sphere under that situation the expected that nonlinearity interaction describe by Mankov equation [3] for the A_x polarization component:

$$\frac{\partial A_x}{\partial z} = \frac{j\beta_2}{2}\frac{\partial^2 A_x}{\partial t^2} - \frac{\alpha}{2}A_x + j\frac{8}{9}\gamma\left(|A_x|^2 + |A_y|^2\right)A_x \quad (2)$$

Equation for A_y don't considered for the sake of compactness. Eq. 2 does not have a closed form solution, unless $\gamma = 0$, or $\beta_2 = 0$. In the former case the system is linear and Eq. 1 can be written in the frequency domain and an inverse linear transfer function can be calculated easily, as discussed above. If chromatic dispersion is be neglected ($\beta_2 = 0$) the equation can be easily solved in the time domain to give:

$$A_x(t, z) = A_x(t, 0)\, e^{j\varphi_x^{NL}(t,z)} \quad (3)$$

Where $\varphi_x^{NL}(t, z)$ is the nonlinear phase shift for the Ax component:

$$\varphi_x^{NL}(t, z) = \frac{8}{9}\gamma\frac{1-e^{-\alpha z}}{\alpha}\left(|A_x(t,0)|^2 + |A_y(t,0)|^2\right) \quad (4)$$

Digital back propagation is a method of nonlinearity compensation which has generated much interest recently. It exploits the knowledge of the physical behavior of the optical fiber as a nonlinear channel, by approximating the inverse nonlinear channel, most commonly described by the nonlinear Schrödinger equation (NLSE). The solution of the NLSE is approximated by the split-step Fourier method (SSFM), commonly used to simulate nonlinear transmission in optical fibers. It requires the inverse nonlinear Schrödinger equation (NLSE) to be solved for the parameters of the optical link. For a single polarization and with spatial domain negated, the NLSE is given by:

$$\frac{\partial E}{\partial(-z)} = (D+N)\,E \quad (5)$$

Where E is the complex field complex field of the received signal, D is the differential operator accounting for linear effects (CD and attenuation) and N is the nonlinear operator, which are given by:

$$D = -\frac{j}{2}\cdot\beta_2\cdot\frac{\partial^2}{\partial t^2}\frac{\alpha}{2}$$

$$N = j\gamma|E|^2 \quad (6)$$

Where, α = Attenuation factor.

β_2=Group velocity dispersion parameter.
γ=Nonlinearity parameter.

When optical link modeled as first-in-last out principle means that first fiber span is the last modeled span and the beginning of each fiber span is the end of each modeled span. It known as Negated spatial domain implementation. Power in a two-span optical system and the corresponding inverse link modeled span shown in Fig 4. The span refers to fiber span in the optical link.

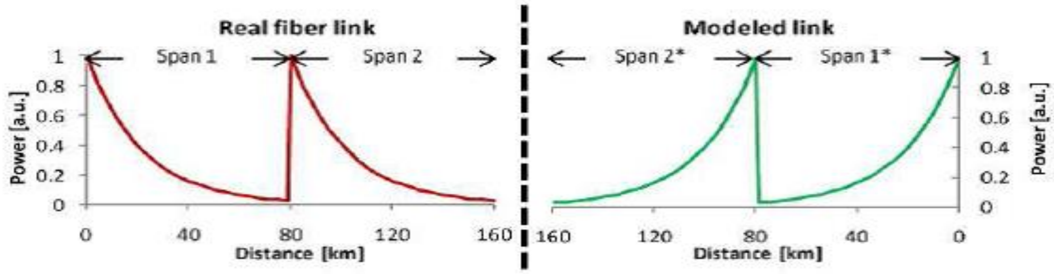


Fig 4: Power vs. propagation distance of a 2-span optical link (left) and the corresponding back propagation link (right) when using inverse NLSE [6]

To calculate numerical solution to Eq.5, the split-step Fourier method (SSFM) is used. The fiber is treated as a series of linear sections where only *D* is considered and dispersion-less nonlinear sections where only *N* is considered. As number of steps increase then we obtain more accurate result with paying price of increment in computational time. In Back propagation technique linear section impairments mitigation exactly same as CD compensation. The nonlinear section of BP is identical to the nonlinear section used in a single-step nonlinearity compensator. The phase shifts for each sample are:

$$\theta_{NL}(t) = k\,\gamma L_{eff}\,|E|^2 \tag{7}$$

Where k is a compensation factor which is optimized and L_{eff} is the effective length of each step. If each BP step compensates for one or more fiber spans, L_{eff} is

