COMPARISON OF DIFFERENT MODULATION FORMATS FOR 8 CHANNEL WDM OPTICAL NETWORK AT 40 GBPS DATARATE WITH NON-LINEARITY

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ABSTRACT

In this paper, we analyzed various modulation formats for wavelength division multiplexed systems operating at data rates 8 X 40 Gb/s = 320 Gb/s. The performance analysis of WDM system for Non return-to-zero (NRZ), Return-to-Zero (RZ) with duty cycle 0.5 and 0.67, Carrier-suppressed return-to-zero (CSRZ), Duo binary RZ (DRZ) and Modified Duo binary RZ (MDRZ) like modulation formats are considered to find optimum modulation format for a 40 Gb/s bit rate optical transmission system. We analyzed performance of WDM system by varying input power from -15 dBm to 10 dBm for a fixed transmission distance of 300 km (considered only SMF length) for all modulation formats mentioned above with 100 GHz and 200 GHz spacing between each channel and also compare performance for 100 GHz and 200 GHz spacing for each modulation formats. Dispersion compensating fiber (DCF) was chosen as a dispersion compensation technique to evaluate the effect of modulation format on them.

Keywords: carrier suppressed return to zero (CSRZ); wavelength division multiplexing (WDM); non return to zero (NRZ); return to zero (RZ); carrier suppressed return to zero (CSRZ); duo binary RZ (DRZ); modified Duobinary RZ (MDRZ)

I. INTRODUCTION

As we head towards new millennium, we are witnessing dramatic transitions in telecommunications industry. That has far reaching implications in every walk of our lives. There are many drivers for these changes. First and foremost is the continuing, relentless need for more capacity in the network. This demand is fuelled by many factors like growth of internet and the World Wide Web, both in terms of number of users and the amount of time, and thus bandwidth taken by each user, is a major factor [1]. Optical fiber fulfill this demand because it offer very large bandwidth so
multiple channels can be transmitted through the common fiber using concept of wavelength division multiplexing technique. For DWDM systems in which the data rate is >10Gb/s/channel, the deleterious effects of dispersion and nonlinearity must be managed to achieve transmission over any appreciable distance [2]. Dispersion management, utilizing alternating fiber segments of opposite dispersion values, is a key technique that keeps the total accumulated dispersion low while suppressing most nonlinear effects. Dispersion compensation is achieved using different techniques like dispersion compensating fiber, fiber bragg grating, optical phase conjugation and electrical equalizer. Among all these technique, dispersion compensation fiber is proposed for compensation of dispersion. Positive dispersion of single-mode fiber (SMF) can be compensated by negative dispersion of dispersion compensating fiber (DCF) in dispersion-managed systems [3], [4]. In conventional standard-fiber transmission lines, the RZ and NRZ formats are the two modulation formats that are most often used. Analysis and investigations have shown that RZ turns out to be superior compared to conventional NRZ systems [5], [6], as long standard single-mode fibers are used as transmission media. As alternatives to RZ and NRZ, several other modulation formats like CSRZ [5], [7], [8] single-sideband RZ (SSB-RZ) [5] and duo binary modulations [7] have been proposed.

At high bit rates, the modulation format, type of dispersion compensation scheme, and channel power become important issues for optimum system design. There are different factors that should be considered for the right choice of modulation format, such as spectral efficiency, power margin, and tolerance against Group Velocity Dispersion (GVD) and against fiber nonlinear effects like Self Phase Modulation (SPM), Cross Phase Modulation (XPM), FWM and stimulated Raman scattering (SRS). Up till now the research for RZ, CSRZ, DRZ and MDRZ formats is available mostly for WDM systems and the comparison of RZ and NRZ formats with CSRZ, Duo binary, MDRZ formats is not available as such in literature. Here, we extend the work reported in [9], [10] to find the most suitable format for higher transmission distance 300km at 40Gb/s data rate (for each channel) for 8 channel WDM system with 100GHz and 200GHz channel spacing. In this paper, NRZ, RZ with duty cycle 0.5 and 0.67, CSRZ, DRZ and MDRZ modulation formats are analyzed together and individually using symmetrical dispersion compensation schemes on the basis of Q value.

