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Design of Symmetric dispersion compensated, long haul, Single and Multichannel Optical Lightwave Systems in Telecommunications: Theory, Background and Simulation Model-A Study

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Abstract: *Here we propose a model on Enhanced- Large Effective Area Fiber (E-LEAF) and Dispersion Compensation Module (DCM) with precise designed Dispersion Compensation Fiber (DCF). The Model is implemented in a long haul Single and Multichannel Optical telecommunication systems with E-LEAF as data transmission Fiber (NZ-DSF) of 1700Km (85 Km SMF×20 loops) length. The DCM is proposed in Symmetric Compensation fashion consisting of 20Km (2Km×20spans) length DCF in Pre-Compensation and Post-Compensation totally comprising of 40Km length DCF for complete Compensation of total Optical Link. Thereby, we study the effect of various Line Coding Schemes like NRZ, RZ, CS-RZ, DUOBINARY and MODIFIED DUOBINARY in single and multichannel optical link with our designed DCM and concluded the suitable line coding scheme for our proposed model. This paper focus on the theoretical background, design procedures, technical terms and finally a simulation model is experimented with proposed parameters to realize the foresaid concepts with various modulation formats.*

I. Introduction

The Telecommunication Industries face a great challenge in providing very high bandwidth for the increasing Population. Thus the great demand has kindled the researchers to find new innovative ideas for effective dispersion less transmission through a long distance. The Wavelength Division Multiplexing method has enormously spread its wing to serve the great need for bandwidth but still constricted to various Dispersion and non-linearities. Many Optical parameters which are in reciprocal to each other are still a major concern on considering long haul set up. The long distance transmission experiences high dispersion which in turn need for Dispersion Compensating Module that should provide good compensation so that the receiver has good differentiation between the optical pulses. Here in our work we focus on this DCM design and study the various Conventional DCF and Proposed DCF by characterizing it with various line coding schemes.

The Fiber with enormous bandwidth capacity is limited to its channel capacity. The Dense Wavelength Division Multiplexing (DWDM) and Ultra WDM use several numbers of channels in order to raise the bandwidth capacity due to restricted channel capacity[1]. Such closely spaced channels provide easy way for non-linearity due to very high power offered by sum of all channel makes it once again more serious. So such system performance can bring disastrous effect if accompanied with high Chromatic dispersion. As the transmitting Bandwidth is fixed, the dispersion is inversely proportional to square of transmitting distance wherein high bit rate results in Intersymbol Interference (ISI) without Chromatic Dispersion Compensation.

So various concepts of dispersion compensation was proposed from earlier times to till date like Pre-Chirping of light source[2], Introducing the spectral inversion at the middle of transmitting span[3], Dispersion Compensation fibers and Fiber Bragg Gratings for narrow bandwidth Compensation[4]. Such that Dispersion Compensating Module with precise designed Dispersion Compensation Fiber serves very high impact on wide band Slope Compensation transmission to reach high echelons in long haul telecommunications.

The figure1 shows various configuration of Dispersion Compensation in which Pre-Compensation provides negative dispersion where complete dispersion could compensated with positive dispersion from SMF, Post-Compensation provides compensation after the pulses experiences positive dispersion from SMF, Symmetric is a combination of Pre- and Post- Compensation where Compensation is done before and after fiber. This would be something important because although Compensation as a challenge is only spoken theme in optical systems, there always been expected some dispersion for good quality transmission which can be evidently seen from Four-Way Mixing (FWM) where mixing efficiency is inversely proportional to Dispersion. Thus Compensating half part of Dispersion could reduce the severity in SMF at the same time proves with small dispersion reducing non-linearities. In our work we propose the Symmetric Compensation fashion in dispersion Compensation as it serves best than Pre- and Post- Compensation schemes as reported[9, 10].