$$L_{eff} = s((1-\exp(-\alpha L_{span})/\alpha) \tag{8}$$

Where L_{span} is the length of each span and s is the number of fiber spans compensated for by each BP step. If each BP step only compensates for a fraction of a span, then L_{eff} is

$$L_{eff} = ((1-\exp(-\alpha L_{step})/\alpha)$$

IV.EXPERIMENTAL SETUP

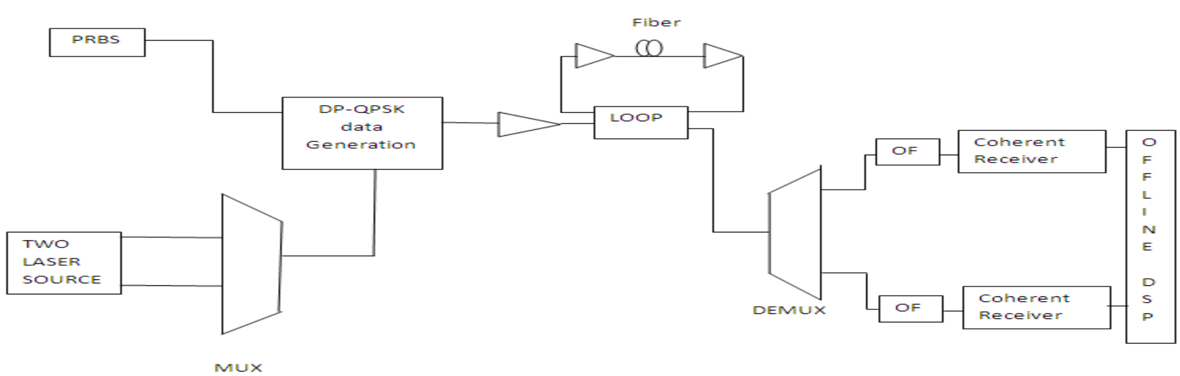


Fig 5: Experimental setup 100 Gbps 2×1 PDM-QPSK System

Fig 5 shows the Experimental setup of 100 Gbps 2×1 PDM-QPSK System which generates two closely spaced WDM channels from single PDM-QPSK transmitter. Two optical signal from CW laser whose frequency centered at 193.1 THz and 193.2 THz multiplexed through Multiplexer by maintaining power level of each channel is -2 dBm.100 GHz spaced apart multiplexed signal applied DP-QPSK generator. PRBS generates the Data signal of sequence length of 2^{15} that given to the DP-QPSK generator. DP-QPSK generator comprises of 4 $Linbo_3$ MZMs that driven through multiplexed optical signal and Data sequence as shown in Fig 6. MZM biased at $2V_{\pi}$=6 volt.

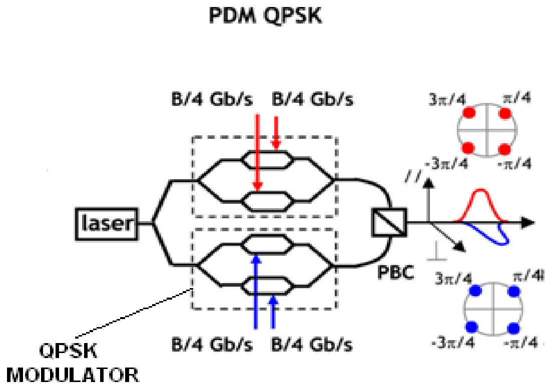


Fig 6: DP-QPSK Generator (PBC: Polarization Beam Combiner)[5]

Transmission testing performed on 80 km fiber with effective area of 80 μm^2 using recirculating loop along with two EDFA which provides pre and post boosting up of optical signal. Parameter of fiber listed as below

