Performance of Multilevel Modulation Formats in 92 Gb/s Systems in the Presence of PMD and Nonlinear Effects

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Abstract—**We simulated two multilevel modulation formats in optical fiber systems in the presence of varying polarization mode dispersion (PMD) and fiber nonlinearities. Carrier suppressed return-to-zero differential quadrature phase shift keying (CSRZ-DQPSK) and polarization shift keying (PolSK) formats are simulated. The maximum data rate used in the system is 92 Gb/s and the length of the fiber is kept fixed at 100 km. Dispersion compensated standard communication fiber models are used in the simulations. Monte Carlo method is used for the simulation where the PMD coefficients are varied from 0 to 2 ps/sqrt(km). For simulating nonlinear coefficients, 0.1 and 1.0 1/W/km are used for the low and high nonlinearities respectively. The performances of the modulating formats are compared in terms of bit error rate (BER). The results show that the PolSK system possesses better PMD tolerance in the presence of nonlinearities.**

Keywords—Polarization mode dispersion compensation, optical communication, modulation formats, DQPSK, PolSK

I. INTRODUCTION

Transmission in optical fiber communication systems is impaired and ultimately limited by the four 'horsemen' of the systems. These are chromatic dispersion, amplified spontaneous emission noise from amplifiers, polarization effects and fiber nonlinearities[1]. For conventional direct-detection single-carrier systems, the impairment induced by a constant DGD scales with the square of the bit rate, resulting in drastic PMD induced degradation for high speed transmission systems [2, 3]. PMD as well as the fiber nonlinearities have been considered as the ultimate barriers to high-speed optical transmission at and over 40 Gb/s. PMD effects are difficult to analyze because they are stochastic in nature and occur due to random variations in the spatially varying birefringence of the optical fibers as well as the polarization dependent loss. The random variation in the fiber changes on a random time scale. Hence modeling the effects of PMD is not straight forward. On the other hand Karr nonlinearity, which is the main source of nonlinearity is deterministic and can be modeled to analyze its effects on data transmission. It leads to phase rotation that is proportional to the intensity at every point in time. When the nonlinearity couples with other transmission impairments such as PMD, it can lead to complex dynamics [4]. Thus PMD which is stochastic in nature and nonlinearity which is deterministic in occurrence should be addressed together for high speed data transmission. The intensity of the light and its changing rate of variation degrade the effects of nonlinearitiescausing nonlinear polarization rotation. Different modulation formats are studied to smooth the changes in variations of light intensity. Different modulation formats showed tolerant to the effects of PMD and nonlinearities differently [5].

There are mainly two broader categories of optical modulation formats. One group of modulation format carries the information in amplitudes and also modulates the optical phases without carrying any information in phases. Modulated phases enhance the robustness of the transmission against PMD, nonlinearities and other impairments. Such formats are non-return-to-zero (NRZ), return-to-zero (RZ), carrier suppressed RZ (CSRZ) and duobinary. The other group of modulation carries the information in the opticalphases. They use the phase shift between the consecutive bits in order to carry and recover the information at receiving end. Example of such formats are differential phase shift keying (DPSK), differential quadrature phase shift keying (DQPSK), CSRZ-DQPSK and PolSK.

We have shown here the set up for two channel CSRZ-DQPSK and four channel PolSK modulation formats. They have advantages over conventional on–off keying (OOK) formats, such as doubling or quadrupling the spectral efficiency and relaxed dispersion management[6].Recently, the PolSK has attracted significant interest as a potential modulation technology in the field of optical communication by utilizing the state of polarization (SOP) of lightwave as signal carrier for high-speed data transmissions [7]. Investigations of multi-level PolSK technology have been carried out widely, which bring the possibility of transmitting more than one bit per symbol and help in increasing the spectral efficiencies [8, 9].However, the impacts of PMD and nonlinearity on RZ-DQPSK and PolSK system have not been investigated yet. In this paper, we present simulation results for investigating their impacts on a two-channel RZ-DQPSK and four-channeldirect-detection PolSK systems.We used a range of PMD coefficients in the presence of varied nonlinearities. The performance of the systems was evaluated mainly in terms of BER.

In this paper, in section two we discussed the system setup with CSRZ-DQPSK and PolSK modulation formats. Then the numerically simulated results are discussed in section three. Finally in section four, a short conclusion is presented.