A. Chromatic Dispersion

Dispersion is one of the most important of impairments that is dominant in single mode fibers [2]. It happens because the refractive index of silica if wavelength dependent. When the light is launched into the fiber, various spectral components will traverse with different group velocities. This is called group velocity dispersion (GVD). It can be calculated mathematically:

\[ T = \frac{L}{V_g} \]  

Here \( V_g \) shows group velocity.
If we want to calculate it based on wavelength we earn

\[ \Delta T = D L \Delta \lambda \]  

D is dispersion parameter in ps/ nm-km [12].

B. Self Phase Modulation (SPM)

It is type of non-linear effect that is occurred because of the light component interaction. This is created because light encounters with different refractive index when travel along the fiber, due to
Kerr effect. Consequently phase shift will be produced and it eventuate a change of pulse frequency spectrum. Refractive Index of optical material has little dependency to the optical Intensity [13].

\[ n = n_0 + n_2 I = n_0 + n_2 \left( \frac{P}{A_{eff}} \right) \]  

(3)

In above formula, \( n \) is real refractive index regarding to SPM effect, \( n_0 \) is our ordinary refractive index, \( n_2 \) is nonlinear index coefficient. The factor \( n_2 \) is variable in silica from 2.2 to 3.4 \( \times 10^{-8} \) \( \mu \text{m}^2/\text{W} \). The consequence of SPM effect is that optical power variation be converted to phase variation in same wave.

C. Cross phase modulation (XPM)

The non-linear refractive index seen by an optical pulse depends not only on the intensity of the pulse but also on the intensity of the other co-propagating optical pulses, i.e., the nonlinear phase modulation of an optical pulse caused by fluctuations in intensity of other optical pulses is called XPM. The result of XPM may be asymmetric spectral broadening and distortion of the pulse shape. XPM hinders the system performance through the same mechanism as SPM: chirping frequency and chromatic dispersion. XPM damages the system performance even more than SPM and influences it severely when the number of channels is large. The XPM-induced phase shift can occur only when two pulses overlap in time. Due to this overlap, the intensity-dependent phase shift and consequent chirping is enhanced, leading to enhanced pulse broadening.

D. Four wave mixing (FWM)

FWM originates from third order non-linear susceptibility \( \chi^{(3)} \) in optical links. If three optical signals with carrier frequencies \( \omega_1, \omega_2, \omega_3 \), co-propagate inside a fiber simultaneously, \( \chi^{(3)} \) generates a fourth signal with frequency \( \omega_4 \), which is related to the other frequencies by \( \omega_4 = \omega_1 \pm \omega_2 \pm \omega_3 \). In general for wavelengths launched into a fiber, the number of FWM channels produced is

\[ M = w^2(w - 1)/2 \]  

(4)

E. Stimulated Raman Scattering (SRS)

In WDM systems, due to the injection of two or more optical signals at different wavelengths into a fiber, optical signal power is transferred from lower wavelength optical channels to the higher wavelength optical channels by SRS effect. This can skew the power distribution among the WDM channels- reducing the signal-to-noise ratio of the lower wavelength channels and introducing crosstalk on the higher wavelength channels.

