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Timing jitter dependence on data format for ideal dispersion compensated 10 Gbps optical communication systems

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Abstract

Simulations for data formats Return to Zero (RZ), Non-Return to Zero (NRZ), RZ-Soliton, Duobinary and their subcategories have been done with and without ideal dispersion compensation for optical communication systems. The results show that, in general, dispersion compensation improves timing jitter. RZ-Rectangular pulses show the smallest value of jitter without compensation. It has been observed that the RZ-Raised Cosine, and Soliton, give minimum jitter after ideal compensation. It has been reported that the BER performance of optical communication system using Duobinary data format is 10^{-8} and 10^{-37} before and after dispersion compensation, respectively. Further the comparative study shows that the timing jitter is the lowest in case of RZ-Soliton (0.0127 ns) after dispersion compensation and 0.0135 ns for RZ-Rectangular data format before dispersion compensation.

Keywords: Timing jitter; Data formats; Dispersion compensation; BER; Q factor

1. Introduction

Today's long-haul transmission systems represent the fourth generation utilizing multiple carrier wavelengths, which has led to an explosion of channel capacity. At the same time, deregulation of telecommunication markets and global success of the internet has driven the demand for higher and higher system capacity. In 1998, existing systems were upgraded to carry up to four coarsely spaced wavelengths. Today, new dense wavelength-division multiplexing (DWDM) systems that will soon deliver up to 1 Tbit/s of data per fiber over transoceanic distances are under construction. Conventionally, the Non-Return-to-Zero (NRZ) modulation format has been used in long-haul transmission systems [1,2]. These systems are based on the fact that fiber dispersion and non-linearities are detrimental effects. NRZ is used advantageously as it provides minimum optical bandwidth and minimum optical peak power per bit interval for a given average power.

However, with increased bitrates it has been shown that Return-to-Zero (RZ) modulation formats offer certain advantages over NRZ, as they tend to be more robust against distortions [3]. For instance, RZ modulation is more tolerant to non-optimized dispersion maps than NRZ schemes [4]. This can be explained by the fact that optimum balancing between fiber non-linearities and dispersion is dependent on the pulse

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shape. A RZ-modulated signal stream consists of a sequence of similar pulse shapes, whereas a NRZ-modulated stream does not. The dispersion tolerance of a signal stream can be derived from the superposition of the dispersion tolerance of the individual pulse shapes. In fact, for the majority of cases, the best results of WDM transmission experiments regarding the distance-bitrate product have been achieved using RZ modulation formats in both terrestrial and transoceanic systems [4].

From the point of view of designing a system, impairments from optical transmission need to be understood. Also we have to understand what are the ways to reduce them, how the receiver affects the signal and whether it can improve the performance. Comparison of modulation formats CRZ, RZ and NRZ in generic undersea system using noise-free simulations has already been done by Sinkin et al. [5]. They separated out the influence of transmission from that of the receiver and compared the performance using three different electrical filters. First, an optimization procedure was performed over a wide range of parameters to achieve the best performance for each format in a given system and then the physical properties and limitations of the formats were studied. It was found that during transmission, rapid stretching and contractions, while in the receiver, concentration of the pulse energy in the center of the bit slot, decrease intersymbol interference. However, to achieve higher spectral efficiency, it is necessary at some point to sacrifice these two properties of RZ formats in favor of formats like NRZ with smaller spectral bandwidth [5,6].

Santhanam et al. presented timing jitter expressions in dispersion-managed light-wave systems that are based on the moment method with the assumption of a chirped Gaussian pulse. A low-power light-wave system employing the RZ format finds that timing jitter can be minimized along the fiber link for an optimal choice of precompensation and postcompensation [7–9]. Thus, study of timing jitter dependence on data formats is becoming important and controlling of timing jitter is a problem for developing long-distance optical communication systems. While designing high-capacity systems, it becomes very important to carefully model system performance before performing laboratory experiments and field trials, as these experiments are costly and time consuming. The huge design space can only be limited by analytical approximations and computer modeling using powerful simulation tools. This work focuses on the characteristics of optical pulse propagation over modern long-haul fiber-optic transmission systems. Major distortions of optical systems arise from pulse timing jitter, which are introduced by various sources along the propagation path. The subject of this work is to investigate by simulation the timing jitter dependence on data format for 10 Gb/s optical communication systems.

