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OPTICAL DISPERSION COMPENSATION USING DIFFERENT MODULATION FORMATS

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ABSTRACT

Optical dispersion is the main impediment to optimal utilization of optical fiber backbone ability to satisfy the capacity need of today's emerging telecommunication networks. In this paper, the investigation of post - and symmetrical dispersion compensation fibers (DCF) have been examined in a 16 and 32 channel 40Gbps dense wavelength division multiplexing (DWDM) system using different modulation formats. Simulation results obtained show a significant improvement in the quality factor and bit error rate when DCF is used. The performance of the methods however shows dependency on the number of channels in the system, the modulation, and the channel condition.

Keywords: Dispersion Compensation Fibers, Bit error rate, Q-factor, Dense Wavelength Division Multiplexing

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I INTRODUCTION

The exponential growth of the internet and the development of high bandwidth applications have created traffic demands that is stretching even the capacity of telecommunication network's backbone (Ericsson, 2019). The imperatives of meeting the 5G key requirement goals suggest that this trend will not abate in the near future (ITU, 2015). Thus, the inexhaustible bandwidth (Verdumen, 2006, Nerkar et al. 2017) promised with the deployment of optical fibre, as one of the preferred backbone solutions, is being exhausted. To meet the growing demands for bandwidth, dense wavelength division multiplexing (DWDM) was developed as a better alternative to the traditional time division multiplexing (TDM) in optical communication. DWDM multiplies the capacity of a single fibre without the need for changing the existing optical system and replacing the fibre.

However, the additional capacity provided by DWDM is affected by transmission impairments, which limit the data rate at which transmission can be effected. These impairments have more intense effects at data rates higher than 30Gbps as the transmission distance increases. Chromatic dispersion, the most severe of the impairments in optical communication link, causes under-utilization of the optical fibre capacity (Asif and Rakesh, 2017) especially in DWDM networks. Thus, there is need for efficient impairment compensation methods to improve system capacity and compensate for dispersion in existing fiber optic links.

Different methods have been proposed for dispersion compensation in optical fibre system. The widely used and deployed is dispersion compensated fibres (DCF) due to its ease of deployment in existing fibre system (Naheeda et al. 2016). DCF are specially designed fibres, having negative dispersion slope, used to compensate the positive dispersion slope accumulated along the link. The three main methods used in applying dispersion compensated fibres are the pre, post, and symmetrical compensation methods. These methods can provide different results depending on the type of communication system they are applied to.

II RELATED WORK

Most of the previous works on DCF in DWDM have been for systems with data rates less than 40Gbps. This is due to the challenge posed by the nonlinearity in optical fibre dispersion at higher data rates. Using DCF, the authors in Kaur et al. (2015) performed dispersion compensation in optical transmission network using Non Return-to-zero (NRZ) modulation utilizing a data source that produces a pseudo-random sequence of bits at a rate of 30 Gbps result. While the obtained Q factor obtained is impressive, the system's limitations are data rate of 30 Gbps, 8 channels and a single modulation format (NRZ). Similar work was presented by Kaur and Sarangal (2015) for a 20 Gbps system. In Singh and

Goel (2016), the authors examined the four wave mixing (FWM) effect on sixteen channels for a 20 Gbps DWDM optical system.

Bagga and Sarangal (2015) evaluated 32 channels WDM and DWDM systems at 20 Gbps using different channel spacing. Similar works are presented in Kaur and Sadawarti, (2015), Manpreet et al. (2015), Joshi and Mehra (2016), and Xia et al. (2019) for DWDM system with transmission data rate of 10 Gbps. The work in Kochumman and Lakshmy (2013) analyze the performance of optical compensation technique on polarization mode dispersion (PMD) compensation and DCF in a two channels WDM system. The results show that optical compensation technique is more suitable for PMD compensation in WDM systems when compared to DCF. Similarly a comparison of post and symetrical DCF in terms of bit error rate (BER) AND Q-factor was done for 2.5 Gbps and 10Gbps in Hossain et al. (2020). Hussein et.al (2019) proposed a hybrid DCF and fiber Bragg grating (FBG) for a 300 Km long haul 10 Gbps optical system.

