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Analysis of Various Compensation Techniques To Reduce Dispersion In An Optical Fibre Transmission Communication System Using Optisystem (Advantages of RZ Over NRZ)

Naveen Rai

Electronics and Communication Engineering
VIT University, Vellore,India
naveen.rai2012@vit.ac.in

Pushkar Prashant

Electronics and Communication Engineering
VIT University, Vellore,India
pushkarprashant@rocketmail.com

Prof Vidhyapati CM

Vit university
School of electronics and communication engineering

Abstract

Dispersion Compensation is an important feature which is needed in an optical communication system in order to nullify the effect of dipsersions that may lead to interfernce. Interference can produce error in the system which is not desired. In this paper, the performance of different dispersion compensation techniques have been analyzed by varying the data rates and the amplifier gain. The compensation techniques are duobinary modulated and are namely reverse dispersion fibre(RDF),dispersion compensation fiber (DCF), optical phase conjugation (OPC) and negative dispersion fibre(NDF).The performance of different compensation techniques have been analyzed on the basis of the eye closure, bit error rate and Q- factor characteristics. Furthermore, we will also see the effectiveness of RZ format over NRZ at higher data rates.

Keywords: dispersion; eye closure; Q-factor; NRZ modulated; RZ.

Introduction

In an optical communication system we try to transmit the maximum number of bits per second over a large distance with the aim of having minimum error. In order to ensure transmission of data over large distance we need to modulate the data before it is transmitted. Modulating the information signal has a lot of advantages such as ensuring transmission over large distance and reducing interference. Their are many modulation formats that can be used to transmit the data at high rates. Different modulation formats have their own advantages and disadvantages. The reason for dispersion can be attributed to the dependency of group index to the wavelength . For different colours with different wavelength the variation in group index causes chromatic dispersion in an optical fiber. This creates an extension of time on the pulses. Dispersion greatly hampers the performance of optical fiber communication. Due to dispersion, optical pulse gets broadened as they travel in a single mode fiber. It also reduces the data rate supported by the fiber for transmission which causes spreading and overlapping of chips and further degrades the system performance due to the increase inter chip interference and a reduction in the received optical power at the receiver. Therefore, if dispersion can be minimized then the performance of the system can be further enhanced. In this paper NRZ modulator has been used which can be used at high bit rates. Like other communication systems optical communication system also faces problems like dispersion, attenuation and non-linear effects that lead to deterioration in its performance. Among them dispersion affects the system the most and it is difficult to overcome it as compared to attenuation and non-linear effects. Thus, it is important to work out an effective dispersion compensation technique that leads to performance enhancement of the optical system. The overall effect of dispersion on the performance of a fiber optic system is known as Intersymbol Interference.This causes the overlapping of the pulses which makes them almost undetectable. Dispersion techniques can be classified into four major categories namely chromatic dispersion, waveguide dispersion, material dipsersion, polarization mode dispersion and modal dispersion.

Modal Dispersion

Modal dispersion occurs in a multimode fibre due to the time delay between lower order modes and the higher order modes causing the spreading of pulses.It leads to inefficient utilisation of the bandwidth. This happens due to the different propagation velocity of the traversing optical signal in different modes. It is also referred to as multimode distortion, multimode dispersion, modal distortion and intermodal delay distortion.

According to the concept of ray optics, modal dispersion can be considered to resemble multipath propagation in which the radio signal reaches the destination via different paths. The optical signal also undertakes multiple paths due to the different angles to the fiber axis with which it enters. Rays entering the fiber with a steeper angle traverse the boundaries of the fibre and undergo multiple reflections due to which they take more time to reach the end of the fibre. The rays that enter with shallower angles reach faster. They undertake almost the direct path to the other end of the fibre.

Modal dispersion leads to inefficient utilisation of the bandwidth. For example, in a step-index fiber with 52 µm core radius the bandwidth will be limited to around 20 MHz per km.

Chromatic Dispersion

Chromatic dipsersion occurs due to the presence of different colours having different wavelengths associated with them. Since, the velocity is a function of the wavelength therefore different colours propagate with different velocities and reach the destination at different times causing dispersion and broadening of the pulse. It is measured in picoseconds of pulse spreading per nanometer of spectral width per kilometer of the fiber length. Chromatic dispersion can be further classified as material and waveguide dipsersion. The effect of chromatic dispersion is mre in case of long haul optical transmission systems where a single mode step- index fibre is used.

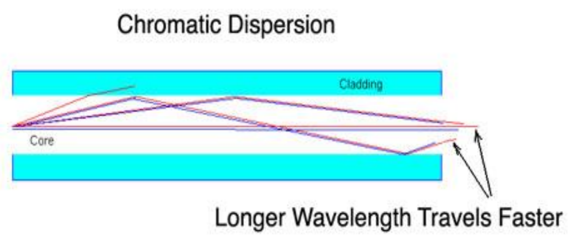

Figure 1: Chromatic Dispersion in an Optical Fibre.

Material Dispersion

The material dispersion happens beacuse of the dependency of the refractive index of the material on the wavelength. The wavelength of the entering optical signal undergoes interaction with the physical matter. This matter is present in the cystalline structure of the glass. Signal with longer wavelengths travel with higher velocities.