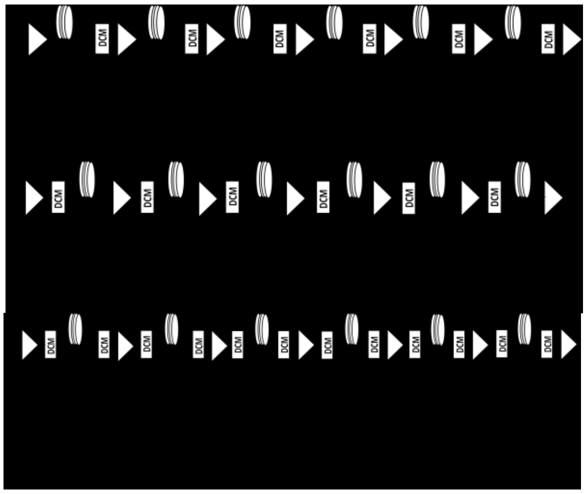


Fig.1. Schematic representation of Dispersion Compensation with a) Post- Compensation b) Pre-Compensation and c) Symmetric Compensation fashion in Optical links

The 40 WDM channels with 10 Gigabit rate transmissions with LEAF and Dispersion Compensation fibers for 600 Km in transmitting and receiving section was reported[8,14]. As an added advantage the performance of Erbium Doped Fiber Amplifier was reported in WDM communication in 1.55μm region which has low loss but high dispersion[5, 14]. Various optical Systems have been configured with the combination of LEAF and RDF fibers[12, 13].The 10 Gigabit transmissions in 32 channels DWDM in C and L band is reported with LEAF and normal RDF for 800 Km[11], transmission of 8 DWDM Channels at 20Gbit over 680 Km using LEAF and RDF[16], 640 Gbit/s over 92 Km in TDM-DWDM with LEAF and RDF[15].In our proposed work we design optical link of 1740 Km with Enhanced-Large Effective Area Fiber (ELEAF) as transmitting fiber (E-LEAF length of 85 Km with 20 loops comprising 1700 Km) with Dispersion Coefficient of ~4 ps/nm-Km which is compensated by Low-Loss DCM with Reverse Dispersion Compensation Fiber (with Dispersion Coefficient of -170 ps/nm-Km) of length 1 Km in front and backside of E-LEAF totally forming 40 Km(2 Km and 20 loops) Compensating Length.

II. Theoretical Background of Pulse propagation and Dispersion in Single-Mode Fibers

Chromatic Dispersion comprises of Material and Waveguide Dispersion. Material Dispersion depicts the Wavelength dependence on refractive index where the spectral components of the laser source (although monochromatic still picture out the Gaussian profile) take up different paths depending upon the refractive index reaching out with different speeds leading to broadening. Waveguide dispersion characterizes with the wavelength dependence of waveguide property i.e., the speed of wavelengths in core is slower than that are present in cladding. So wavelengths that are leaked in cladding travel faster than core leading to broadening. But in Single mode fibers material dispersion is of importance than waveguide dispersion.

The non-linearity in fiber is dependent on the intensity of light propagating in it. So if the dielectric term is replaced with the non-linearity term we get the wave equation as follows for the non-linear medium[30],

$$\nabla^2 E = \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} + \chi^{(1)}\frac{1}{c^2}\frac{\partial^2 EE}{\partial t^2} + \chi^{(2)}\frac{1}{c^2}\frac{\partial^2 EE}{\partial t^2} + \chi^{(3)}\frac{1}{c^2}\frac{\partial^2 EEE}{\partial t^2} + \cdots \quad (1)$$

The term $(1+\chi^{(1)})$is the dielectric constant of the medium. The linear refractive index of the medium is $n = \sqrt{1+\chi^{(1)}}$. The last two terms in the equation are the non-linear terms. Since for silica the value of $\chi^{(2)}$ is negligibly small the wave equation is reduced to,

$$\nabla^2 E = \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} + \chi^{(1)}\frac{1}{c^2}\frac{\partial^2 EE}{\partial t^2} + \chi^{(3)}\frac{1}{c^2}\frac{\partial^2 EEE}{\partial t^2} + \cdots \quad (2)$$

For time harmonic field with angular frequency ω , the equation reduces to

$$\nabla^2 E + \frac{\omega^2}{c^2}(n + n_2|E|^2)E = 0 \quad (3)$$

The electric field can be written as

$$E = F(r,\phi)A(z)e^{j(\omega t - \beta z)} \quad (4)$$

Where the cylindrical coordinate system is assumed and F(r,ϕ)is the modal field distribution and A(z) is a slowly varying envelope function of z. The modal field distribution satisfies the linear wave equation giving as,

$$\nabla^2 F + \left(\frac{\omega^2 n^2}{c^2} - \beta^2\right)F = \nabla^2 F + (\beta_o^2 - \beta^2)F = 0 \quad (5)$$

The propagation constant β gets contributions from two effects, one due to dispersion, that is its dependence on frequency, and other due to loss and non-linear effects.