II. SIMULATION MODELS

Generally the polarization state of a continuous light propagating in fibers with randomly varying birefringence will be elliptical. Due to the random change of birefringence, the polarization state will also change randomly during propagation. The polarization state of different parts of the pulse can be different. The changed polarization state is of importance when coherence detection scheme is employed. But PMD induced pulse broadening is of more concern at higher bit rate and long distance communication. The effect of both PMD and nonlinearity can be studied by generalizing the coupled NLS equations in terms of normalized amplitudes u and v such that [10]:

$$u = A_x\sqrt{\gamma L_D}e^{i\Delta\beta_z/2} \text{and} v = A_y\sqrt{\gamma L_D}e^{-i\Delta\beta_z/2} \quad \ldots\ldots (1)$$

Using the normalized distance and time, the NLS equation takes the form:

$$i\left(\frac{\partial u}{\partial\xi} + \delta\frac{\partial u}{\partial\tau}\right) + bu + \frac{1}{2}\frac{\partial^2 u}{\partial\tau^2} + \left(|u|^2 + \frac{2}{3}|v|^2\right)u + \frac{1}{3}v^2u^* = 0 \text{ and}$$

$$i\left(\frac{\partial v}{\partial\xi} - \delta\frac{\partial v}{\partial\tau}\right) - bv + \frac{1}{2}\frac{\partial^2 v}{\partial\tau^2} + \left(|v|^2 + \frac{2}{3}|u|^2\right)v + \frac{1}{3}u^2v^* = 0 \ldots (2)$$

where ξ = z/L_D, τ = (t - $\overline{\beta_1}z$)/T_0, $\overline{\beta_1}$= ½(β_{1x} + β_{1y}), $b = \frac{T_0^2(\Delta\beta)}{2|\beta_2|}$, $\delta = \frac{T_0}{2|\beta_2|}\frac{d(\Delta\beta)}{d\omega}$, γ is the nonlinear coefficient and L_D is the dispersion distance. Using Jones vector $|U\rangle$ and Pauli matrices σ_i (i = 1, 2 and 3), equation (2) can be written as:

$$i\frac{\partial|U\rangle}{\partial\xi} + \sigma_1\left(b|U\rangle + i\delta\frac{\partial|U\rangle}{\partial\tau}\right) + \frac{1}{2}\frac{\partial^2|U\rangle}{\partial\tau^2} + s_0|U\rangle - \frac{1}{3}s_3\sigma_3|U\rangle = 0 \ldots (3)$$

where $|U\rangle = \binom{u}{v}$ and Stokes parameters are:

$$s_0 = \langle U|U\rangle = |u|^2 + |v|^2, \quad s_1 = \langle U|\sigma_1|U\rangle = |u|^2 - |v|^2$$

$$s_2 = \langle U|\sigma_2|U\rangle = 2Re(u^*v), \; s_3 = \langle U|\sigma_3|U\rangle = 2Im(u^*v) \ldots .(4)$$

The increased bit rate affects T_0. The fiber length (L = 100 km) is much larger than coupling length (L_C), and the differential group delay (DGD) is approximated as [1]:

$$\Delta\tau_{rms}(L) = \Delta\tau_0\left(\sqrt{2}\frac{L_c}{L}\right)\left(e^{-L/L_c} - 1 + \frac{L}{L_c}\right)^{\frac{1}{2}} \quad \ldots\ldots\ldots\ldots (5)$$

The average DGD is given by $\langle\Delta\tau\rangle = \delta_{PMD}\sqrt{L}$ where δ_{PMD} is the PMD coefficient.