2. System description and results

Fig. 1 indicates a simulation model of an optical communication system at 10 Gb/s around 1550 nm central wavelength. The simulation has been carried out using a commercial simulation package OptSim^{TM}. Simulation is done for 140 km length of standard single-mode (SM) fiber for obtaining a permissible value of BER $\sim 1 \times 10^{-12}$. Standard SM fiber has loss 0.2 dB/km, and dispersion 16 ps/nm/km at reference frequency. It has zero dispersion at 1391.53354633 nm wavelength, fiber average beat length 5 m and fiber PMD 0.1 ps/km$^{0.5}$.

CW Lorentzian Laser used was having center emission wavelength 1550 nm, CW power 1 mW and FWHM linewidth 10 MHz as main characteristics. Ideal dispersion compensator was used as ideal fiber grating having a total compensating dispersion at the reference frequency −1600 ps/nm, wavelength 1550 nm. Amplitude dual-arm Mach Zehnder modulator is used here to modulate the optical signal of desired format having the following parameters: excess loss 0 dB, offset voltage corresponding to the phase retardation in the absence of any (on both arms) electric field 0.5 V, extinction ratio 20 dB, chirp factor 0 and average power reduction due to modulation 3 dB. Optical splitter of attenuation 0 dB at each output port was used to see before ideal dispersion compensation. Electrical scopes with Gaussian filter was used to observe change in performance. PIN diode detects the optical signal, i.e. conversion into electrical signal having the following characteristics: quantum efficiency 0.7, responsivity (at reference frequency) 0.8751 A/W, −3 dB bandwidth 20 GHz, dark current 0.1 nA, reference wavelength 1550 nm. It keeps quantum noise on.

Fig. 2(a) depicts eye diagram NRZ, i.e. NRZ-Rectangular data format before dispersion compensation for the optical communication system taken. Fig. 2(b) shows eye diagram after dispersion compensation. Greater opening of the eye diagram leads one to expect less timing jitter value. For the system under

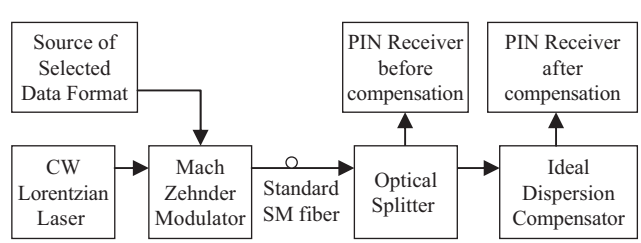

Fig. 1. Optical communication model considered for simulation.

consideration, the measured values show improvements: Q from 6.726 to 16.455 dB, BER from 0.0171 to 2.717e−11 and timing jitter from 0.024 to 0.015 ns (listed in Table 1). Fig. 3(a) shows eye diagram NRZ-Raised Cosine data format before dispersion compensation for the optical communication system under consideration. Fig. 3(b) indicates eye diagram after dispersion compensation, greater opening of the eye diagram tempts one to expect less timing jitter value.

The measured values of NRZ-Raised Cosine listed in Table 1 show improvements, e.g. for Q from 7.407 to 18.262 dB, for BER from 0.0102 to 7.269e−16 and for timing jitter from 0.026 to 0.015 ns. Between these two NRZ type formats, one can interpret from Table 1 and Figs. 2(a, b) 3(a, b) that ideal dispersion compensation is decreasing timing jitter aprox. by 0.009 ns, is decreasing BER by a factor of approx. 1e−7 compared to that for NRZ-Rectangular, where decrease in NRZ-Raised Cosine type is by approx. 1e−14 and improvement in Q factor is by nearly 10 dB for each. NRZ-Raised Cosine type data format is better because non-linearities are affecting less in comparison to NRZ-Rectangular. Also ideal rectangular shape of optical pulse is difficult to maintain through the length of optical fiber. For all NRZ data type improvement in timing jitter is because of peculiar modulation pattern generated by it [3,5].