Some works done on a 40 Gbps system investigated either lower number of channels, or investigated single modulation format. For example, the work done by the authors of Panda et al. (2016) was focused on performing simulation analysis on an 8 channel WDM system at 40Gbps. Similarly, in Singh and Seehra (2013), a comparison of a WDM and a DWDM system with 8 channels was done using different modulation formats while Ranjani et al (2012) and Kaur and Sarangal (2012) investigated just a single modulation format, the NRZ. Even though these are for systems with 40 Gbps data rate, the 8 channels made the maximum achieved capacity to be very limited. The work in Gupta et al. (2016) shows that FBG is a better dispersion compensation technique than DCF for an optical system with a transmission rate of 40 Gbps. Using a single modulation format, the authors of Xie et al. (2015) analysed the effect of different input power level in a 40 Gbps optical system.

The challenge in current fiber communication networks is to employ the available bandwidth of optical fiber with the highest efficiency and the lowest cost to meet up with the existing bandwidth demand. The aforementioned works have either evaluated systems at low data rate, low channel utilization or single modulation format or a combination of these. To this end, in this paper, we build on and expand the earlier works. Specifically, we design a DWDM system of 16 and 32 channels both at 40 Gbps over 300 Km and 240 Km fibre length respectively. Furthermore, using post and symmetrical DCF compensation schemes, we investigate the dispersion in a 16 and 32 channels DWDM system at 40 Gbps using different modulation (Return-to-Zero (RZ), NRZ, Modified-Duobinary Return-to-Zero (MDRZ), and Carrier-Surpressed Return-to-Zero(CSRZ)) formats.

III SYSTEM MODEL AND METHODS.

Assuming a DWDM optical transmission system with a 16 or 32 channels modulated optical pulse inputs as depicted in Fig 1. The propagation of the pulses through the optical fibre transmission link is governed by the Schroedinger equation given as (Naheeda et al. 2016):

$$\frac{\partial A}{\partial d} + i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} = -\frac{\alpha}{2}A + i\gamma|A|^2 A \qquad (1)$$

where A is the amplitude of the pulse envelope, d is the transmission distance, β_2 is the group velocity dispersion parameter, α is the attenuation constant, while γ is the non-linear parameter. β_2 is the second order derivative of the propagation constant β, i.e.,

$$\begin{aligned} \beta_2 &= \frac{\partial^2 \beta}{\partial \omega^2} \\ \beta &= \frac{\omega n}{c} = \frac{2\pi n}{\lambda} \end{aligned} \qquad (2)$$

where ω is the optical frequency, n, is the refractive index, c is the speed of light and λ is the wavelength. Mathematically β_2 is related to dispersion (D) itself by the following:

$$D = -\frac{2\pi c}{\lambda^2}\beta_2 \qquad (3)$$

However, it is worth noting that the dispersion in optical fibre link is a combination of material and waveguide dispersion (Wang et al., 2018). Mathematically, this is given as:

$$D(\lambda) = D_m(\lambda) + D_w(\lambda)$$
$$D_m(\lambda) = \frac{\lambda}{c}\frac{\partial^2 n_m}{\partial \lambda^2} \qquad (4)$$
$$D_w(\lambda) = \frac{\lambda}{c}\frac{\partial^2 R_e[n_{\text{eff}}]}{\partial \lambda^2}$$

where n_m is the refractive index of the material while $R_e[n_{\text{eff}}]$ is the real part of the fundamental mode's effective refractive index.