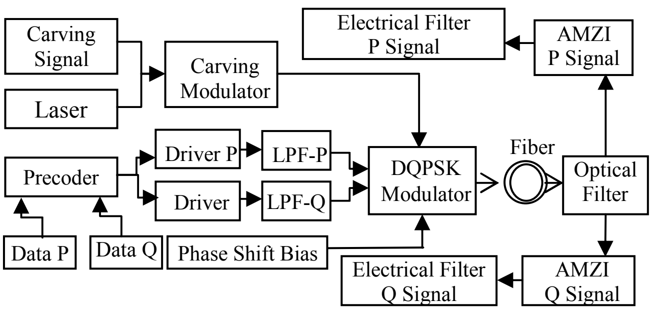

Figure 1: CSRZ- DQPSK Transmitter and Receiver sections

DQPSK is a four-level phase modulation format, where each symbol is coded with one out of four possible phase transitions, i.e. the phase change between two adjacent symbols. As each symbol has four possible states, two bits are transmitted againsteach symbol, and the symbol rate is therefore half of the bit rate B. This reduced bandwidth leads to significant cost reduction compared to systems where the symbol rates are equal to bit rate B. As the symbol rate is reduced, the spectral width is significantly reduced. DQPSK signal at bit rate B has the same spectral width as an OOK signal at bit rate B/2 [4].

Figure 1 depicts theblock diagramof transmitter and receiver sections of CSRZ-DQPSK system. The transmitter section takes two input data streams which are termed as in-phase (P) and quadrature (Q) binary signals. A precoder converts a pair of bit streams into a pair of encoded *P* and *Q* DQPSK bit streams suitable for controlling a DQPSK modulator. A carving signal modulates the carrier signal from the laser in a Mach-Zehnder modulator (MZM) which is shown as Carving Modulator. A second MZM takes four inputs: P and Q data, carved modulated carrier and phase shift bias. Finally two channel RZ-DQPSK modulated signal passes through the fiber. At the receiver, the two asymmetric Mach-Zehnder interferometers detect the P and Q data.

When a linearly polarized light is launched in an optical fiber as the input, the electrical component (**E**) of the light breaks up into two orthogonal sub-components. It occurs due to the random change in birefringence. P and Q signals are labeled by u and v signals respectively, then the two sub-components of u and v signals are denoted by E_{1u}, E_{2u}, E_{1v} and E_{2v} respectively. The sub-components at the receiver end are given by [3]:

$$E_{1u}(t) = \frac{1}{2}\left[E(t)e^{\frac{j\pi}{4}} + E(t-T)\right],$$

$$E_{2u}(t) = \frac{1}{2}\left[E(t)e^{\frac{j\pi}{4}} - E(t-T)\right]$$

$$E_{1v}(t) = \frac{1}{2}\left[E(t)e^{\frac{-j\pi}{4}} + E(t-T)\right],$$

$$E_{2v}(t) = \frac{1}{2}\left[E(t)e^{\frac{-j\pi}{4}} - E(t-T)\right] \ldots\ldots\ldots\ldots\ldots (6)$$

If the input signal to the demodulator is Aexp(jφ) and φ is the phase angle, thenthe balanced receiver current at the detector will be:

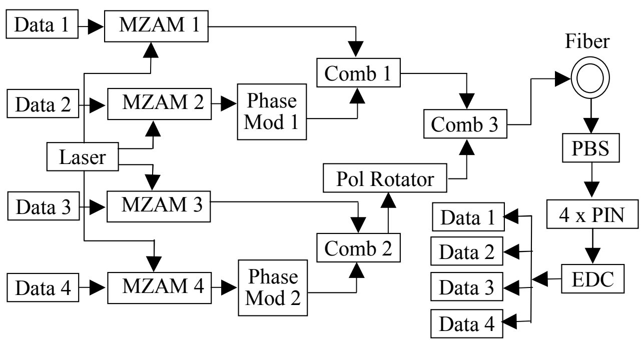

Figure 2: PolSK Transmitter and Receiver sections (MZAM: Mach-Zehnder Amplitude Modulator, Comb: Optical Combiner, PBS: Polarization Beam Splitter, EDC: Electronic Dispersion Compensator)

$$i_u = |E_{1u}|^2 - |E_{2u}|^2 = A^2cos\left(\varphi_n + \frac{\pi}{4} - \varphi_{n-1}\right)$$
$$= \frac{\sqrt{2}}{2}A^2[\cos(\Delta\varphi) - \sin(\Delta\varphi)]$$
$$i_v = |E_{1v}|^2 - |E_{2v}|^2 = A^2cos\left(\varphi_n - \frac{\pi}{4} - \varphi_{n-1}\right)$$
$$= \frac{\sqrt{2}}{2}A^2[\cos(\Delta\varphi) + \sin(\Delta\varphi)] \quad \text{.....................(7)}$$

Two asymmetric Mach-Zehnder interferometers (AMZI) use the modulated optical signal from the optical filter to detect i_u and i_v to recover P and Q signals respectively. Finally the electric filters are used to P and Q signals as shown in Figure 1.