So, we write as $\beta = \beta(\omega) + \Delta\beta$, where,

$$\Delta\beta = \frac{\omega_o}{c}\frac{\int_0^{2\pi}\int_0^{\infty}\Delta n\,|F(r,\emptyset)|^2 r dr d\emptyset}{\int_0^{2\pi}\int_0^{\infty}|F(r,\emptyset)|^2 r dr d\emptyset} \quad (6)$$

Now we have, $\Delta n = n_2|E|^2 - j\frac{\alpha}{2}\frac{c}{\omega_o}$ where α is the attenuation constant of the fiber. Now we can approximate, $(\beta_o^2 - \beta^2) \sim 2\beta_o(\beta_o - \beta)$ and the equation of the envelop function becomes,

$$\frac{\partial A}{\partial z} - j(\beta_o - \beta(\omega) - \Delta\beta)A = 0 \quad (7)$$

By taking Fourier transform of the equation (7) we have as, where $\tilde{A}$ is the Fourier transform of A which is defined as,

$$\tilde{A}(\omega - \omega_o) = \int_{-\infty}^{\infty} A(t)\, e^{-j(\omega-\omega_o)t} dt \quad (8)$$

And the inverse Fourier transform is defined as

$$A(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{A}(\omega - \omega_o)\, e^{j(\omega-\omega_o)t} d\omega \quad (9)$$

Now let us expand $\beta(\omega)$ in Taylor series around β_o as $\beta(\omega) = \beta_o + (\omega - \omega_o)\beta_1 + \frac{1}{2}(\omega - \omega_o)^2\beta_2 + \frac{1}{6}(\omega - \omega_o)^3\beta_3 + \ldots$ (10)

Where, $\beta_n = \left(\frac{\partial^n \beta}{\partial \omega^n}\right)_{\omega-\omega_0}$. By Substituting for $\beta(\omega)$ in the envelop equation and retaining only up to the second derivative terms of β, we get,

$$\frac{\partial \tilde{A}}{\partial x} + j(\omega - \omega_o)\beta_1\tilde{A} + j\frac{1}{2}(\omega - \omega_o)^2\beta_2\tilde{A} + j\Delta\beta\tilde{A} = 0 \quad (11)$$

Now by taking inverse Fourier transform the equation of the envelop is,

$$\frac{\partial A}{\partial z} + \beta_1\frac{\partial A}{\partial z} - j\frac{1}{2}\beta_2\frac{\partial^2 A}{\partial t^2} + j\Delta\beta A = 0 \quad (12)$$

Substituting for $\Delta\beta$ in the equation the equation of Non-Linear Schrodinger's equation as,

$$\frac{\partial A}{\partial z} + \beta_1\frac{\partial A}{\partial z} - j\frac{1}{2}\beta_2\frac{\partial^2 A}{\partial t^2} + \frac{\alpha}{2}A + j\gamma|A|^2 A = 0 \quad (13)$$

where, we define the non-linearity coefficient γ and A_{eff} as,

$$\gamma = \frac{n_{2\omega_o}}{cA_{eff}} \quad (14)$$

$$A_{eff} = \frac{\left(\int_0^{2\pi}\int_0^{\infty}|F(r,\emptyset)|^2 r dr d\emptyset\right)^2}{\int_0^{2\pi}\int_0^{\infty}|F(r,\emptyset)|^4 r dr d\emptyset} \quad (15)$$

We can identify the various terms of the equation (13) as follows:

(a)The first term gives the rate of change of the wave envelop as a function of distance.

(b)The second term is related to the group velocity since,

$$\beta_1 = \left(\frac{\partial\omega}{\partial\beta}\right)^{-1} = (Group\ velocity)^{-1} = Group\ delay \quad (16)$$

(c)The third term gives the group velocity dispersion (GVD) of the envelope.

(d)The fourth term is due to the loss (attenuation) on the optical fiber.

(e)The fifth term is due to the fiber Kerr non-linearity.

