Performance of Different Modulation Formats in 40 Gb/s Optical Systems in the Presence of Polarization Mode Dispersion and Nonlinear Effects

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***Abstract*—We simulated different modulation formats in optical fiber systems in the presence of polarization mode dispersion (PMD) and fiber nonlinearities. Non-return-to-zero (NRZ), return-to-zero (RZ), chirped RZ (CRZ), carrier suppressed RZ (CSRZ), duobinary, differential phase shift keying (DPSK), differential quadrature phase shift keying (DQPSK) and CSRZ-DQPSK formats are simulated. The maximum data rate used in the system is 40 Gb/s and the length of the fiber is kept fixed at 100 km. Standard communication fiber models are used. Monte Carlo simulation method is used for high and low PMD coefficients and for varied nonlinear coefficients. The performance of different formats is compared in terms of differential group delay (DGD). The results show that RZ-DQPSK is better PMD tolerant in the presence of nonlinearities.**

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

I. Introduction

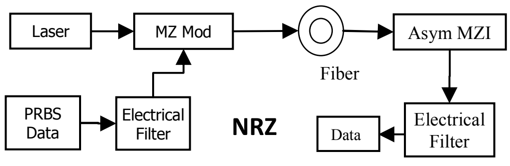
Transmission in optical fiber communication systems is impaired and ultimately limited by the four 'horsemen' of optical fiber communication systems - chromatic dispersion, amplified spontaneous emission noise from amplifiers, polarization effects and fiber nonlinearities [1, 2]. For conventional direct-detection 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 [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 an uncertain 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 it couples with other transmission impairments such as PMD, it can lead to complex dynamics [4 and 5]. Thus PMD which is stochastic in nature and nonlinearities which is deterministic in occurrence should be addressed together for high speed data transmission. Since the intensity of the light and its rate of variation cause degrade the effects of nonlinearities and introduce nonlinear polarization rotation, different modulation formats are proved effective in smoothening the changes in variations of light intensity. Thereby the signal becomes tolerant to the effects of PMD and nonlinearities [6-8].

There are mainly two broader categories of modulation formats. One group of optical modulation format carries the information and also modulates the optical phases without carrying any information. It enhances the robustness of the transmission against PMD, nonlinearities and other impairments. Such formats are NRZ, RZ, CRZ, CSRZ and duobinary. The other group carries the information in the optical phases. They use the phase shift between the consecutive bits in order to carry and recover the information at receiving end. Such formats are DPSK, DQPSK and RZ-DQPSK. We have shown here the set up for RZ-DQPSK modulation format since it has advantages over conventional on–off keying (OOK) modulation, such as doubling in spectral efficiency, relaxed dispersion management and four-fold increase in polarization-mode dispersion (PMD)-limited transmission length [9, 10]. In this simulation, we used high and low PMD coefficient in the presence and absence of nonlinearities. The performances of the systems are evaluated mainly in terms of DGD.

In this paper, at first we discussed the system setup with different modulation formats with special emphasis to RZ-DQPSK. Then the simulation and the results will be discussed. Finally a short conclusion will be presented.

II. Modulation Formats

NRZ is the oldest and the simplest modulation format. This modulation is obtained by switching a laser source between ON or OFF in accordance to the modulating data bits. As shown in Figure 1(a), the Mach-Zehnder Modulator (MZM) performs the task of modulation. It receives two inputs; the continuous wave (CW) as the carrier from the laser and the modulating signal from the electrical filter which receives the data at 40 Gb/s from the pseudo-random bit sequence (PRBS).