Figure 2 shows a simplified block diagram of PolSK Transmitter and receiver sections. Here two DQPSK modules are used. Data 1 and Data 2 are modulated in upper module and Data 3 and Data 4 are modulated in lower module. Data 2 and Data 4 are passed through a phase modulator. It changes the phase of the input optical signal as a function of the electrical driving voltage. Combiner 1combines the modulated optical signals from MZAM 1 and 2. Similarly combiner 2combines the modulated optical signals from MZAM 3 and 4. Combiner 3combines the modulated combined optical signal from combiner 1 and optical signal from the polarization rotator. Polarization rotator rotates the state of polarization of the combined modulated optical signal from combiner 2.Theparameters to be specified for polarization rotator are related to the Stokes representation of polarization, and correspond to the angles of rotation around the three axes in the Stokes space. The Poincare sphere rotation angles about S1, S2 and S3 are set to 0, 0 and 180 degrees respectively. The transfer functionis assumed to be linearwhich is converted in terms of phase shift with the applied voltage. This is a good approximation for realistic phase modulators based on the electro-optic effect in $LiNbO_3$ devicesin which the output and input electric fields with nonzero excess loss (EL) are related as:

$$\boldsymbol{E}_{out} = 10^{-\frac{EL_{dB}}{20}} e^{j\varphi} \boldsymbol{E}_{in} \text{ where } \varphi = \pi\left(\frac{V_{in}-V_0}{V_\pi}\right) \quad \text{.....(8)}$$

The state of polarization of the output of lower module is rotated by 180°. Then the outputs of both the modules are combined at combiner 3 to get the four channel PolSK modulated signal. The signal is passed through the fiber after necessary amplification. At the receiver after due filtration, the signal is passed through the polarization beam splitter (PBS).The input optical signal is split into the two polarization components by aPBS. The two resulting signal components are sent to two 90 degree hybrids that allows "beating" between local oscillator and incoming signals.Four outputs of the PBS are fed to four PIN detectors. Four detected electrical signalsare passed through the EDC for electrical dispersion compensation. The outputs of the EDC are the four received data.

III. SIMULATION AND DISCUSSION

The simulation is carried out using split step Fourier method following coarse step algorithm with the assistance of RSoft and MATLAB. In the simulation of PolSK system, 65,536 bits were used for each of the four channels. But for RZ-DQPSK system, 2,048 bits were simulated. More bits were simulated for PolSK system because the performance of PolSK system was evaluated basing on the actual bit error count. The bit errors are counted basing on the actual average errors of the four channels. For both the systems, the lengths of the fibers are kept fixed at 100 km. The bit rate of each of the four channels of PolSK system was 23 Gb/s and hence the simulated bandwidth was 23 x 4 = 92 Gb/s. On the other hand the bit rate of each of two channels of CSRZ-DQPSK system was 23 Gb/s and hence the simulated bandwidth was 23 x 2 = 46 Gb/s. Gb/s. The power of the optical boosters and amplifiers were adjusted to achieve the optimum operating condition. Only 5 dBm and 10 dB amplifiers are used as booster and power amplifier before and after the fiber respectively for the PolSK system. But 2 dBm and 10 dB amplifiers are used as booster and power amplifier before and after the fiber respectively for the RZ-DQPSK system. The performances of both the systems are evaluated in terms of BER for different nonlinearities as shown in Figures 3 and 4.