From eqn. (13) it is very clear that β_1 and β_2 takes up the mode propagation constant $\beta(\omega)$ and described in eqn. (10). Now we describe the phase velocity as, $\beta_2=\omega_0/\beta_0$ while the pulse broadens by the factor of $T=L\times[\beta_2]\times\Delta\omega$, where L is the length of propagation, $[\beta_2]$ is the dispersion constant and $\Delta\omega$ is the spectral width of the pulse. The Dispersion is related as,

$$D = \frac{d}{d\lambda}\frac{1}{V_g} \sim \frac{\lambda}{c}\frac{\partial n^2 n(\lambda)}{\partial\lambda^2} \quad (17)$$

The group refractive index is given as $n_g = n + \omega\frac{\partial^2 n(\lambda)}{\partial\lambda^2}$, we relate the Dispersion as,

$$D = -\frac{2\pi c}{\lambda^2}\frac{d^2\beta}{d\omega^2} = -\frac{2\pi c}{\lambda^2}\beta_2 \quad (18)$$

III. Data transmission fibers and Dispersion Compensation Fibers(DCF)

Various types of fiber have been manufactured till date to meet the requirement of good quality communication. ITU-T has standardized various types of fiber for the DWDM applications starting from Conventional Single Mode Fiber G.652. Fiber vendors like Corning, Alcatel, Sumitomo, Draka, ATT/Lucent, Pirelli (FOS) design fibers in respect to enhancement in Effective Core area, Ultra low Dispersion Slope etc. The very recent developed fiber types in reference to pre-existing fibers are shown in the table1[2].

E-LEAF as an extended version of Non-Zero Dispersion Shifted Fiber (NZ-DSF) is a registered trademark of Corning, Truewave is of Lucent and Tetalight is of Alcatel. In our proposed link we use the E-LEAF fiber as the transmission fiber. The specification of various fiber vendors are tabulated in table1[17]. The E-LEAF with very low Dispersion Co-efficient of ~4ps/nm.Km in the operating region of 1500nm has reduced the need of DCF length for Compensation with normal Dispersion Compensation Fibers. The proposed model and Conventional Model is tabulated in tabulated in table2.

The Chromatic dispersion accumulated along the length of the fiber limits the transmission length. For a direct modulated laser and indirect modulated laser, the limited transmission length is given by[30, 31],

for direct modulated laser, $L = \frac{1}{4B|D|\sigma_{\lambda}}$ (19)

for indirectly modulated laser $L = \frac{2\pi c}{16|D|\beta^{2}\lambda^{2}}$ (20)

where, B is the bitrate, D is the Dispersion constant, σ_{λ} is the spectral width and λ is the wavelength. Thus for direct modulated laser the transmission is limited to L~42 Km, for 2.5 Gb/s at D=16 ps/nm.Km and for indirect modulated laser we have length limited to ~500Km and ~30 at 2.5Gbps and 10Gbps bitrate for given D=16 ps/nm.Km. So a compensating structure is required to break this limitation of transmission pre-dominantly in long haul applications.

So it becomes major event to introduce a compensation fiber installed between the transmission links so as to make the pulse reach with good differentiation. Many trends of DCF evolved till today in various fashion to have very effective transmission such as low loss fiber, high Figure Of Merit (FOM) fiber etc., with each fiber has the specific target of attainment. In our proposed link we use Low loss DCF with negative Dispersion of -170 ps/nm.Km in symmetric fashion totally comprising of 2 Kilometers as half (1 Km) before and half (1 Km) after the NZ-DSF Enhanced- Large Area Fiber.

S.No.	Fiber types	Abbreviation	Zero Wavelength	Dispersion@1550nm (ps/nm.Km)	Slope@1550nm (ps/km.nm^2)
1	Standard Single Mode Fiber	SMF	1300-1324	16-18 (17 typical)	~0.056
2	Corning LS	LS	~1570	-3.5 to –0.1 (-1.4 typical)	~0.07
3	Dispersion Shifted Fiber	DSF	~1550	~0	~0.07
4	True Wave Classic	TW-C	~1500	0.8 – 4.6 (2 typical)	~0.06
5	True Wave Plus	TW+	~1530	1.3 - 5.8	
6	True Wave reduced Slope	TW-RS	~1460	2.6 - 6	<0.05 (0.045 typical)
7	Corning E-LEAF	E-LEAF	~1500	2 - 6 (4 typical)	~0.08
8	Alcatel Teralight	TERALIGHT	~1440	5.5 - 9.5 (8 typical)	~0.058
9	True-Wave Reach	TW-REACH	~1405	5.5 - 8.7	<0.45