II. DISPERSION COMPENSATION USING DISPERSION COMPENSATING FIBER

In optical network, optical fiber offers very large bandwidth but it suffers from one problem of dispersion. Dispersion means broadening of the pulse in time domain due to the difference in the group velocity of different modes. It has two effects, 1) it reduces the energy contain in the pulse and 2) it results in spreading of pulse so it interfere with adjacent pulse so it creates ISI effect. So, it limits the data rate. There are mainly three types of dispersion. 1) Modal dispersion 2) chromatic dispersion and 3) Polarization mode dispersion (PMD). Modal dispersion is mainly occurred in MMF because of the difference in group velocity of different modes. Chromatic dispersion because of the material and waveguide property of the fiber. PMD because of the different polarization states of the mode travel with different group velocity.
System performance degrades due to this dispersion effect. So dispersion should be minimized using different techniques to improve performance. In this paper, to minimize dispersion effect, dispersion compensation fiber technique is adopted. Dispersion compensating fibers have negative dispersion of -80 to -90 ps/nm.km and used to compensate the positive dispersion of the single mode fiber. In optical WDM network, performance degradation is due to the chromatic dispersion, fiber nonlinearity, and accumulation of amplified spontaneous emission noise due to periodic amplification. Due to the nonlinear propagation of signal in optical fiber, system performance mainly decided by the power levels at the input of different types of fibers and also on the position of the DCF. A DCF must have low insertion loss, low optical nonlinearity and also it must offers large negative dispersion coefficient to minimize the size of a DCF. By placing one DCF with negative dispersion after, before or symmetrical fashion, compensate dispersion induced by SMF and the first order dispersion should be zero.

\[ D_{SMF} \times L_{SMF} = -D_{DCF} \times L_{DCF} \quad (5) \]

Where \( D_{SMF} \), \( D_{DCF} \) are dispersion coefficients and \( L_{SMF} \), \( L_{DCF} \) are length in order of SMF and DCF. Compensation is done by three different methods depending on the position of the DCF:

1) Pre-Compensation
2) Post Compensation
3) Symmetrical Compensation

Symmetrical compensation scheme can greatly reduce the fiber nonlinear effects, this program better than the pre compensation and post compensation program [14]. So, we have proposed symmetrical compensation program for our analysis.

III. TRANSMITTERS FOR DIFFERENT MODULATION FORMATS

F. Non return to zero (NRZ)

The Fig. 1(a), (b) shows the diagram of the NRZ transmitter and the spectrum of the modulated signal. The intensity of the carrier light wave is modulated by the applied electric field which voltage varies with a determined function. The Mach zehnder modulator (MZM) is driven at the quadrature point of the modulator power transfer function with an electrical NRZ signal. We can see that the spectrum has a strong carrier component and there are deep nulls at the multiples of the bit rate. We can see from Fig. 1(b) that the carrier frequency contains too much power but no information. Thus, techniques to reduce the power content of the signal are necessary.

The NRZ pulses possess a narrow optical spectrum due to the lower on-off transitions. The reduced spectral width improves the dispersion tolerance, but on the other hand it affects the inter-symbol interference (ISI) between the pulses. This is evident for isolated spaces between sequences of marks where the energy of neighboring marks becomes transformed in the time slot of the isolated space resulting in ISI effects.
G. Return to zero (RZ)

The schematic diagram of the RZ format is shown in Fig. 1(a) but use RZ pulse generator instead of NRZ. The RZ pulse occupies just a part of the bit slot, so it has a duty cycle smaller than 1 and a broad spectrum. Fig. 2 shows optical spectrum of RZ modulation. The RZ signal amplitude between adjacent 1’s returns to zero. A RZ signal with the same average power of a NRZ signal has a spectrum peak-power twice larger. The main characteristic of RZ modulated signals is a relatively broad optical spectrum, resulting in a reduced dispersion tolerance and a reduced spectral efficiency. The RZ pulse shape enables an increased robustness to fiber nonlinear effects and to the effects of PMD. The mathematical representation of a generated RZ signal is

\[
F_{out} (RZ) = \frac{1}{2} F_{in}(t)(e^{j(\pi(0.1\sin(2\pi ft)))+\pi}) + e^{-j(\pi(0.5\sin(2\pi ft)))-\pi})
\]

\[
= - \cos(0.314159 \sin(2\pi ft))
\]
**Fig. 2.** Optical spectrum of RZ format

**H. Carrier suppressed return-to-zero (CS-RZ)**

![Block diagram of CSRZ modulation format](image)