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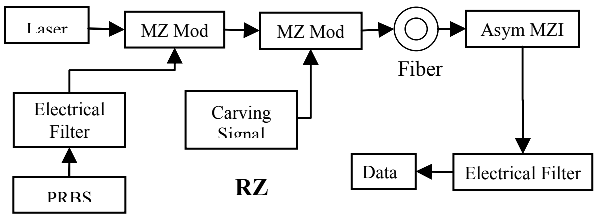

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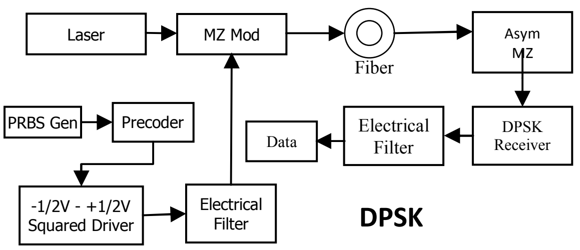

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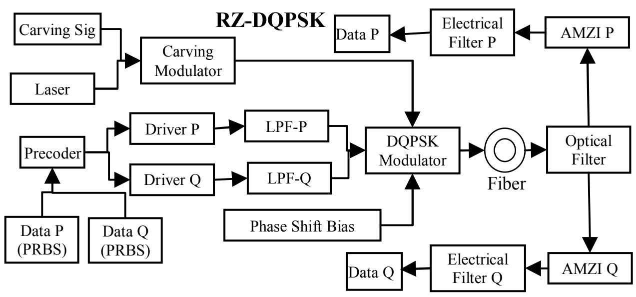


(d)

Figure 1: (a) NRZ, (b) RZ, (c) DPSK and (d) RZ-DQPSK Systems

Figure 1(b) shows the block of RZ modulation system. It has the same set up like the NRZ system except the second MZM and the carving signal. Figure 1(c) shows the setup for DPSK system. Here the data information is encoded in the phase instead of in the amplitude. A precoder is used in the original data sequence. Figure 1(d) shows a RZ-DQPSK setup. It 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 [4, 5]. As each symbol has four possible states, two bits are transmitted for each symbol, and the symbol rate is therefore half of the bit rate B. This reduced bandwidth leads to significant cost reduction compared to a binary system where all components need a bandwidth sufficient for a bit rate B. As the symbol rate is reduced, the spectral width is significantly reduced.

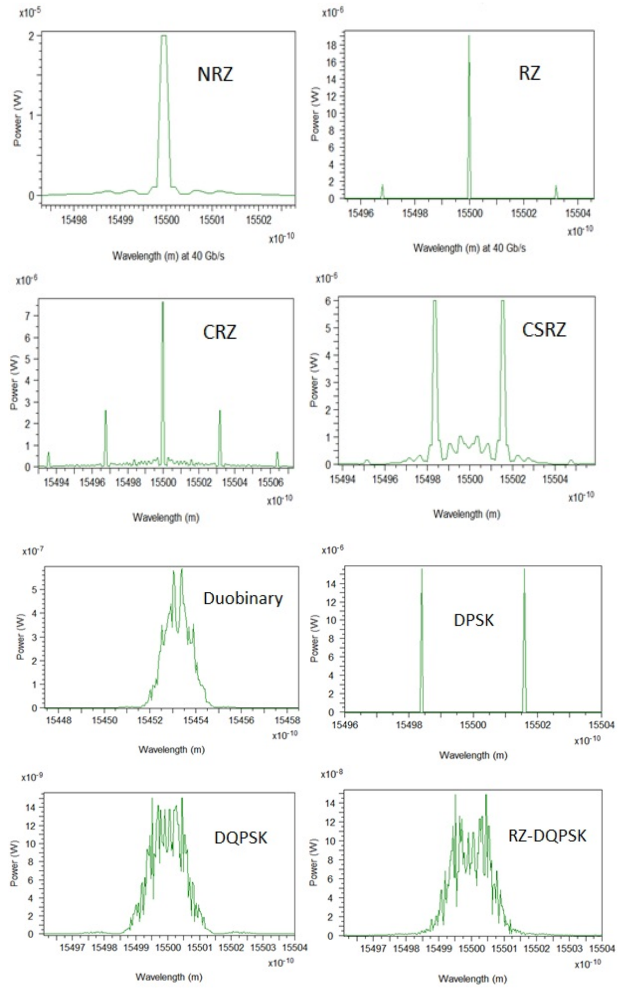


Figure 2: Received signal spectrum of different systems

A DQPSK signal at bit rate B has the same spectral width as an NRZ signal at bit rate B/2. RZ-DQPSK transmitter which takes input encoded in-phase (P) and quadrature (Q) binary signals and produces an RZ-DQPSK optical output signal. A precoder converts a pair of bit streams into a pair of encoded *P* and *Q* bit streams suitable for controlling a DQPSK modulator. If binary input bit streams are *a* and *b*, and encoded output bit streams are *p* and *q*, then the *k*th output bits satisfy the relationships:

$$p_k = \overline{(a_k \oplus b_k)}.(a_k \oplus p_{k-1}) + (a_k \oplus b_k).(b_k \oplus q_{k-1})$$
$$q_k = \overline{(a_k \oplus b_k)}.(b_k \oplus q_{k-1}) + (a_k \oplus b_k).(a_k \oplus p_{k-1}) \quad \text{……….} (1)$$

Driver P and driver Q convert the input binary signals into electrical waveforms.

Figure 2 shows the output signal spectrum of different modulation systems. RZ has a very narrow spectrum than NRZ system. Besides the advantages like its suitability for dense wavelength division multiplexing (DWDM), one disadvantage is that its sharp intensity change worsens the nonlinear effects. CRZ also has the similar advantage and disadvantage. The problem of RZ system is addressed by suppressing the carrier. It gives rise to two lobes and the sharp change in the intensity is reduced. Among the formats where the amplitude of the carrier holds the information, duobinary format shows a good prospect with its broad and slow-rise which helps in countering the nonlinear effects. The DPSK spectrum also has similar spectrum like CSRZ system. In DQPSK, the spectrum top is broader but the rise is sharp. This limitation is overcome by applying the feature of CSRZ system. Thus RZ-DQPSK possesses the advantages of most of other formats. It has a spectrum that is robust to nonlinear effects and it carries the information in carrier phase thus it has the robustness to polarization effect.

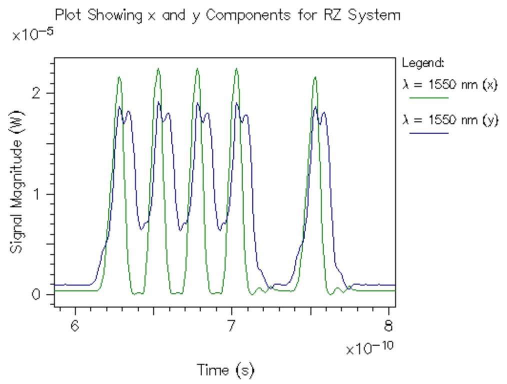
III. YSTEM MODEL AND SIMULATION RESULTS

An electrical component **E** of polarized light in an optical fiber breaks up in to two sub-components due to the random change in birefringence. The sub-components are given by [4]:

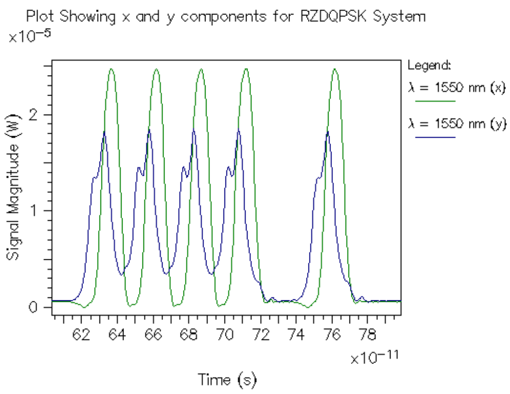
$$E_{1u}(t) = \frac{1}{2}\left[E(t)e^{\frac{j\pi}{4}} + E(t-T)\right], E_{2u}(t) = \frac{1}{2}\left[E(t)e^{\frac{j\pi}{4}} - E(t-T)\right]$$
$$E_{1v}(t) = \frac{1}{2}\left[E(t)e^{\frac{-j\pi}{4}} + E(t-T)\right], E_{2v}(t) = \frac{1}{2}\left[E(t)e^{\frac{-j\pi}{4}} - E(t-T)\right] \quad \ldots\ldots\ldots\ldots\ldots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