Table1. Fiber types from different vendors

Fiber Parameters	Units	Standard SMF(ITU G.652)	Standard NZ-DSF(ITU G.655)[32]	Proposed Fiber
Operating Wavelength	*nm*	1310	1500	
Attenuation Constant	*dB/km*	0.5	0.35	***0.2***
Dispersion	*ps/nm.km*	16.5	2.8-3.7	***4***
Dispersion Slope	*ps/km.nm^2*	0.058	0.07	***0.085***
Mode field Diameter	*μm*	8.6-9.5	8-11	***9.2-10***
Relative Dispersion Slops(RDS)	*nm^{-1}*	0.0036	0.025	***0.02***
Polarization Mode Dispersion (PMD)	*ps/√km*	≤0.5	≤0.5	***<0.1***
Effective Area (A_{eff})	*μm^2*	85	52, 56	***72***

Table2. Differentiation of optical specification between Standard SMF, NZ-DSF and proposed model[24, 25,26,28,32].

3.1 Theoretical Background on Dispersion Compensation

The pulse propagation in linear case is governed by[22,30],

$$\frac{\partial A}{\partial z} + i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} - \frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3} = 0 \quad (21)$$

Using the Fourier transform. The solution for the above equation is given as,

$$A(z,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \mathring{A}(0.\omega)\exp(\frac{i}{2}\beta_2\omega^2 z + \frac{i}{6}\beta_3\omega^3 z - i\omega t)d\omega \quad (22)$$

Fiber acts as an Optical Filter with the transfer function as follows,

$$H_f(z,\omega) = \exp(i\beta_2\omega^2\frac{z}{2} + \beta_3\omega^3\frac{z}{6}) \quad (23)$$

All dispersion Compensation Scheme implements a compensating “Filter” that cancels this phase factor in the above equation.

If $H(\omega) = H_f^*(L,\omega)$ the output can be restores then the Optical field after the filter is given by,

$$A(L,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \mathring{A}(0.\omega)\exp(\frac{i}{2}\beta_2\omega^2 L + \frac{i}{6}\beta_3\omega^3 L - i\omega t)d\omega \quad (24)$$

By expanding the phase of H (ω) in a Taylor's series we get as,

$$H(\omega) \simeq |H(\omega)| exp\left[i(\phi_o + \phi_1(\omega) + \frac{1}{2}\phi_2\omega^2 + \frac{1}{6}\phi_3\omega^3)\right] \quad (25)$$

Constant phase ϕ_o and the time delay ϕ_1 can be ignored. Now the dispersion is compensated when $\phi_2 = -\beta_2 L$ and $\phi_3 = -\beta_3 L$. Signal is restored perfectly when $|H(\omega)| = 1$ and the higher-order terms in the expansion are negligible.

3.1.1 Condition for Dispersion Compensation

Let us consider two filters of length L_1 and L_2, now the optical field after these two filters can be given by, $A(L_1 + L_2, t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{A}(0.\omega)\, H_{f1}(L_1, 0) H_{f2}(L_2, 0) \exp(-i\omega t) d\omega$ (26)

In the second fiber which is considered to be the Dispersion Compensation Fiber is designed such that $H_{f1}(L_1, \omega) H_{f2}(L_2, \omega) = 1$, the pulse will fully recovered to its original shape. So, the conditions for perfect dispersion Compensation are,

$$\beta_{21}L_1 + \beta_{22}L_2 = 0 \quad (27)$$

$$\beta_{31}L_1 + \beta_{32}L_2 = 0 \quad (28)$$

In terms of Dispersion Parameter and Dispersion Slope S, we shall state equations as,

$$D_1L_1 + D_2L_2 = 0 \quad (29)$$

$$S_1L_1 + S_2L_2 = 0 \quad (30)$$

Such that, for a compensated link, the product of total chromatic dispersion accumulated and fiber length of transmitting fiber must be equal to the product of total chromatic dispersion accumulated and fiber length of compensating fiber.

3.1.2 Dispersion Compensation for multichannel (WDM) Systems

For multichannel system the DCF must compensate wide number of channels. So, such compensation of different wavelength with different propagation times is a great challenge in the design. In such case we speak about the Slope Compensation. This slope compensation gives out a centered compensation confining all number of channels making the total system to work within the compensated structure.