**Fig. 3.** (a) Schematic of CSRZ modulation format (b) Optical spectrum of CSRZ format

CSRZ is a special form of RZ where the carrier is suppressed. The main target of this modulation format is a reduction of the nonlinear impairments in a channel and an improvement of the spectral efficiency in high bit rate systems. The difference between CSRZ and conventional RZ is
that the CSRZ signal has a $\pi$ phase shift between adjacent bits. This phase alternation, in the optical domain, produces no DC component; thus, there is no carrier component for CSRZ. It can be expected that the dispersion tolerance of CSRZ modulation can be improved due its reduced spectral width compared to RZ modulation. Generally speaking, the formulation of CSRZ optics signal demands two electro-optic modulators as the Fig. 3(a), suggests. It is the first MZ modulator that encodes NRZ data. After that, the generated NRZ optical signal is modulated by another MZ modulator to produce a CSRZ optical signal. The mathematical representation of a generated CSRZ signal is

$$E_{out \ (CSRZ)} = \frac{1}{2} E_{in}(t) \left( e^{j(\pi(0.5 \sin(2\pi ft+\pi)))} + e^{j(\pi(0.5 \sin(2\pi ft)-\pi))}\right)$$

$$= -j \sin \left( 1.5708 \sin(2\pi ft) \right)$$

(7)

The carrier component of CSRZ signal spectrum is suppressed due to the external modulation at zero point in the second MZM. The spectrum shown in Fig. 3(b), two sidebands that carry the information and also, other two upper and lower second harmonic sidebands.

**I. Duobinary return to zero (DRZ)**

![Fig. 4. (a) Schematic of DRZ modulation format (b) Optical spectrum of DRZ format](image)
Fig. 4(a) illustrates the schematic of the 40 Gb/s duo-binary transmitter. The duo binary was generated by first creating an NRZ duo binary signal using a duo binary precoder, NRZ generator and a Duo binary pulse generator. The generator drives the first MZM, and then cascades this modulator with a second modulator that is driven by a sinusoidal electrical signal with the frequency of 40GHz Phase = -90°. The duo binary precoder used here is composed of an exclusive-or gate with a delayed feedback path. DRZ formats are very attractive, because their optical modulation bandwidth can be compressed to the data bit rate B, that is, the half-bandwidth of the NRZ format 2B as shown in Fig. 4(b).

J. Modified duo binary RZ (MDRZ)

![Diagram of MDRZ modulation format](image)

**Fig. 5.** (a) Schematic of MDRZ modulation format. (b) Optical spectrum of MDRZ format

Fig. 5(a) displays the schematic for the production of the MDRZ modulation format. In this, first NRZ duo-binary signal is generated that drives the first MZM and then connecting this modulator with a second modulator that is driven by a sine wave generator with the frequency of 40GHz and phase -95. Fig. 5(b) shows the optical spectrum of MDRZ signal. The
generation of MDRZ signal is almost identical to the DRZ signal, except the delay -and-add circuit is replaced by a delay-and-subtract circuit. In the duo binary signal used earlier where the phase of bits ‘1’s are modified only after a bit ‘0’ appear whereas in the modified duo binary signal the phase is alternated between 0 and $\pi$ for the bits ‘1’. The phase of all the "zero" bits is kept constant and a $180^0$ phase variation between all the consecutive "ones" is introduced [12].

IV. SIMULATION SETUP

Fig. 6 shows a schematic of simulation setup of an 8 channel WDM optical communication system at 40 Gb/s with the central frequency 192.9 THz. The parameters for both simulation and fiber used in the system model are supplemented in Table1.