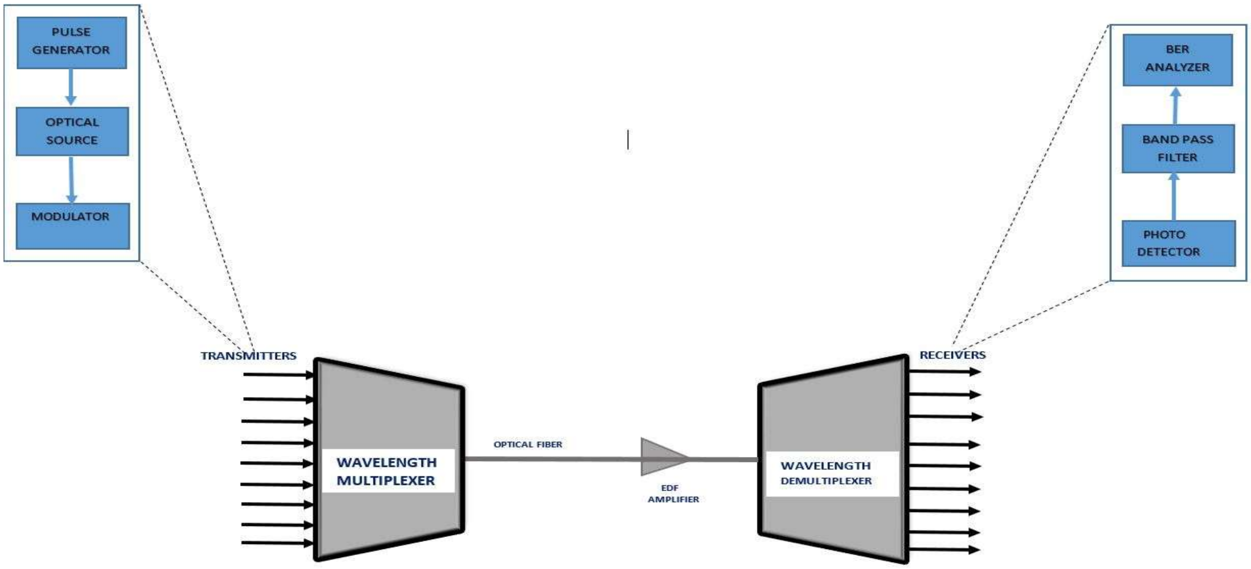


Fig 1: A Schematic of the System Model.

As seen from equations (3) and (4), dispersion varies with wavelength. The implication of this is that compensating for the group velocity dispersion over the entire bandwidth in an optical communication link becomes a challenging task. It also limits the transmitting distance of the optical link. This limiting transmission length (L) is expressed as:

$$L < (16|\beta_2|B^2)^{-1} \qquad (5)$$

where β is the bit rate.

Thus, the challenge is to minimize dispersion accumulation along the communication link in-order to ensure signal transmission over a wider range of distance and at higher capacity. The DCF technique is used to achieve this by cancelling out the positive dispersion and dispersion slope along the path of communication link with its negative dispersion and dispersion slope.

In practice, this is achieved by a concatenation of the DCF with the actual optical fibre link in such a way that the net sum of the product of the length and dispersion of the two fibres is reduced to a minimum, ideally zero. This condition is simply expressed as:

$$D_{\text{eqv}} = D_{\text{DCF}}(\lambda)L_{\text{DCF}} + D_{\text{SMF}}(\lambda)L_{\text{SMF}} \qquad (6)$$

where the subscript SMF stands for the actual communication link single mode fibre while DCF is for the dispersion compensating fibre. Equation (6) applies similarly to the dispersion slope, by replacing the dispersion in the expression with its dispersion slope equivalent. To account for both at the same time the Kappa value (K) given as $K = \frac{D}{D_{slope}}$ can be substituted in (6) in place of $D(\lambda)$. Therefore the overall objective of the DCF technique is:

$$\min_{[C_R]}\left[D_{\text{eqv}} = \frac{C_R K_{\text{DCF}} + K_{\text{SMF}}}{1 + C_R}\right] \qquad (7)$$

where C_R is the compensation ratio is given by $\frac{L_{DCF}}{L_{SMF}}$.

III (a) Simulation Set-up

The simulation tool used for the analysis is Optisystem 14.0. The simulation modules consist of a transmission module, transmission link, and the receiver module. Table 1 provides other simulation parameters. In the transmitter module, binary pseudorandom data is modulated to generate optical signals to be transmitted at 40 Gbps. For each channel, an optical signal is generated using laser light at different wavelengths. The multiplexer then combines the channels (16 /32 in this work) and transmit them over a single channel.

Table 1: Simulation Parameters

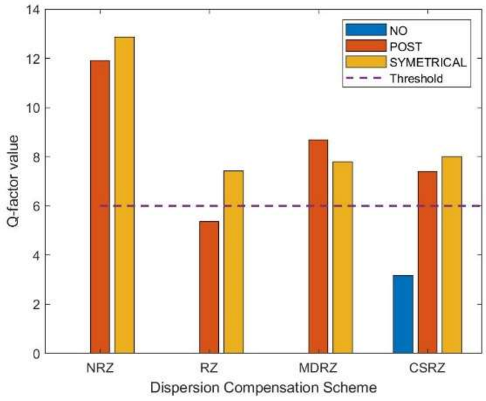
Parameters	Values
Wavelength	1550nm
No. of Channels	16, 32
Modulation Schemes	NRZ, RZ, CSRZ, MDRZ
Data Rate	40 Gbps
Light Source	CW Laser
Fiber	SMF
Receiver	PIN Detector
Fiber Length	50 Km
EDFA Gain	10 dBm
Dispersion Coefficient	17 ps/nm/Km
Channel Spacing	200 GHz
Number of loops	6
Compensation Method	DCF
DCF Length	10 Km