In any emitted optical signal there is a spectrum of multiple wavelengths. These different wavelengths interact with the crystalline structure of the physical material. This makes pulses travel with different velocities and reach the destination at different times. As the wavelength increases (and frequency decreases), material dispersion decreases. Therefore a signal with a wavelength of 1700 nm would suffer less material dispersion as compared to a 1330 nm signal.

Waveguide Dispersion

The reason for this type of dispersion can be attributed to the physical structure of the waveguide. Waveguide dipsersion plays a significant role in a complex index profile fiber rather than a simple step index profile fibre.

In this, the refarctive index of the core and the cladding differs. Whenever a signal enters into the fibre some of it travels through the core and some portion of it travels thorugh the cladding. The difference in the refractive index of the core and the cladding causes the pulse to disperse.

Polarization Mode Dispersion
Birefringence along the length of the fiber makes different polarization modes to travel at different speeds which leads to rotation of the polarization orientation along the fiber.

Dispersion Compensation

Dispersion compensation refers to the technique of reducing the dispersion produced in an optical fibre transmission system. This basically refers to chromatic dispersion. It can also be used to reduce the distortion produced in the signals. Dispersion compensation also finds it's use in the telecommunication industry. Dispersion becomes significant at high data rates. Without compensation methods the pulses will overlap wih each other. The excessive broadening will make recovering of the signal very tideous. As the datarates increase the spectral bandwidth of the signal becomes large. Therfore, it is required that some dipsersion compensation technique is utilised for efficient communication.

Performance Metrics

In this paper, we have analyzed the effectiveness of four different dispersion compensation techniques. Their performance is analyzed by varying the data rates and the gain of the amplifier. For evaluation, different parameters such as the Q factor, eye height , eye diagram and the BER are analyzed.

Q Factor

Q factor is a very important parameter in studying the performance of a system. Technically speaking, it speaks about the under damping of a system. The system can be a resonator or an oscillator. It is a dimensionless quantity. Resonators with high value of Q factor are considered for practical applications. It can also be used to relate bandwidth with the central frequency.

Q factor is one of the important performance metrics in optical communication. It gives the ratio of the signal power to the noise power. The higher value of Q factor ensures low relative energy loss of the system . For any system a high value of Q factor is desired.

$$\text{Q Factor} = (S_{power}) / (N_{power})$$

Eye Diagram

The eye diagram is like an oscilloscope which allows us to analyze in a graphical manner. The digital signal from the receiver is continuously sampled. The obtained result is applied to the vertical input. Because of the coding patterns used the result resembles an eye between two lines.It can be used to analyze the inter symbol interference and the channel noise generated. The various parameters that one can get from an eye diagram are eye height, eye overshoot, eye width and eye closure.

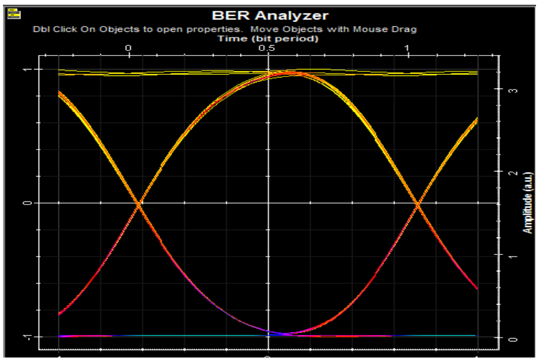

Figure 2: Eye Diagram Analyzer

Table 1: Perfomance Metrics and Their Significance

Parameter	*Significance*
Q factor	Signal to Noise Ratio
Eye Height	Additive noise in the signal
Eye Overshoot	Peak distortion due to interruptions in the signal path
Eye Width	Timing synchronization & jitter effects
BER	Measure of incorrect received

Bit Error Rate

BER is a measure of the number of recieved bits in a communication system over a channel that have been altered . It can happen due to noise, distortion, bit synchronisation errors or interference. The BER can be measured by using the following realation:-

$$BER= (1/2)\text{erfc}(\sqrt{E_b}/\sqrt{N_o})$$

where erfc is the error function, E_b is the bit energy(energy consumed per bit) and N_o is the noise density. The formula for bit error rate is different for different modulation techniques.

Dispersion Compensation Techniques

The different dispersion compensation techniques analyzed in this paper are negative dispersion fibre (NDF), reverse dispersion fibre (RDF), optical phase conjugation (OPC) and dispersion compensation fibre (DCF). The performance of all the compensation techniques have been studied by simulating their respective circuits on the OptiSystem 13 software. The data rates and the amplifier gain are varied to study the operation of the various compensation techniques.

The first dispersion compensation technique is negative dispersion fibre (NDF). The schematic diagram of the simulated circuit is given in figure 3. It consists of duobinary signalling. The transmitter section comprises of the data source which is a user defined bit sequence generator, a non-return-to-zero (NRZ) pulse generator, a CW laser source with output power of 13 dBm and frequency of 193.1 THz. The bit sequence considered for transmission is 11101110. The modulator used is a Mach-Zender modulator with extinction ratio of 30 and symmetry factor of -1. The different bit rates taken are 2, 2.5, 3, 3.5 and 5 Gigabits per seconds. The data from the Mach-Zender modulator is fed into a control loop with the loop counts as 2. The loop consists of the neative dipsersion fibre with attenuation of 0.212 dB/km and a negative dipsersion of -2.5 ps/nm/km. The wavelength considered is 1550 nm. The length of the fibre is taken to be 100 km.