Fig. 4(a) shows eye diagram RZ-Rectangular data format before dispersion compensation for the model of optical communication system described above. Fig. 4(b) indicates eye diagram after dispersion compensation, greater opening of the eye diagram qualitatively leads to expect less timing jitter value. For this case, the measured values show improvements: Q from 6.021 to 16.160 dB, BER from 0.0227 to 1.001e−10 and timing jitter remains the same (see Table 1). For the

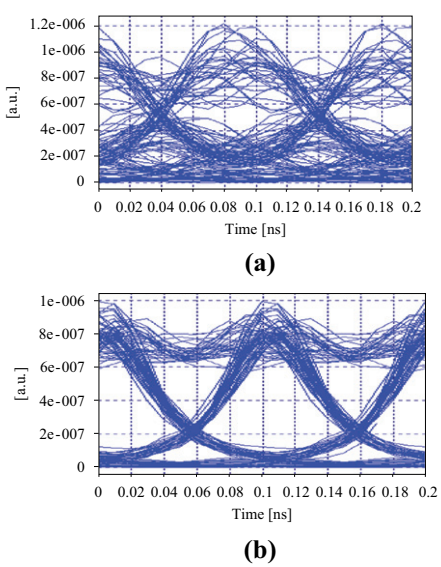

Fig. 2. Eye diagram for NRZ data format for standard SM fiber at 140 km and wavelength of 1550 nm (a) before dispersion compensation and (b) after dispersion compensation.

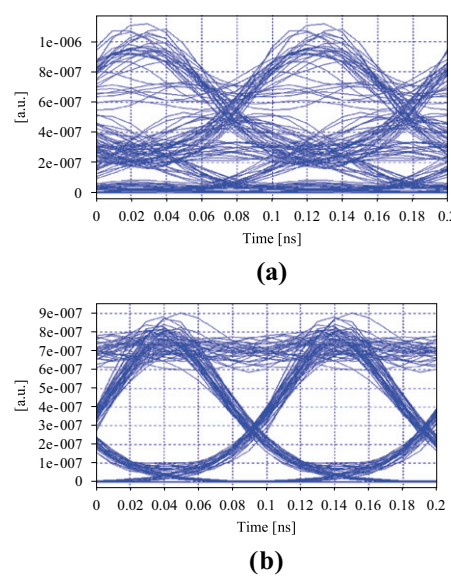

Fig. 3. Eye diagram for NRZ-Raised Cosine data format for standard SM fiber at 140 km and wavelength of 1550 nm (a) before dispersion compensation and (b) after dispersion compensation.

Table 1. Q factor, BER and timing jitter before and after dispersion compensation at 140 km

S. no.	Data format	Q factor (dB)		BER		Jitter (ns)	
		Before	After	Before	After	Before	After
1	NRZ-Rectangular	6.726	16.455	0.0171	2.717e−11	0.024	0.015
2	NRZ-Raised Cosine	7.407	18.2621	0.0102	7.269e−16	0.026	0.015
3	RZ-Rectangular	6.021	16.160	0.0227	1.001e−10	0.014	0.014
4	RZ-Raised Cosine	6.021	10.433	0.0227	0.0004	0.015	0.015
5	RZ-Super Gaussian	6.021	13.745	0.0227	5.547e−7	0.019	0.016
6	RZ-Soliton	6.021	16.135	0.0227	7.016e−11	0.022	0.013
7	Duobinary	14.866	22.376	1.723e−8	1.039e−37	0.023	0.019

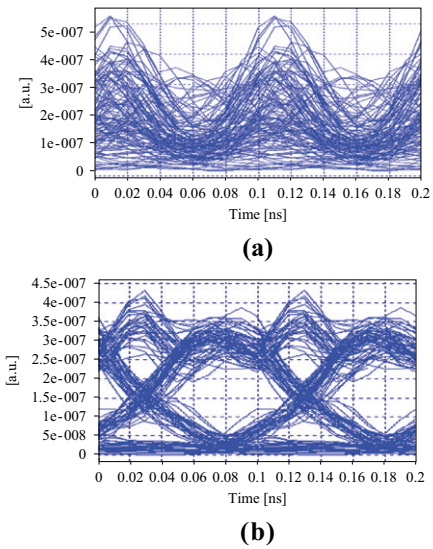

Fig. 4. Eye diagram for RZ-Rectangular data format for standard SM fiber at 140 km and wavelength of 1550 nm (a) before dispersion compensation and (b) after dispersion compensation.