The transmission link contains the single mode fiber (SMF) of length 50 Km and DCF of length 10 Km for post compensation and two (2) $DCFs$ each of 5 Km length and two (2) $SMFs$ of 25 Km length used in single-span for symmetrical compensation. The number of spans is taken to be five (5) and four (4) for 16 and 32 channels DWDM systems respectively. So the total length of fiber is equal to 300 Km and 240 Km respectively for both compensation set-ups. At the receiver side, the 1:16 and 1:32 de-multiplexer with dynamic noise of 3dB splits the signals to 16 and 32 different channels. The output of the de-multiplexer is detected by a PIN photodetector and passed through fourth-order low-pass Bessel electrical filter with a cut-off frequency of 32 GHz (0.8 *Bitrate).

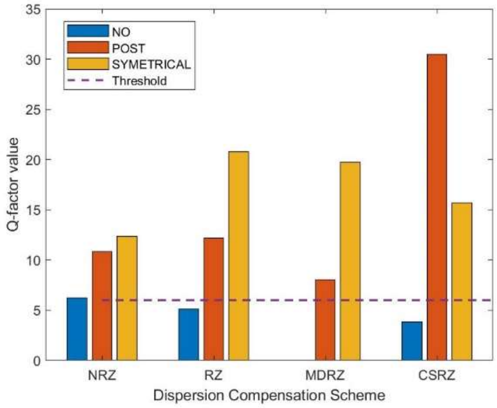
The performance metrics used in the simulation are Q-factor and BER. Simulations are done for both systems (16 & 32 channels) without any compensation, then for post and symmetrical compensations using DCF. The acceptable Q-factor and BER threshold used in the simulation are 6 and 10^{-9} respectively. The values of these two metrics are then taken for each of the four modulation formats NRZ, RZ, MDRZ, and CSRZ.

IV DISCUSSION OF RESULTS

We begin the analysis of the obtained results with the 16-channels system. Fig 2 shows the effect of the dispersion compensation on the Q-factor of the 16-channels DWDM system transmitting at 40Gbps. In Fig 2a, we plotted the values for the worst of the 16 channels against the acceptable minimum threshold. As can be seen for the case where there is no compensation applied, the Q-factor fell below the threshold (the black dotted line). In fact, except for the CSRZ modulation format, the value for the other modulation formats are zero.



(a) Q-factor of the worst channel



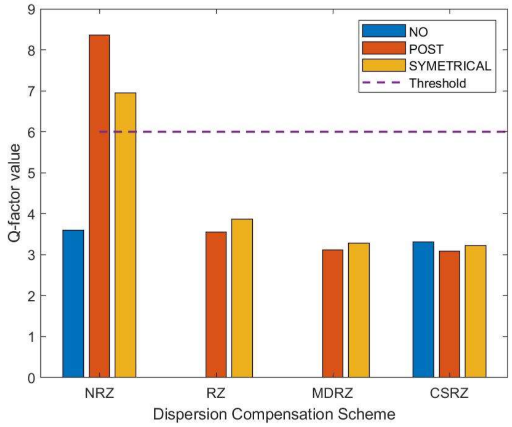
(b) Q-factor of the best channel

Fig 2: Q-factor of DCF using different modulation formats for the 16-channels DWDM.

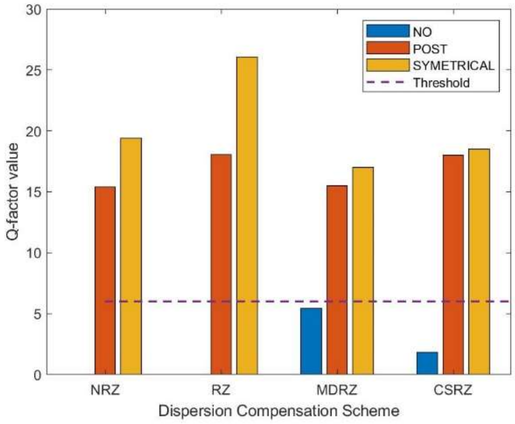
The symmetrical compensation technique however ensures better Q-factor for the modulation format even for the worst channel, while the value of the post compensation for the RZ modulation fell short of the threshold. In the best channel (Fig 2b), the value for all modulation is above the threshold. For the worst channel, the NRZ symmetrical compensation provides the best Q-factor value while in the case of the best channel, it is the RZ with the best value.