The signal from the fibre goes through the optical amplifier having a gain of 20 dB and noise figure of 4 dB. The noise center frequency of the amplifier is 193.1 THz and a noise bandwidth of 13 THz. The signal is then received by the PIN photodetector with a responsivity of 1 A/W and a dark current of 10 nA. The center frequency of the PIN photodetector is 193.1 THz. A low pass Bessel filter is used at the receiver with a cutoff frequency of 0.7*symbol rate.

A BER analyzer is used to see the resulting eye diagram. Parameters like eye height, eye width, eye overshoot can be measured from it. The other metrics considered are Q factor and the bit error rate. The significance of each parameters have been discussed in table 1.

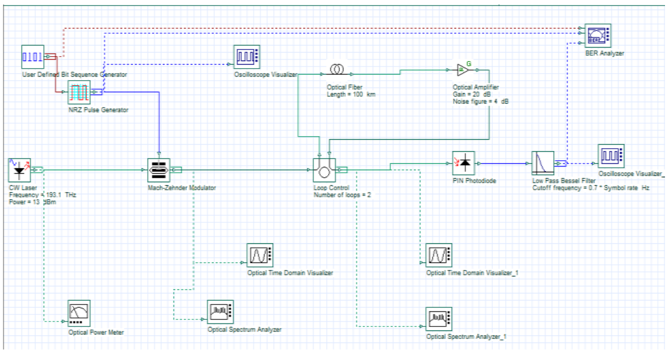

Figure 3: Negative Dispersion Fibre Setup in OptiSystem.

The second dipsersion compensation technique considered is optical phase conjugation. In this compensation technique non linear optical effects are used.The direction of propagation of each plane wave is reversed. This makes the retruning beam to follow the path of the incident beam. Optical phase conjugation is also known as time reversal reflection.

The setup of the optical phase conjugation is almost similar to NDF. The transmitter section comprises of the data source which is a user defined bit sequence generator, a non-return-to-zero (NRZ) pulse generator, a CW laser source with output power of 5 dBm and frequency of 193.1 THz. The bit sequence considered for transmission is 11101110. The setup is shown in figure 4. Thus, the transmitter section remains the same. Two optical fibres of length 50 km each are considered. For the first fibre the attenuation is 0.2 dB/km. The dispersion is -2 ps/nm/km and the dispersion slope is 0.21 ps/nm^2/K. The PMD coefficient is 0.5 ps/sqrt(km). The mean scattering section length is 50m. Effective area is considered to be 30 µm^2. The signal from the optical fibre passes through the phase shifter. The phase shifter is having a phase shift of 2.57070 degrees at a 100% efficiency.

The phase shifted signal enters the second optical fibre having the same attenuation and dispersion. The dispersion slope is 0.08 ps/nm^2/km. The effective area of the fibre is 80 µm^2. The mean scattering section length is considered to be 500m. The signal out of the second fibre passes through the optical amplifier with a gain of 20 dB initially which is varied gradually. The noise figure of the amplifier is 4 dB. The loop control is having a loop count of 2. A low pass Bessel filter is used with cutoff frequency of 0.7*Symbol rate and depth of 100 dB. Optical time domain visulaizer and spectrum analyzer are used for a better understanding of the signal propagation.

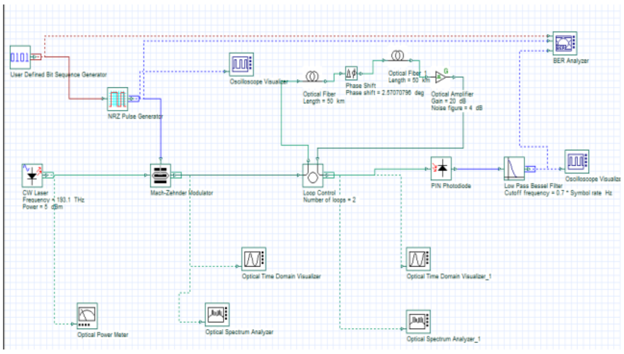

Figure 4: Optical Phase Conjugation Setup in OptiSystem.

For the performance analysis of reverse dipsersion fibre (RDF), the transmitter section remains the same . The specifications of the used components can be obtained from NDF or OPC specifications. The bit sequence transmitted is 11101110. For transmission purpose two optical fibres are used. Each have a length of 50 km with 1:1 ratio. The total length of the channel is 100 km. For the first fibre the attenuation is 0.25 dB/km and the wavelength is 1550 nm. The dispersion is 16 ps/nm/km and the dispersion slope is 0.08 ps/nm^2/K. Value of beta1 and beta2 are -20 ps^2/km and 0 ps^3/km. Effective area is 80 µm^2 and the differential group delay is 0.2 ps/km.