If the input signal to the demodulator is Aexp(jφ), and the balanced receiver current will be:

$$i_u = |E_{1u}|^2 - |E_{2u}|^2 = A^2 cos\left(\varphi_n + \frac{\pi}{4} - \varphi_{n-1}\right) = \frac{\sqrt{2}}{2}A^2[\cos(\Delta\varphi) - \sin(\Delta\varphi)]$$
$$i_v = |E_{1v}|^2 - |E_{2v}|^2 = A^2 cos\left(\varphi_n - \frac{\pi}{4} - \varphi_{n-1}\right) = \frac{\sqrt{2}}{2}A^2[\cos(\Delta\varphi) + \sin(\Delta\varphi)] \quad \ldots\ldots\ldots (3)$$



(a)



(b)

Figure 3: Components of (a) RZ and (b) RZDQPSK Systems

Figure 3 shows the u and v components in RZ and RZDQPSK systems. The amount of power that is carried by each component at any instant of time changes randomly. But the total power in two components remains the same. Table 1 shows the differential group delay (DGD) in picosecond (ps) due PMD and nonlinear effects. Since the occurrence of PMD is random in nature, Monte Carlo method is used in this simulation using 30 seeds. The DGD shown in the Table 1 is the mean of 30 seeds. Figure 4 shows the DGD for PMD 0.05 and 5 ps/(km)$^{0.5}$. Since the nonlinear coefficient is n_2/A_{eff}. We considered A_{eff} a value equal to 70 10^{-12} m^2 and nonlinear coefficient (n_2) changed as 0, 4e-23 and 5e-20 for simulating no nonlinearity, low nonlinearity and high nonlinearity conditions. All other parameters are kept almost similar for all formats.

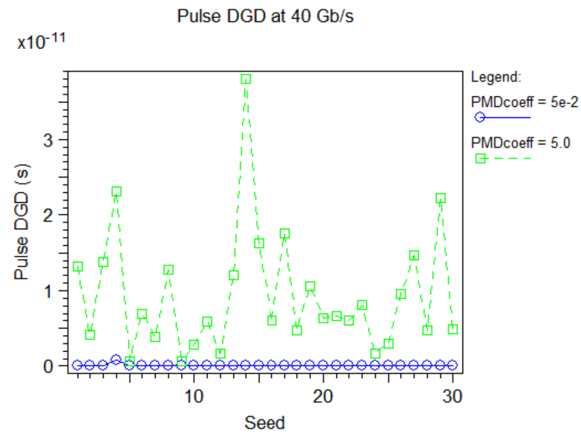


Figure 4: The DGD graph for 30 Seeds

Table 1a DGD of various Modulation Formats in ps

Data	NL	PMD	NRZ	RZ	CRZ	CSRZ
10 GB	None	0.05	0.078	0.103	0.174	0.056
		5	7.639	11.859	6.976	5.092
	Low	0.05	0.080	0.103	0.174	0.056
		5	7.639	11.859	6.976	5.092
	High	0.05	0.080	0.237	0.178	0.055
		5	7.634	11.836	7.155	5.004
40 GB	None	0.05	0.051	0.065	0.155	0.056
		5	4.340	9.429	3.699	3.526
	Low	0.05	0.051	0.065	0.155	0.056
		5	4.340	9.429	3.699	3.526
	High	0.05	0.051	0.091	0.158	0.055
		5	4.347	9.427	3.650	3.511

Table 1b DGD of various Modulation Formats in ps

Data	NL	PMD	Duo	DPSK	DQPSK	CSRZ-DQPSK
10 GB	None	0.05	0.157	0.069	0.052	0.004
		5	42.04	1.952	18.351	0.586
	Low	0.05	0.157	0.069	0.052	0.004
		5	42.04	1.952	18.351	0.586
	High	0.05	0.135	0.069	0.0521	0.004
		5	42.03	1.942	18.351	0.586
40 GB	None	0.05	0.175	0.068	0.054	0.005
		5	14.258	1.716	22.187	0.687
	Low	0.05	0.175	0.068	0.054	0.005
		5	14.257	1.716	22.187	0.687
	High	0.05	0.258	0.068	0.0542	0.005
		5	14.309	1.704	22.187	0.687