The BER performance is shown in Table 2 for the different modulation formats using the two extremes of the channel condition (worst and best) for our analysis. It is seen that using DCF (either post or symmetrical), there is a significant improvement in the BER value. Similar to the Q-factor, the RZ modulation using post compensation, in the case of the channel quality being poor, fell short of the acceptable threshold of 10^{-9}. In terms of packet loss, the RZ modulation produces the worst performance for both post and symmetrical compensation when the channel condition is poor but produces the best values when the channel condition is very good.

It is also seen that while under poor channel condition, the NRZ post compensation has the best Q-factor value, under good channel condition, it is the RZ post compensation with the best value. There also seems to be a reversal in terms of the better technique between post and symmetrical compensation for the NRZ modulation format. In the worst channel, the post compensation is better than the symmetrical, while the reverse is the case for the best channel.



(a) Q-factor of the worst channel



(b) Q-factor of the best channel

Fig 3: Q-factor of DCF using different modulation formats for the 32-channels DWDM

In Fig 3 we plot the Q-factor value of the 32-Channels DWDM system. For the channels with the worst performance (Fig 3a), it is seen that the post and symmetrical compensation for the trio of RZ, MDRZ, and CSRZ, perform poorly, well below the threshold value, while the NRZ exceeds the threshold value. However, under improved channel conditions, the DCF compensation techniques performed well above the threshold.

Table 2: BER performance of the different modulation formats in the 16-Channel DWDM

Modulation Format	Worst Channel			Best Channel		
	No	Post	Symm	No	Post	Symm
NRZ	1.0	5.1×10^{-33}	3.0×10^{-38}	1.0	5.5×10^{-54}	1.7×10^{-84}
RZ	1.0	4.2×10^{-8}	5.7×10^{-14}	1.0	1.4×10^{-73}	1.9×10^{-150}
MDRZ	1.0	1.8×10^{-18}	2.6×10^{-15}	2.7×10^{-8}	1.3×10^{-54}	3.9×10^{-65}
CSRZ	3.2×10^{-2}	6.0×10^{-16}	5.1×10^{-16}	7.8×10^{-4}	6.3×10^{-73}	5.3×10^{-77}

A quick examination of the BER values in Table 3 indicates degradation in the performance compared with the 16-Channels system. However, for good channel conditions, the obtained values are well below the threshold for both post and symmetrical compensation. This story is slightly different when the channel condition is poor.

Table 3: BER performance of the different modulation formats in the 32-Channel DWDM

Modulation Format	Worst Channel			Best Channel		
	No	Post	Symm	No	Post	Symm
NRZ	1.5×10^{-4}	3.0×10^{-17}	1.7×10^{-12}	2.1×10^{-10}	8.3×10^{-28}	2.0×10^{-35}
RZ	2.7×10^{-3}	1.8×10^{-4}	5.4×10^{-5}	1.5×10^{-7}	2.6×10^{-34}	2.4×10^{-96}
MDRZ	1.0	8.1×10^{-4}	4.7×10^{-4}	1.0	4.2×10^{-16}	6.6×10^{-87}
CSRZ	1.1×10^{-4}	9.7×10^{-4}	5.9×10^{-4}	5.7×10^{-5}	6.4×10^{-204}	5.6×10^{-56}

V CONCLUSION

In this paper, the investigation of optical dispersion for a 16-channels and 32-channels 40Gbps DWDM systems using post and symmetrical DCF has been presented. The results indicate significant improvement in the systems well above the minimum Q-factor and BER threshold for reliable communication. For the 16-channels system, the obtained BER and Q-factor values for all the modulation formats, even when the channel condition is very poor, is very impressive, except for an exception with post compensation using RZ modulation. With an increase in the system channels, there is a drop in these values. However, for the 32-channels system, when the channel is poor, the performance is below the threshold. This work has demonstrated that the performance of both post- and symmetrical compensation using DCF methods depends on the number of channels in the system, the modulation, and the channel condition.

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