The second fibre has an attenuation of 0.24 dB/km with a dispersion of -16 ps/nm/km. The dispersion slope is 0.21 ps/nm^2/K. The effective area of the fibre is 30 µm^2. The Raman contribution value of the fibre is 0.18. The lower and the upper calculation limit of the fibre are 1200 nm and 1700 nm respectively. The responsivity of the PIN photodiode is 1 A/W and the dark current value is 10 nA. For analysis purpose a BER analyzer and an ocilloscope is used in the circuit. The circuit is shown in figure 5. After detailed analysis it has been found that reverse dispersion fibre gives better results for long haul communication systems. This is explained in the results and analysis section. Dispersion compensation fibre can also be used along with reverse dipsersion fibre for long haul communication systems at high data rates. They show better results as compared to negative dipsersion fibre and optical phase conjugation.

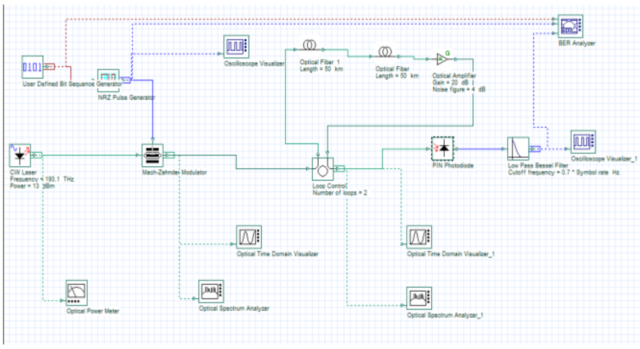

Figure 5: Reverse Dispersion Fibre Circuit in OptiSystem

The last compensation technique used is dispersion compensation fibre (DCF). The bit sequence generator is initially given a data rate of 2 Gbps. NRZ pulse generator have maximum amplitude of 1 a.u. and both Rise and Fall time are 0.05 bit. The circuit is shown in figure 6. A CW laser is taken as a optical source having frequency value of 193.1 THz with sweep power level 13 dBm. Mach-Zender modulator have the excitation ratio 30 dB and symmetry factor of -1. Here, two optical fibres are used for the compensation. The first one is a dispersion compensation fibre (DCF) and the second one is the standard single mode fibre (SSMF). The DCF has a length of 17 km and attenuation of 0.6 dB/km. The dispersion is -80 ps/nm/km and the dispersion slope is 0.21 ps/nm^2/K. The PMD coefficient is 0.5 ps/sqrt(km). The effective area of the fibre is 30 µm^2 and Fract. Raman contribution is 0.18. The value of n_2= 3e-020 m2/w, Raman self-shift time 1 = 14.2 fs and Raman self-shit time 2 = 3 fs. The orthogonal Raman factor is 0.75.The maximum non linear phase shift of the fibre is 5 mrad. The lower and the upper calculation limit are 1200 nm and 1700 nm respectively.

The length of the second fibre is 83 km with attenuation of 0.25 dB/km. The dispersion is 16 ps/nm/km and the dispersion slope is 0.08 ps/nm^2/K. The PMD coefficient is 0.5 ps/sqrt(km). The effective area of the fibre is 80 µm^2 and Fract. Raman contribution is 0.18. The maximum non linear phase shift is 3 mrad. The upper and lower calculation limit remains the same. The optical amplifier has a gain of 20 dB and noise figure of 4 dB. The loop control has a loop count of 2. A BER analyzer is used for reading the eye diagram parameters.

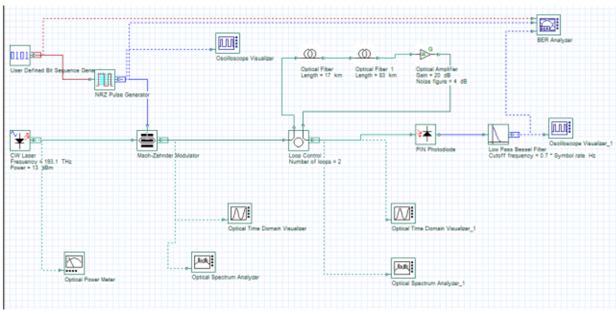

Figure 6: Dispersion Compensation Fibre Circuit

Results & Analysis

For the analysis purpose different data rates of 2, 2.5, 3, 3.5 and 5 Gbps are considered with the amplifier's gain remaining constant. In the second case, data rate is kept constant and the gain of amplifier is varied. The amplfier gain is taken to be 15, 20, 25, 35 and 40 dB. The results obtained for different data rates and amplifier gain for NDF is given in table 2 and table 3. The eye diagram for some of the cases are also shown.

Table 2: NDF (amplifier's gain= 20 dB)

Data Rate	Q Factor	Eye Height	Min. BER
2	239.284	0.0113	0
2.5	145.836	0.0111	0
3	41.419	0.0102	0
3.5	19.651	0.0087	$2.754e^{-086}$
5	4.867	0.0029	$5.635e^{-007}$

It can be observed that as we increase the data rate the performance of the system starts to decrease. It is beacuse of the increase in the dipsersion produced in the optical fibre communication system. The Q factor value starts to decrease. This indicates an increase in the noise power or decrease in the obtained signal power. The bit error rate also strats to increase which is not desired for an effcicent communication.