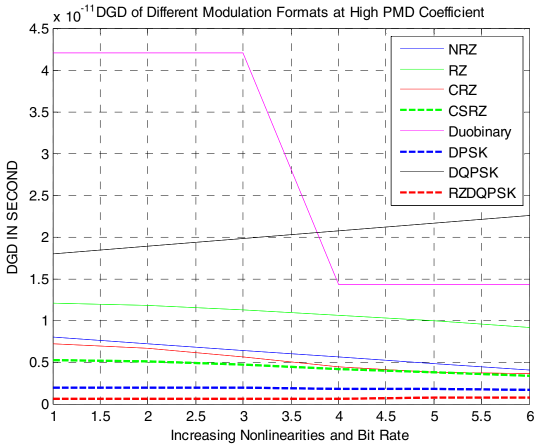


Figure 5: DGD comparison of low PMD coefficients

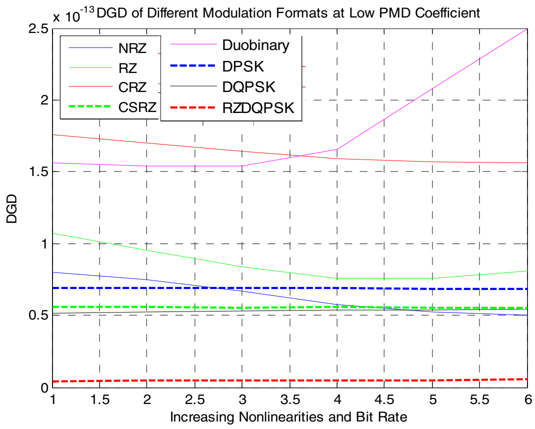


Figure 6: DGD comparison of high PMD coefficients

Figure 5 shows the comparison of DGD of different modulation formats with low PMD coefficient where the coefficient value is taken equal to 0.05e-15 s/m$^{0.5}$. The legend shows eight modulation formats. The horizontal axis represents an increasing nonlinear coefficient and increasing bit rate. Bit rate 10 Gb/s and 40 Gb/s are simulated. For nonlinearities three conditions are examined: no nonlinearity, low linearity and high linearity. The graph shows that Duobinary system has highest DGD at lower bit rate (10 Gb/s) and low nonlinearity which reduces considerably at high bit rate (40 Gb/s) and at high nonlinearity. On the other hand DQPSK system's DGD increases with the increase of bit rate. But for all parameter values, the RZ-DQPSK exhibits the lowest DGD. The readings suggest that the increase in nonlinearity do not degrade the system performance in the presence of PMD. Rather for some system, the DGD decreases with the increase of nonlinearity as seen in the case of CSRZ and RZ-DQPSK systems.

Figure 6 shows the comparison of DGD of different modulation formats with high PMD coefficient where the coefficient value is taken equal to 5e-15 s/m$^{0.5}$. The graph displays the performance of eight modulation formats. Here also the horizontal axis represents an increasing nonlinear coefficient and increasing bit rate. For nonlinearities three conditions are examined: none, low and high linearity. The graph shows that CRZ system has highest DGD at lower bit rate (10 Gb/s) and low nonlinearity which reduces considerably at high bit rate (40 Gb/s) and at high nonlinearity. On the other hand Duobinary system has an increased DGD with the increase of bit rate and nonlinearity. RZ system has shown an inconsistent value of DGD at high PMD value. But for all parameter values with high PMD coefficient the RZ-DQPSK exhibits the lowest DGD. For some systems, the DGD decreases with the increase of nonlinearity as seen in the case of NRZ, DPSK and RZ-DQPSK systems.

IV. CONCLUSION

We have shown the simulation of different modulation formats focusing the effect of PMD and nonlinearity in terms of DGD. RZDQPSK modulation system shows the best performance. We have also shown that the effect of PMD reduces for some modulation systems with increased nonlinearity. The optical power spectra of different modulation formats suggest that RZ-DQPSK system combines maximum advantages of all formats. DGD diagram of different DQPSK modulations also suggest that RZ-DQPSK system has the best performance with lowest DGD with low as well as high PMD values. RZDQPSK has shown better prospect in meeting the requirement of high bit transfer through optical communication network well beyond 40 Gb/s.

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