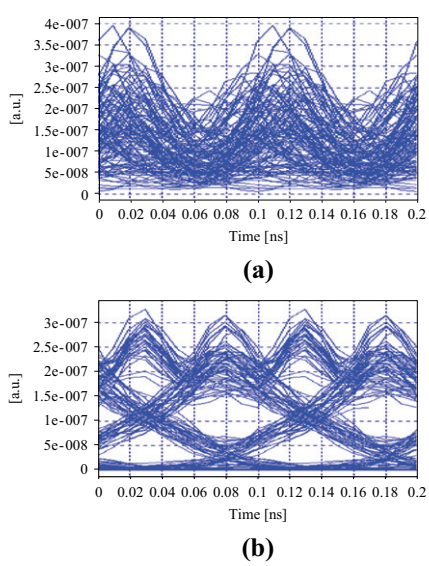

Fig. 5. Eye diagram for RZ-Raised Cosine data format for standard SM fiber at 140 km and wavelength of 1550 nm (a) before dispersion compensation and (b) after dispersion compensation.

model of optical communication system undertaken, Fig. 5(a) shows eye diagram RZ-Raised Cosine data format before dispersion compensation. Fig. 5(b) shows eye diagram after dispersion compensation. Greater opening of the eye diagram leads one to expect less timing jitter value. As per the values listed in Table 1, the measured values show improvements: Q from 6.021 to 10.433 dB, BER from 0.0227 to 0.0004 and timing jitter from 0.015 to 0.015 ns.

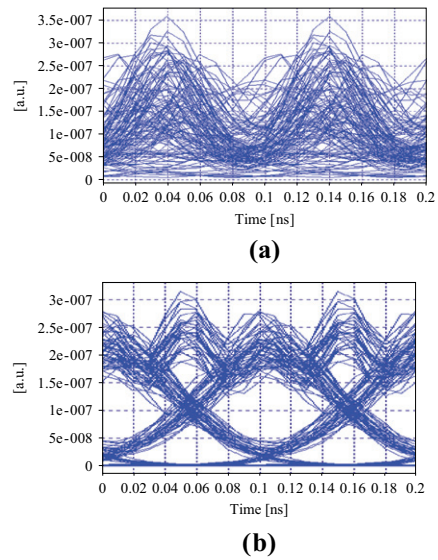

Fig. 6. Eye diagram for RZ-Super Gaussian data format for standard SM fiber at 140 km and wavelength of 1550 nm (a) before dispersion compensation and (b) after dispersion compensation.

Fig. 6(a) shows eye diagram RZ-Super Gaussian data format before dispersion compensation for the optical communication system model. Fig. 6(b) shows eye diagram after dispersion compensation, greater opening of the eye diagram means qualitatively less timing jitter value. From Table 1, the measured values listed indicate improvements: Q from 6.021 to 13.745 dB, BER from 0.0227 to 5.54e−7 and timing jitter from 0.019 to 0.016 ns. Improvement here found is because of dispersion compensation by ideal dispersion compensator.

Fig. 7(a) shows eye diagram RZ-Soliton data format before dispersion compensation for the optical communication system described above. Fig. 7(b) shows eye diagram after dispersion compensation. Greater opening of the eye diagram, i.e. qualitatively, indicates less timing jitter value. For the system under consideration, the measured values show improvements: Q from 6.021 to 16.135 dB, BER from 0.0227 to 7.016e−11 and timing jitter from 0.022 to 0.013 ns (listed in Table 1). Among various RZ types of data formats considered, best performance is shown by RZ-Rectangular, RZ-Soliton data and RZ-Raised Cosine format type of pulses. Soliton shows decrease in timing jitter by 0.009 ns.

From the point of view of BER and Q, again RZ-Soliton and RZ-Rectangular are the best performing data formats after ideal dispersion compensation. They give a BER decrease of approximately 1e−9 and 1e−8 for the data formats, respectively. Q value increases by 10 dB for both. Second best performance is given by RZ-Super Gaussian data format after ideal dispersion compensation. It increases Q value by 7 dB, decreases BER by 1e−5 and timing jitter by 0.003 ns. RZ-Raised gives poor performance even after ideal dispersion