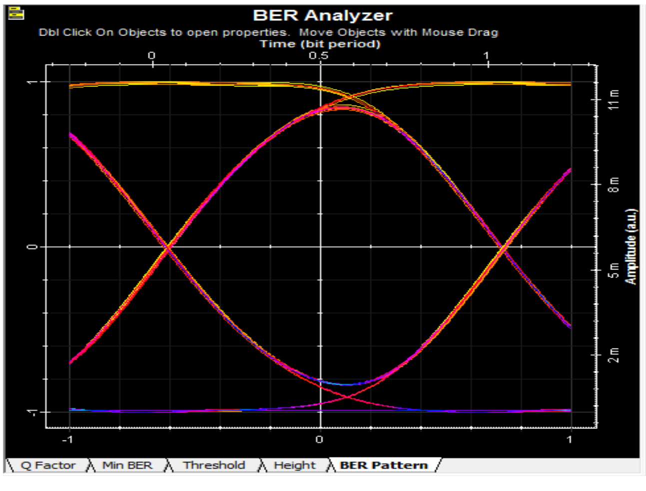

Figure 7: Eye Diagram for NDF at 3.5 Gbps.

The eye diagram for NDF at 3.5 Gbps is shown in figure 7. The opening of the eye and the shape of the eye degrades with the increase in the data rates. The eye diagram for 10 Gbps data rate is shown in figure 8. The shape of the eye is highly distorted with low value of Q factor.

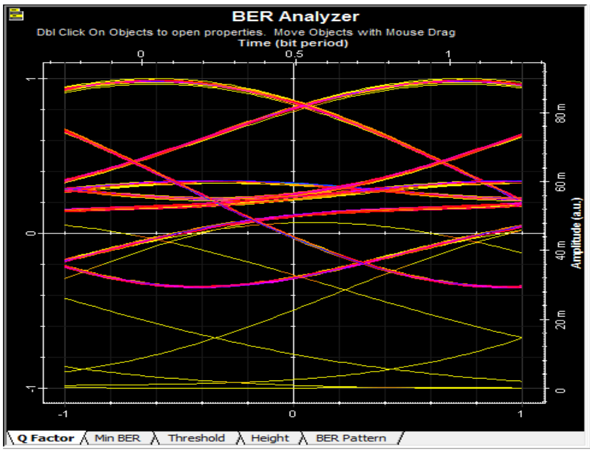

Figure 8: Eye Diagram at 10 Gbps.

Table 3: NDF (data rate= 2.5Gbps)

Gain	Q Factor	Eye Height	Min. BER
15	115.449	0.0011	0
20	145.836	0.0111	0
25	167.002	0.1117	0
35	16.769	8.4712	$1.911e^{-063}$
40	4.261	23.432	$9.782e^{-006}$

In order to analyze the performance of the compensation technique the gain of the amplifier is increased. The performance of the system improves gardually with the gain of the amplifier. After a certain value of gain (approx. 30 dB) it again starts to decrease indicating a threshold applicable value for the amplifier's gain.

The eye diagram for NDF operating with an amplifier's gain of 25 dB and a data rate of 2.5 Gbps is shown in figure 9.

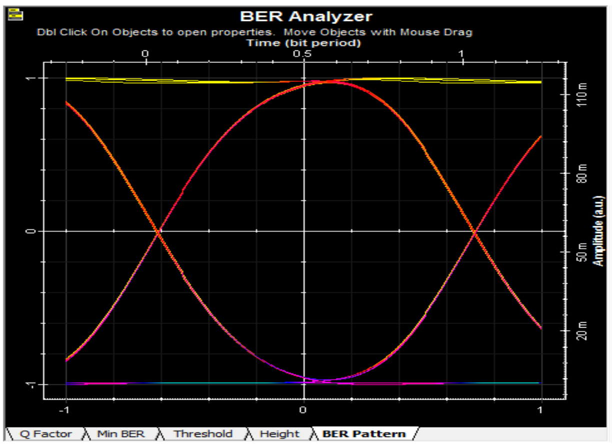

Figure 9: NDF With 25 Db Amplifier's Gain

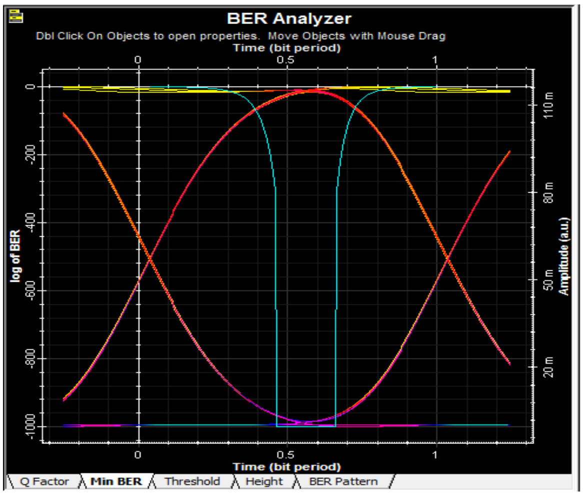

Figure 10: Eye Height of NDF at 2.5 Gbps

Given below is the performance evalustion of an optical phase conjugation system with variable data rates. The gain of the amplifier is kept constant. A similar trend is observed for OPC. The increase in data rate degrades the performance of the system.