The Slope condition $S_1L_1 + S_2L_2 = 0$ must be satisfied. As the dispersion constants D_1 and D_2 are wavelength dependent $D_1L_1 + D_2L_2 = 0$ is replaced with,

$$D_1(\lambda_n)L_1 + D_2(\lambda_n)L_2 = 0 \text{ (For n=1, 2, 3 ....N)} \quad (38)$$

Near the zero Dispersion Wavelength of the fiber,

$$D_j(\lambda_n) = D_j^c + S_j(\lambda_n - \lambda_c) \quad (39)$$

The Dispersion Slope of DCF should satisfy,

$$S_2 = -S_1\frac{L_1}{L_2} = -S_1\frac{D_2}{D_1} \quad (40)$$

Basically, we shall have as, the "Relative Slope Dispersion" (RDS) of the transmitting and dispersion compensation fibers must be equal for perfect slope Compensation and given as,

$$RDS = \frac{S}{D} \quad (41)$$

Where, 'S' is the Dispersion Slope and 'D' is the Dispersion Constant. Also a fiber may contain multiple types of fiber in a link. In such case arbitrary form of $\beta_2(z)$ can be given by,

$$A(z,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{A}(0.\omega) \exp(\frac{i}{2}\theta_a(z)\omega^2 - i\omega t) d\omega \quad (42)$$

where, $\theta_a(z) = \int_0^z \beta_2(z')dz'$ is the accumulated dispersion. Finally, the dispersion management requires $\theta_a(L) = 0$, so we always need total compensation at end of the link as,

$$A(L,t) = A(0,t) \quad (43)$$

3.2 *Proposed and Conventional DCM module:*

A spool of DCF is confined within the module of metal box which contributes various physical disturbances like insertion loss, splice loss etc. Different reflections may take place from the connected end between transmission fiber and Compensating fiber which are the major factors of consideration. Normally NZ-DSF has very small Dispersion Co-efficient of 4.5ps/nm.km, accumulated dispersion is very less considering Standard SMF (SSMF). In such case very small DCF (-150ps/nm.km to design value needed) is enough to compensate and access high FOM compared to SSMF. So such types DCF, if designed with less physical disturbances from DCM can yield very good qualitative approach. The proposed and Conventional DCF to various fibers are tabulated in table3.

Figure2. Figures showing DCM of Power form-Avanex (left) and Corning (right) vendors

IV. Simulation Model

In our Simulation model we have implemented the proposed link and studied the various line coding Schemes like NRZ, RZ, CS-RZ, Duobinary and Modified Duobinary in both Single and Multichannel Lightwave Systems. Here we focus on link design, after to it we analyze the performance of line coding schemes and report their quality based on Quality factor and Bit Error Rate (BER). In order to inspect the model we have experimented with various parameter sweeps by changing bitrate, Power, length of transmission, Dispersion Slope etc. In the first section we realize the Single channel Lightwave system with and without compensation and experiment the above said line coding schemes. Secondly we do the same in multichannel systems.

The single channel simulation model consists of E-Leaf proposed fiber (transmission fiber) of length 85 Km for 20 spans comprising 1700km and DCM with proposed DCF of length 40 Km (2Km×20spans). The link1 and link2 in the model shows the Compensation blocks as Pre- and Post- Compensation respectively. Both forms the Symmetric fashion with 1 Km DCF and EDFA of 0.46dB in it. The in-line amplifier is with the gain of 17dB after the transmission fiber. Here the EDFA's are designed with the gain such that it compensates only the losses in the fibers and no booster amplifiers or additional gain is added to the EDFA. The losses accumulated by E-LEAF (α=0.2×length 85 Km = 17dB) and DCF (α=0.46×length 1Km = 0.46dB) is compensated by EDFA gain of 17dB and 0.46dB respectively. Now the multichannel system is multiplexing this single channel system for 6 channels. Each channel is run with the bitrate of 5Gbps totally the system comprising 30Gbps and has the channel spacing of 0.8nm. The multichannel lightwave system setup is shown in the figure3.