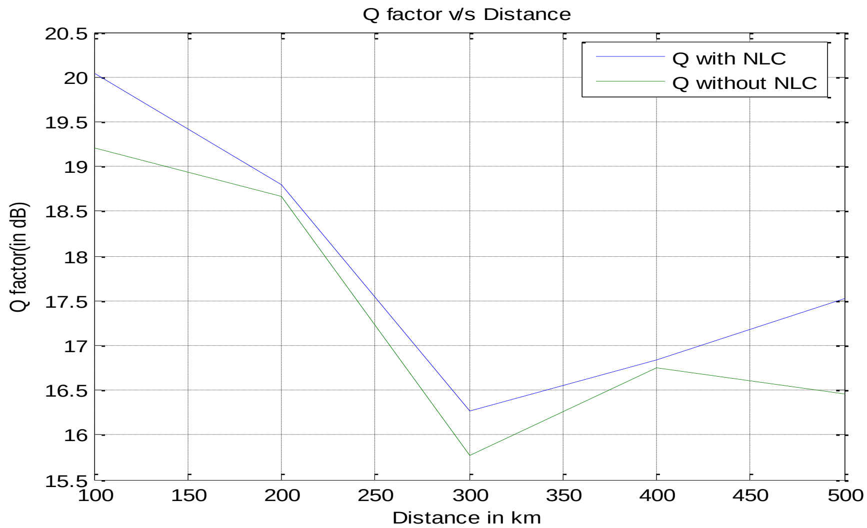
Table 1: Parameter of fiber

Parameter	Value
Reference wavelength	1550 nm
Length	80 km
Attenuation	0.185 dB/km
Dispersion	16.75 ps/nm/km
Dispersion slope	0.075 ps/nm^2/km
PMD co-efficient	0.05 ps/sqrt(km)

Optical signal after span is demultiplexed then filtered through the optical filter after that signal is coherently detected as shown in Fig 2. The DSP for QPSK component performs several important functions to aid in recovering the incoming transmission channel after coherent detection. It can be used with coherent systems designs that utilize QPSK modulation with single polarization (X channel) or dual polarization (X and Y channel) multiplexing.

V.RESULT AND DISCUSSION

For analyzing the effect of NLC (Nonlinear compensator) on system we simulate the system by considering key part as DSP module. Simulation carried out for different distance by measuring Q-factor (in dB) with NLC and without NLC at DSP module side. From that we plot the graph of Q-factor v/s Distance as shown in Fig 7.Q-factor value is decreasing as distance increasing due to linear and nonlinear impairments. But, value of Q-factor with NLC is higher as compared to value of Q-factor without NLC as shown in Fig 7 because of by mitigating nonlinearity through NLC enhancing the performance of system in terms of Q-factor. Fig 8 (a) and (b) shows the Constellation diagram of PDM-QPSK after DSP calculation with NLC.As distance increase then difference between Q-factor value with and without NLC also increase.



hFig 7: Graph plot of "Q-factor v/s Distance" with and without NLC

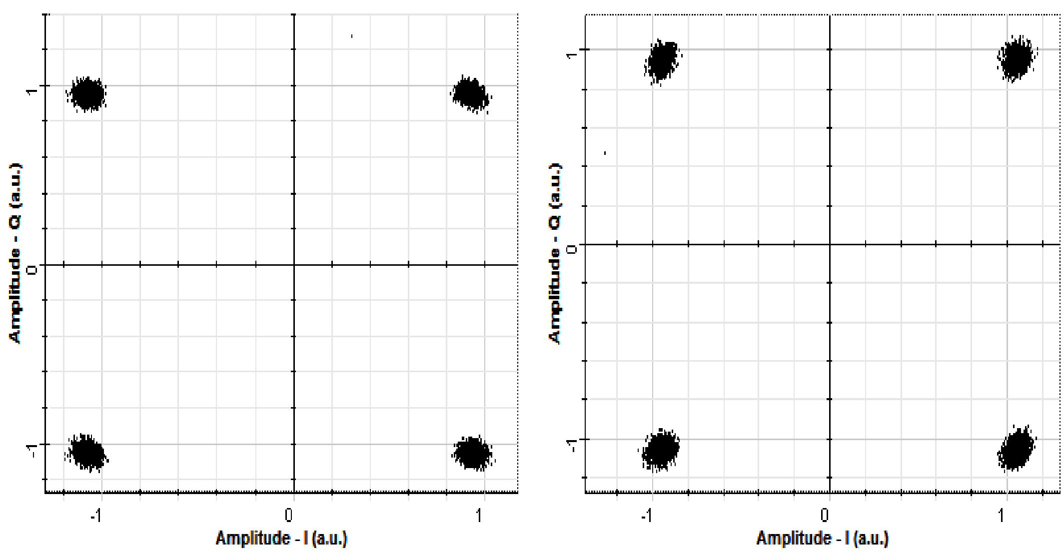


Fig 8 (a): Constellation of X component (b): Constellation of Y component

VI.CONCLUSION

We demonstrate the 100 Gbps 2×1 PDM-QPSK System which generates two closely spaced WDM channels from single PDM-QPSK transmitter. Nonlinearity is limitation factor for the long haul high speed optical communication. Nonlinearity of signal is compensated by Back propagation algorithm of DSP. Performance of system enhanced through the mitigation of nonlinearity which

we experimentally verified. For short Distance the performance of system approximately same for with and without NLC. But, for long distance performance of system is degraded without NLC.

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