Table 4: OPC (amplifier's gain= 20 dB)

Data Rate	Q Factor	Eye Height	Min. BER
2	345.341	0.0197	0
2.5	220.419	0.0196	0
3	49.238	0.0182	0
3.5	20.961	0.0153	$7.064e^{-098}$
5	5.566	0.0010	$1.299e^{-008}$

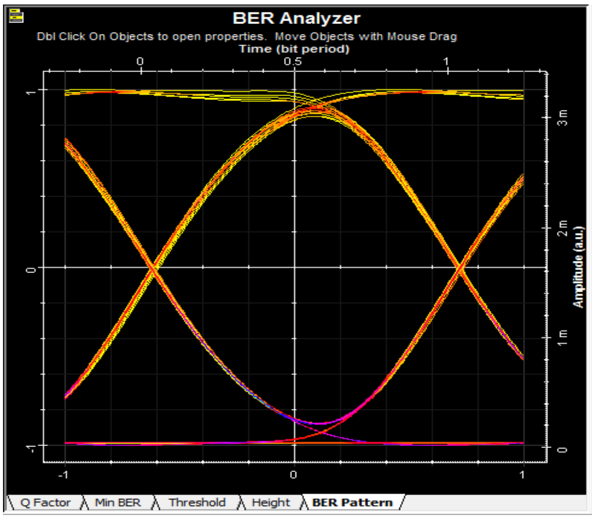

Figure 11: Eye Diagram of OPC at 3.5 Gbps

Table 5: OPC (data rate= 2.5 Gbps)

Gain	Q Factor	Eye Height	Min. BER
15	99.79	0.0003	0
20	220.419	0.0196	0
25	168.012	0.1945	0
35	14.702	14.097	$2.60e^{-049}$
40	34.953	27.682	$5.125e^{-268}$

As seen from the above table the Q factor decreases after a gain of 30 dB. A small amount of BER is also introduced in the system. The gain of the amplifier can be increased upto a threshold value. Beyond the threshold, the gain has no major effects on the performance of the system . The eye diagram for Optical Phase Conjugation at a data rate of 2.5 Gbps and with an amplifier's gain of 25 dB is shown in figure 12. The eye pattern is also shown in the figure. The pattern indicates the efficient operation of the OPC technique.

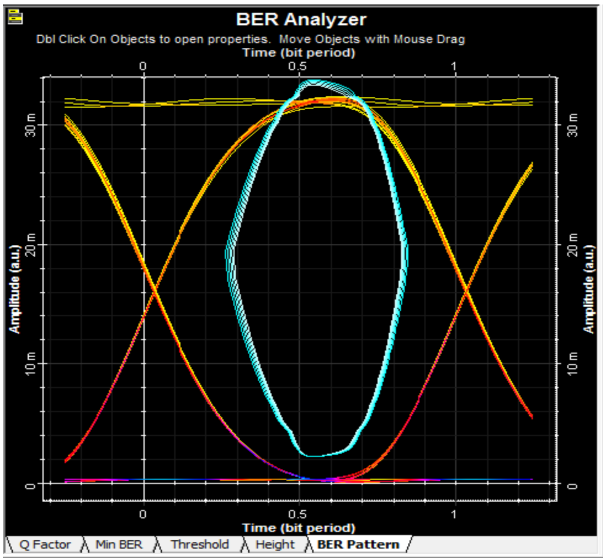

Figure 12: Eye Diagram for OPC at 25 dB.

Table 6: RDF(amplifier's gain= 20 dB)

Data Rate	Q Factor	Eye Height	Min. BER
2	139.554	0.00244	0
2.5	73.281	0.00241	0
3	72.442	0.00235	0
3.5	25.652	0.00201	$1.861e^{-145}$
5	5.604	0.0008	$1.044e^{-008}$

The reverse dispersion fibre performance evaluation has been shown in table 6 and 7 respectively. At a same data rate it is found to perform better than the other compensation techniques. The trend in the system performance remains the same. An increase in the data rate yields poor results.

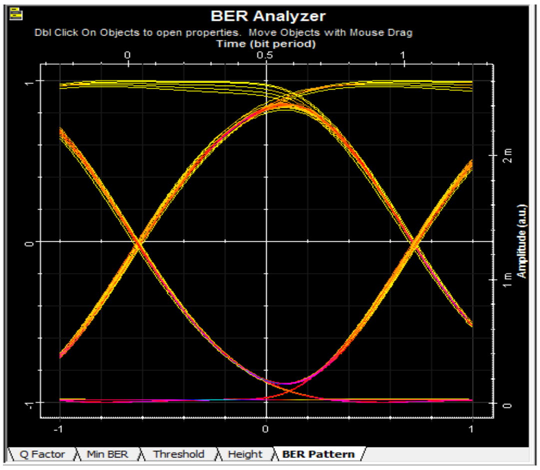

Figure 13: Eye Diagram for RDF at 3.5 Gbps.