In WDM network, to achieve high capacity and high speed data transmission with higher accuracy, the dispersion and other non-linearity must be compensated. For this purpose, some dispersion compensation scheme must be used periodically in the link. In this paper we have proposed dispersion compensation using DCF and we have done simulation using symmetrical compensation as mentioned above for 8 users and each has a data rate of 40 Gb/s. We have proposed different modulation formats like NRZ, RZ with duty cycle 0.5 and 0.67, CSRZ, MDRZ and DRZ and analyzed the optical system in terms of Q factor because only OSNR could not accurately measure the system performance, especially in WDM systems.
TABLE I: SIMULATION PARAMETERS

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
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</thead>
<tbody>
<tr>
<td>Bit rate</td>
<td>8 X 40 Gb/s = 320 Gb/s</td>
</tr>
<tr>
<td>Length of SMF</td>
<td>50 km</td>
</tr>
<tr>
<td>Length of DCF</td>
<td>5 km x 2</td>
</tr>
<tr>
<td>No. of spans</td>
<td>6</td>
</tr>
<tr>
<td>Dispersion coefficient of SMF and DCF</td>
<td>17 ps/nm.km and -85 ps/nm.km</td>
</tr>
<tr>
<td>Dispersion slope of SMF and DCF</td>
<td>0.075 ps/nm2.km and -0.3 ps/nm2.kmm².km</td>
</tr>
<tr>
<td>Attenuation factor of SMF and DCF</td>
<td>0.2 dB/km and 0.5 dB/km</td>
</tr>
<tr>
<td>Affective areas of SMF and DCF</td>
<td>70 µm² and 22 µm²</td>
</tr>
<tr>
<td>Gain of Inline EDFA placed after SMF and DCF</td>
<td>10 dB and 2.5 dB</td>
</tr>
<tr>
<td>Noise figure of EDFS</td>
<td>6 dB</td>
</tr>
</tbody>
</table>

The combined electric field of all 8 channels is then propagated through the fiber, and propagation of the resultant optical field is simulated by solving the nonlinear Schrödinger equation using a split-step Fourier analysis [2]. The total field approach is adopted for our simulation model, and the simulated spectral range is more than three times the bandwidth occupied by the WDM channels [2].

The simulation setup is composed of transmitter, fiber and receiver. The WDM transmitter consists of a CW laser source for each channel, data modulators and the optical multiplexer. To the output port of the CW laser a data modulator has been connected. Optical signals from 8 data modulators are fed to the 8 input ports of an optical multiplexer. Here different modulators are used as explained earlier. The transmission channel at 320 GB/s is designed by using the fiber parameters of DCF and SMF in such a way that the dispersion is compensated exactly. The gain of the erbium doped fiber amplifier (EDFA) placed after each fiber is such that it compensates the losses of the preceding fiber. The noise figure of the amplifiers is constant and set to 6 dB. The signal is then launched over 6 spans of standard single mode fiber (SMF) of 50km each. In symmetrical compensation scheme, as shown in Fig, two DCF fibers of 5 km are used before and after of the SMF fibers of 50 km length. Here three in-line EDFA have been used in the link. The affective areas of SMF and DCF are assumed to be 70 and 22 µm², and the included nonlinear processes are SPM, XPM, FWM, and stimulated Raman scattering. In the receiver the signal is de-multiplexed via optical de-multiplexer with BW of 2R and 4R for NRZ and RZ respectively where R is the bit rate, after detected by PIN detector with responsivity 1 A/W, passed through the low pass Bessel filter with cut off frequency 0.8*Bit rate. The filtered electrical signal is given to the 3R Regenerator. 3R Regenerator output is connected directly to the BER analyzer which is used as a visualize to generate graphs and results such as eye diagram, BER, Q value, eye opening etc.

V. RESULTS AND DISCUSSION

In optical communication systems, only optical signal to noise ratio (OSNR) could not accurately measure the system performance, especially in WDM systems. Q, typically functioning as a quality factor, becomes one of the important quality indicators to measure the optical performance by which to characterize the BER.

The six modulation formats have been numerically compared for symmetrical dispersion compensation schemes for 8 x 40 GB/s WDM system in terms of received maximum Q value using
Split Step Fourier Transform method. To analyze the system, the results of the first channel have been taken, as this is the worst-case scenario (end channels).