Identities	Units	Conventional DCM				Proposed Prototype DCM
		With SMF	With NZ-DSF			
			LEAF	TERALIGHT	TRUEWAVE	
Dispersion	*ps/nm.km*	-120	-180	-187	-173	-170
Attenuation	*dB/Km*	0.428	0.63	-	-	0.46
Splice loss (typical)	*dB*	0.35(typical)				
Figure of Merit (FOM)	*ps/nm/dB*	280	286	-	-	370
Relative Dispersion Slope (RDS)	nm^{-1}	0.0034	0.020	0.0065	0.010	0.00288
Effective Area (A_{eff})	μm^2	18-21	11-13	15-17	15	16
n_2/A_{eff}	*1/W*	1.7×10^{-9}	2.8×10^{-9}	1.9×10^{-9}	1.9×10^{-9}	1.9×10^{-9}
Insertion loss	*dB*	≤7.4	≤5.3	≤5.7	≤4.3	≤5.3
Polarization Mode Dispersion (PMD)$^+$	*ps/√km*	≤7.4	≤2.8	≤1.9	≤1.9	≤1.9

+ PMD is an averaged value over the wavelength range from 1525 to 1565nm using the Jones Matrix method.

Table3. Description on DCM for different vendors and proposed prototype[6,7, 18,19, 21, 27, 28, 29, 33]

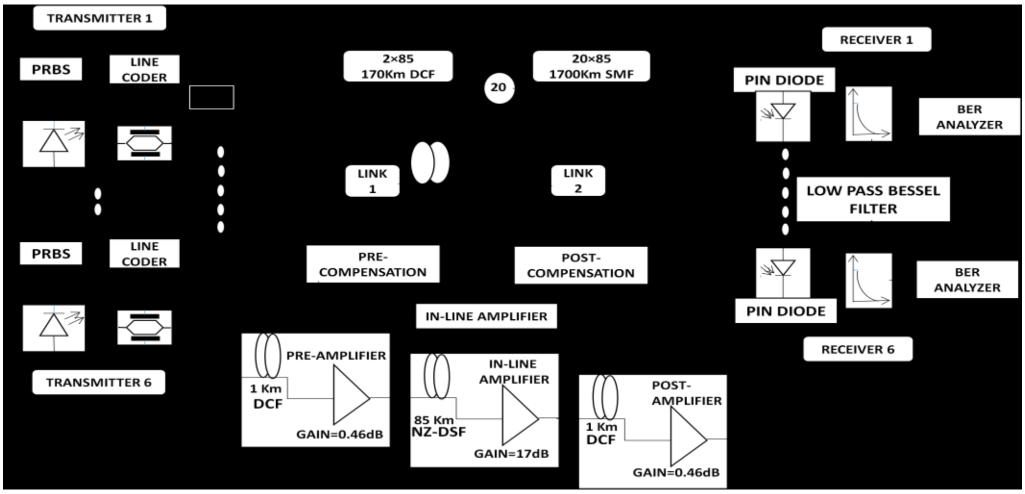


Figure3. Proposed model for Multichannel system with 6 channels

V. Results and Discussions

In this section we present the results of Line Coding analysis in our proposed link, first in Single channel systems and in Multichannel system. In order to differentiate the efficiency of formats with inter- and intra-channel impairments we have divided so and finally concluded the suitability.

5.1Single Channel System

As already stated in equation (20) the bit rate is restricted to the transmission distance. As, for indirectly modulated laser the transmission distances are limited to ~500km and ~30km with bitrate 2.5Gbps and 30Gbps respectively. So, in order to analyze the nature of the different line coding schemes in normal condition a small length of fiber with 20Km is analyzed for different bitrates with an input Power of 5mW as shown in the figure4. The shaded region depicts the rate within 10Gbps, where we could find the Modified duobinary, RZ, duobinary, NRZ formats has an extreme Quality factor with 592.84, 454.43, 213.84 and 88.43 respectively can be mostly considered as ideal case in 2.5Gbps. But when the bit rate increases there is a high fall down of the formats which have performed with high Quality factor earlier. But the NRZ format which has started with Quality factor of 88.43 is been consistent even after 10Gbit rate which prove its Dispersion tolerance with other formats even in high rates. In fig.5, the single channel system is analyzed with 10Gbit rate, where the BER of NRZ proves to be good compared to other formats with Q-factor of 17.002 and 17.68 at 5mW and 15mW respectively. Although, under poor condition duobinary performs better to other formats it is not at acceptable range. An analysis for 2.5Gbps and presented fig.6 which shows that at lower bit rates Modified Duo-binary Coding to be best with high Quality factor even at low powers. It should be remembered that Modified Duo binary format was the worst performed format comparatively at near 4Gbps.So, it is needed a complete analysis on high dispersion tolerance of every formats. Here, although NRZ is the last performed format but on taking practical orientation it has a very good Quality factor of near 100 at high powers[34,35,37].