Table 7: RDF (data rate= 2.5Gbps)

Gain	Q Factor	Eye Height	Min. BER
15	42.845	0.0002	0
20	73.281	0.0024	0
25	121.201	0.0245	0
35	46.867	2.2961	0
40	15.271	17.5423	$5.015e^{-053}$

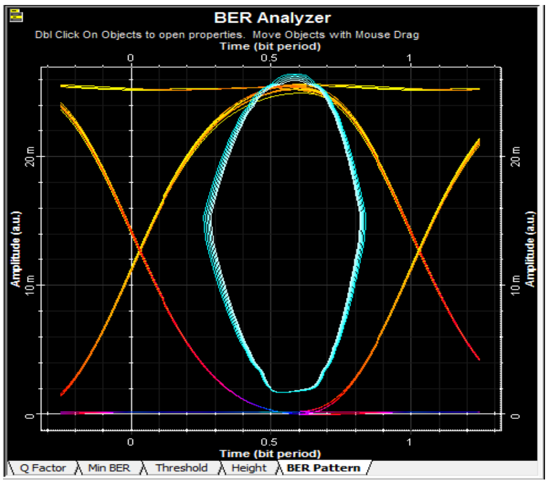

Figure 14: Eye Diagram for RDF at 25 dB.

Reverse dispersion fibre also has a limitation witht the amplifier's gain. Beyond the gain of 30 dB it is found to denude the system's performance. Therefore, a threshold value should be considered depending on the required application.

The last compensation technique analyzed is the dispersion compensation fibre. The DCF's performance is also inversely related to the data rate. At low data rates of upto 3.5 Gbps it gives poor reults as compared to the NDF, RDF and the OPC. However, at a high data rate of 5 Gbps it is found to give a high value of Q factor when compared to other techniques. There is also an increase in the eye height as the value increases from 0.00010 to 0.03121. The details of it are given in table 8.

Table 8: DCF (amplifier's gain= 20 dB)

Data Rate	Q Factor	Eye Height	Min. BER
2	33.944	0.00011	$5.57e^{-253}$
2.5	22.691	0.00012	$1.75e^{-114}$
3	23.615	0.0001	$1.056e^{-123}$
3.5	18.981	0.00010	$1.022e^{-080}$
5	55.831	0.03121	$2.742e^{-009}$

Table 9: DCF (data rate= 2.5Gbps)

Gain	Q Factor	Eye Height	Min. BER
15	10.834	$9.259e^{-006}$	$9.172e^{-028}$
20	22.695	0.0001	$1.75e^{-114}$
25	42.035	0.0011	0
35	89.321	0.1246	0
40	59.452	1.2521	0

The performance analysis of the DCF at a data rate of 2.5 Gbps and varying amplifier's gain is shown in table 9. The increase in the gain of the amplifier helps to compensate the produced dipsersion in the system more effectively. After a gain of 35 dB , the system starts to degrade with a decrease in the Q factor. The eye diagram for the DCF at a gain of 25 dB is shown in figure 15.

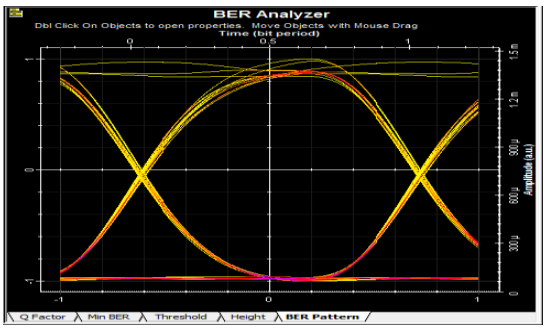

Figure 15: Eye Diagram for DCF at 25 dB.

The dispersion compensation fibre has been found to be effective for long haul transmission systems. It gives better results as compared to the conventional DCF system alone. The circuit diagram for DCF long haul system is given in figure 16. The corresponding eye diagram for the system along with the Q factor is shown in figure 17. For long range communication distance it gives a better value of Q factor and eye height.

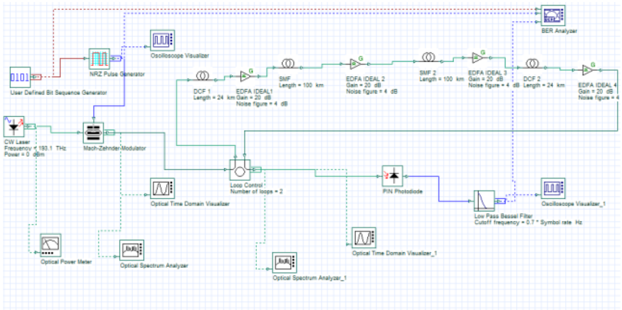

Figure 16: DCF Long Haul Transmission Circuit.