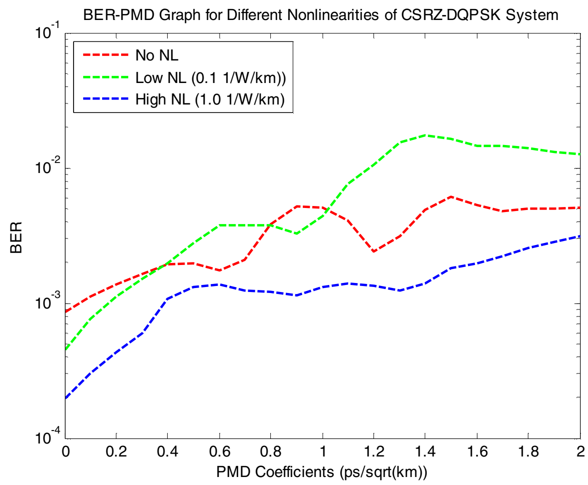

Figure 3: BER-PMD graph of CSRZ-DQPSK system for different nonlinearity values

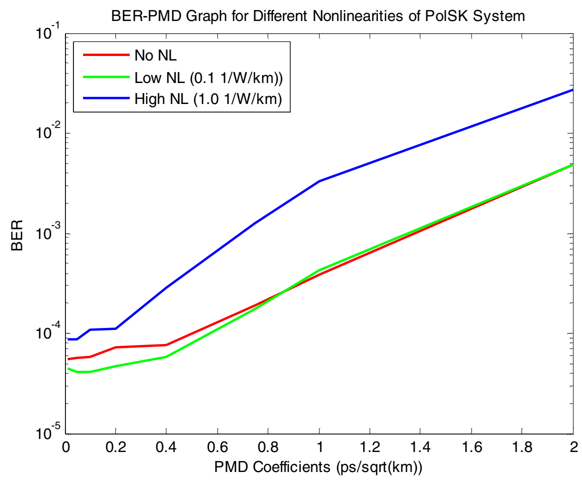

Figure 4: BER-PMD graph of PolSK system for different nonlinearity values

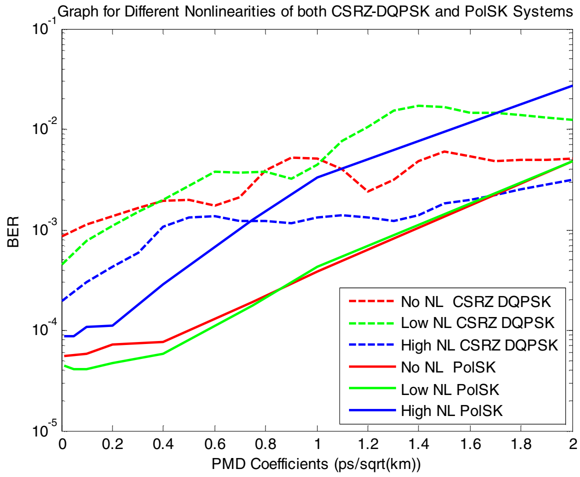

Figure 5: BER-PMD graph of both CSRZ-DQPSK and PolSK systems for different nonlinearity values

Figure 5 shows the comparison of both CSRZ-DQPSK and PolSK systems for different nonlinearity values. The range of PMD coefficient used for the simulation is extended from 0-2 ps/sqrt(km) though presently standard fibers are found at around 0.1 ps/sqrt(km). For No-NL condition, the nonlinearity is not included in the simulation. For Low-NL, the nonlinearity coefficient is set to 0.1 1/W/km and for High-NL, the nonlinearity coefficient is set to 1.0 1/W/km.

The horizontal axis represents an increasing PMD coefficient and vertical axis represents the increasing bit error rate (BER). The simulated results show that the performance of PolSK system is better than that of CSRZ-DQPSK system considering bandwidth and PMD tolerance in the presence of nonlinearities. Figure 5 shows that PolSK system gives best operating condition at low value of PMD coefficient within 0.2 ps/sqrt(km). It is interesting to note that within this range the presence of low nonlinearity improves the system performance. It is clear that PolSK system is affected by PMD and nonlinearity but it supports very high bit rate.

IV. CONCLUSION

We have carried out the simulation of CSRZ-DQPSK and PolSK systems to determine the effect of PMD and nonlinearity in terms of BER. PolSK modulation system shows better performance. One important aspect of two systems is that the power of the optical boosters and the amplifiers of both the systems are very less and increased power impairs the polarization state of both the systems. The simulations show that PolSK system provides better bit rate support. The PolSK system improves the spectral efficiency double than that of CSRZ-DQPSK. The advanced digital signal processing has made it possible to correctly recover the error free data which is received at BER less than 0.5 exp(-3) at the cost of increased data overhead by 7%. That indicates that the PolSK system presented here has the potentiality to face the future generation need of high data capacity systems. PolSK system is almost linearly tolerant to PMD and nonlinearity at their lower values.

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