Fig. 7, 8 shows the graphical representation of Q value as a function of signal input power after a transmission distance of 300 km for symmetrical-compensation schemes respectively for various modulation formats. It can be seen for all the modulation formats that as the signal input power increases, Q

![Fig. 7. Q value as a function of signal input power after a transmission distance of 300 km for 200 GHz spacing](image)

This can be understood from the fact that for low powers, the performance of DWDM systems improves with the increase in input power. However, at higher powers, the wavelengths tend to overlap each other causing more dominance of non-linear effects like XPM and FWM caused by optical Kerr’s effect and thus reduce the Q value.

As shown Fig. 7 for 200GHz spacing and -15 to 0 dBm power level, NRZ gives the best performance while RZ 0.5 gives the worst performance in terms of Q value. As power level above 0 dBm, performance of NRZ suddenly degrades and achieves Q=0 at 10 dBm and for MDRZ and DRZ achieves highest Q value up to 5 dBm. For power level 5 to 10 dBm, Q value decrease for all modulations causing more dominance of non-linear effects like XPM and FWM.

![Fig. 8. Q value as a function of signal input power after a transmission distance of 300 km for 100 GHz spacing](image)

As shown Fig. 8 for 100GHz spacing and -15 to -5 dBm power level, CSRZ gives the best performance while MDRZ gives the worst performance in terms of Q value. For power level -5 to 0
dBm, CSRZ gives the best but degrades for NRZ for all next power levels and gets Q=0. For power level 0 to 5 dBm CSRZ and RZ 0.5 and for 5 to 10 dBm MDRZ gives the best performance.

Fig. 9. Comparison of Q value for NRZ as a function of signal input power after a transmission distance of 300 km between 100 GHz and 200 GHz spacing

Fig. 10. Comparison of Q value for RZ 0.5 as a function of signal input power after a transmission distance of 300 km between 100 GHz and 200 GHz spacing

Fig. 11. Comparison of Q value for RZ 0.67 as a function of signal input power after a transmission distance of 300 km between 100 GHz and 200 GHz spacing

We have also shown the effect of frequency spacing between each channel for all modulation formats individually. As shown in Fig. 9, NRZ gives better value of Q for 200 GHz than 100 GHz spacing. As shown in Fig. 10, RZ 0.5 gives better value of Q for 100 GHz than 200 GHz spacing. As shown in Fig. 11, RZ 0.67 gives better value of Q for 100 GHz and -15 to -5 dBm input power level but for -5 to 10 dBm power it gives better for 200 GHz spacing. As shown in Fig. 12,
CSRZ gives better value of Q for 100 GHz spacing. As shown in Fig. 13, DRZ gives better value of Q for 100 GHz spacing up to 0 dBm power but after it optical system with 200 GHz spacing gives better. As shown in Fig. 14, MDRZ gives better value of Q for 100 GHz spacing for -15 to -10 dBm, after that same performance up to 0 dBm and again system performance improves for 100GHz spacing up to 10 dBm.
VI. CONCLUSION

In this paper, we have simulated 8 channel 40 Gb/s WDM channel with 100 and 200 GHz spacing over 300 km transmission distance using various modulation formats like NRZ, RZ 0.5, RZ 0.67, CSRZ, DRZ and MDRZ and analyzed performance of the system for the symmetrical dispersion compensation using DCF by varying signal input power. The outcome of the analysis is that for different power level and channel spacing, each modulation format gives the different performance. For 200 GHz spacing, NRZ gives better for lower power level up to 0 dBm but for higher power level MDRZ and DRZ gives the best. For 100 GHz spacing, CSRZ gives better for lower power level up to 5 dBm but for higher power level RZ 0.5 and MDRZ have the superior performance. We have also analyzed each modulation formats for 100 and 200 GHz spacing. For 200 GHz spacing, NRZ for all power level, RZ 0.67 for moderate power level and DRZ for higher power level gives better than 100 GHZ spacing. For 100 GHZ spacing, RZ 0.5, CSRZ and MDRZ gives better for all power level but RZ 0.67 and DRZ gives better Q value for low power level.

REFERENCES