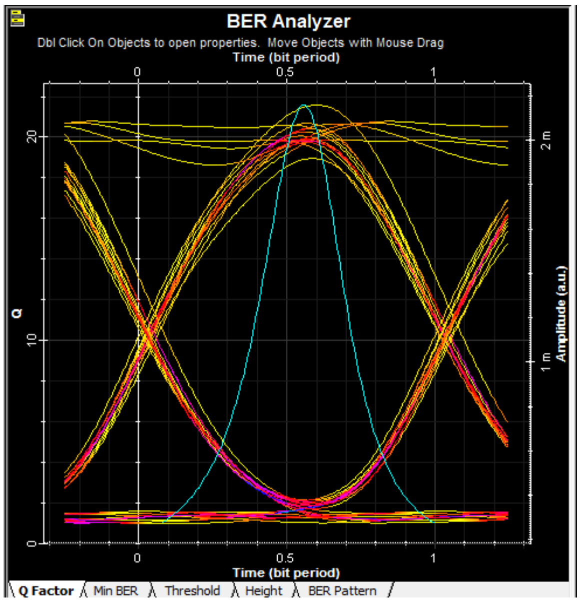

Figure 17: Eye Diagram for DCF Long Haul Transmission.

For a transmission distance of 248 km it gives a Q factor of 22.316 and an eye height of 0.00145. This is a much better result as compared to any other compensation technique for such a large transmission distance. The circuit is simulated at a data rate of 3 Gbps.

Return To Zero Modulation

Earlier, the optical modulation format used for optics based communication systems was non return to zero format (NRZ). During that time,dispersion caused in an optical fibre was the most adverse effect of all. But, it is observed that at very high bit rate, like 40 Gbps, non linearity starts to play a major role. Due to this the RZ format gets an edge over the conventional NRZ format. The main reason for this is the large bandwidth of RZ signal as compared to the NRZ signal. The large bandwidth causes higher broadening of the pulses. Due to this the amplitude of the signal reduces as the pulses are broadened because of dipsersion. This turns out to be a blessing in disguise because nonlinearity is associated with signal intensity. Since width of a pulse for RZ is narrow as compared to NRZ, therefore the pulse has high peak power for any given average power. This leads to a broad eye opening for RZ as compared to NRZ which yields better receiver sensitivity. Due to better sensitivity of the receiver, the transmission distance can be increased for the same input transmitter power.

Therefore, RZ has an advantage over NRZ on the basis of the nonlinearity effects and can be used for long range communications. The eye diagram for a NDF system using RZ moduation is shown in figure 18. The RZ gives a Q factor of 8.648 at a data rate of 5 Gbps as compared to NRZ which gives a value of 4.867. The minimum bit error rate is also decreased in the case of RZ . The BER decreases from 5.138×10^{-3} to 8.801×10^{-15}. Although RZ gives better results when compared with NRZ, it has severe drawbacks such as the impairments caused by intrachannel interaction between dispersion and nonlinearity. In order to improve the performance of the system the effects of impairments should be reduced.

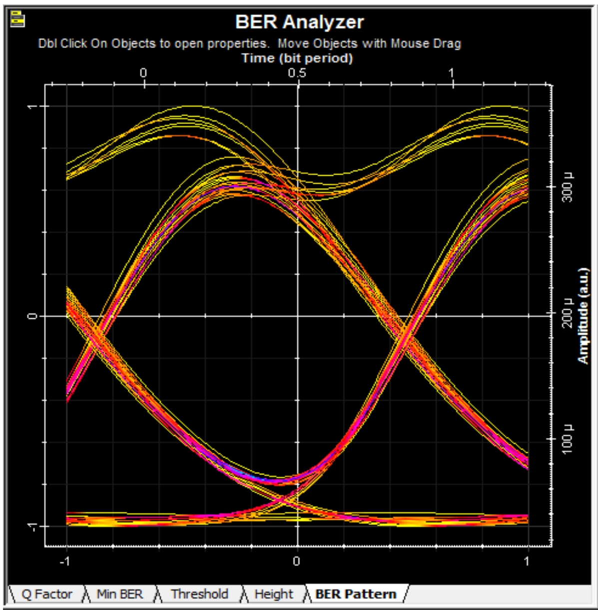

Figure 18: NDF technique with RZ modulation.

Conclusion

In any optical fibre transmission communication system, dipsersion is inevitable. In order to reduce the dipsersion produced in the system, one should know when to apply a particular type of technique. Different compensation techniques have different suited conditions. Some can be used for low data rates and some for high data rates. For long haul transmission systems we have different compensation techniques with optimum results. After simulating the various compensation schemes and observing the values of Q factor, Min BER and eye height the following points can be inferred:-

- As the data rate increases the OPC provides the most efficient results. It's Q factor and other parameters are better as compared to other techniques. This can be verified from table 2, 4, 6 and 8.
- For long haul transmission DCF technique is preferred over other techniques. It gives better results for a distance of 248 km .
- Other compensation techniques give poor results for a distance over 150 km.
- At high data rates RDF and DCF are recommended.
- The performance of the system can be improved by using RZ modulator instead of NRZ modulator. This can be verified from figure 16.
- OPC follows an opposite trend with respect to increase in the amplifier's gain. The Q factor starts to decrease with the increase in the amplifier's gain.
- For high gain of the amplifier (beyond 40 dB), the performance of the system starts to degrade.
- For lower values of amplifier's gain NDF performs the best followed by RDF.
- At high amplifier's gain the given trend is followed (DCF> RDF> NDF), on the basis of performance.

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