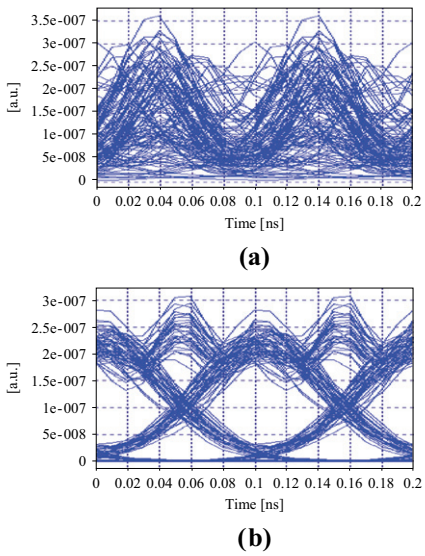

Fig. 7. Eye diagram for RZ-Soliton data format for standard SM fiber at 140 km and wavelength of 1550 nm (a) before dispersion compensation and (b) after dispersion compensation.

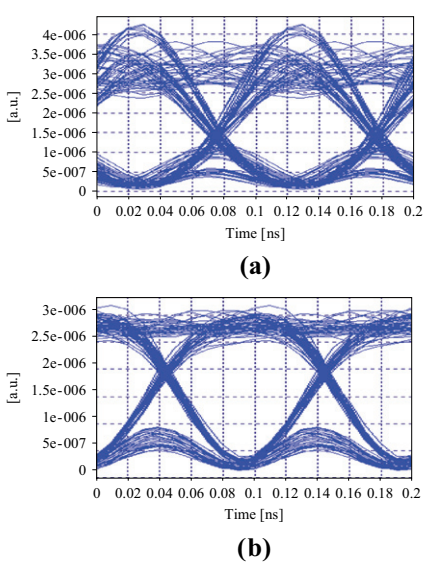

Fig. 8. Eye diagram for Duobinary data format for standard SM fiber at 140 km and wavelength of 1550 nm (a) before dispersion compensation and (b) after dispersion compensation.

compensation. This behavior of RZ-Soliton is because non-linearities affect the least with this and at same time in guiding mechanism chirping and GVD balance tries to maintain the shape of the optical pulse. RZ-Rectangular shape is an ideal case rarely used because retaining rectangular shape is a challenge in itself. In total, all RZ data type formats are causing less timing jitter as claimed by Andre Richter [3].

Fig. 8(a) shows eye diagram Duobinary data format before dispersion compensation for the optical communication system model taken. Fig. 8(b) shows eye diagram after dispersion compensation. Greater opening of the eye diagram tempts one to expect less timing jitter value. The measured values show improvements: Q from 14.866 to 22.376 dB, BER from 1.723e−8 to 1.039e−37 and timing jitter from 0.023 to 0.019 ns, see Table 1.

Duobinary comes out the best among various RZ and NRZ data formats and its subcategories in comparison to it. This behavior is because of compression of data in Duobinary data format.

In general, it has been observed that there is improvement in timing jitter after ideal dispersion compensation for all data formats. Smallest jitter in RZ-Rectangular pulses before compensation but pure rectangular pulses are not easy to maintain and generate for long distances and hence are rarely used. Other practical realizable data format is RZ-Raised Cosine and -Soliton have second minimum jitter. Q factor after compensation improves by 10.4 dB for RZ-Raised Cosine and to 22.4 dB for Duobinary data format. BER after ideal dispersion compensation is 0.0004, the largest for RZ-Raised Cosine, and 1.039×10^{-37}, the smallest for Duobinary data format under similar conditions of optical communication systems. Timing jitter decreases for NRZ data format by 0.009 ns, all RZ formats not showing decrease in timing jitter but RZ-Soliton type shows decrease by 0.009 ns. In overall observation of figures and Table 1, Duobinary data format shows improvement in every department considered, i.e. Q value, BER and timing jitter because of the compression data.

3. Conclusion

In general, there is reduction in timing jitter after dispersion compensation for all NRZ, and all RZ data formats except RZ-Rectangular, RZ-Raised Cosine and RZ-Super Gaussian under the same conditions of an optical communication system. Ideal dispersion compensation is always a requirement to limit timing jitter in case of NRZ data type formats and RZ is tolerant toward timing jitter. The most suitable data format is RZ-Soliton among other RZ data type formats for timing jitter reduction for optical communication system. If BER, Q value is considered in addition to timing jitter. The Duobinary data format is considered to be the best data format for optical communication systems even before dispersion compensation.

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