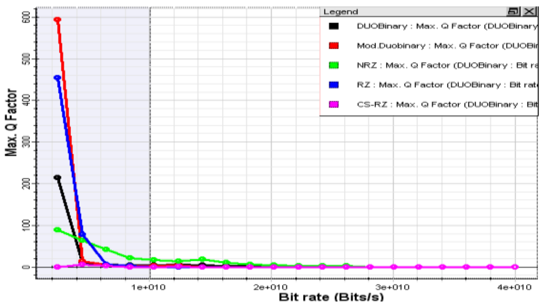


Figure4. Performance analysis at various bitrates

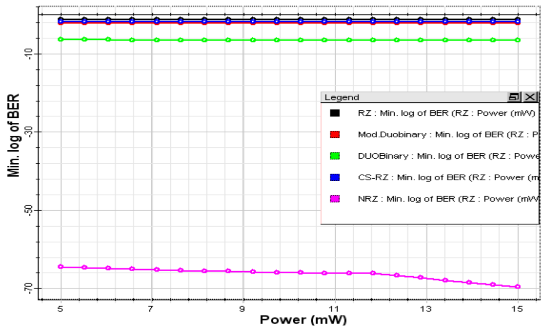


Figure5. Bit error Rate Analysis at 10Gbps system

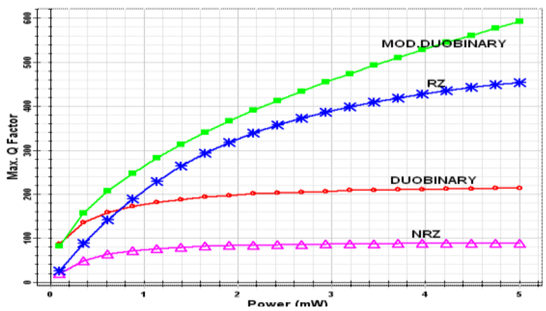


Figure6. Line Coding analysis at 2.5Gbps for different Powers

Now, the proposed model of 1700Km long symmetric dispersion Compensated system is analyzed with 1Gbit rate and the results can be seen from fig.8. Even at 100% Dispersion Compensation and accounting low bit rate the performance of Class-1 Partial response coding (Duo binary and Modified Duo binary) are not satisfactory compared to traditional Line Codes RZ and NRZ. It is evident that even at 5mW the Quality factor of Modified Duo binary Coding is 20 while other yielded very high. This is because Duo binary coding as a multilevel coding requires high Signal to Noise ratio to yield same probability error as other formats does. Although Duo binary and Modified Duo binary may have an excellent feature of ISI avoidance, dedication of such high power for a single channel may not be appreciated on considering DWDM systems as it may lead to high non-linearity accounting sum of powers of all channels.

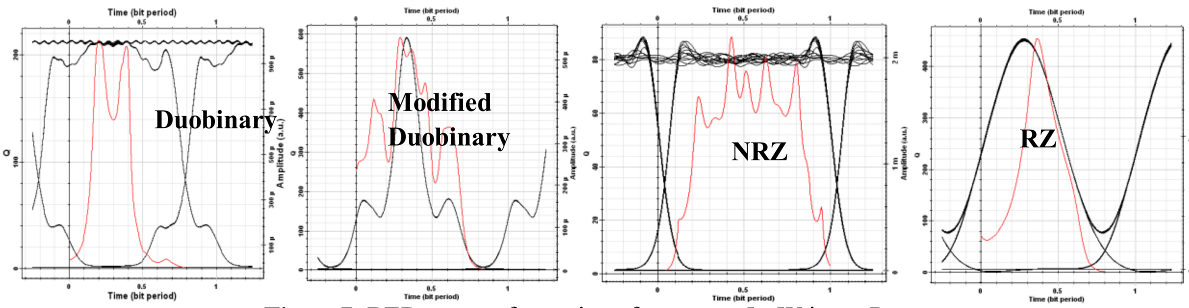


Figure7. BER pattern for various formats at 5mW input Power

But on Considering NRZ and RZ they yield high Q-factor even at very low powers making themselves more suitable for DWDM systems. So, the traditional Non-Return to Zero and Return to zero is focused for our model and their results are produced in fig.11 and corresponding values to be referred in the appendix. At lower bit rate of 2.5Gbps, RZ performed with high Q-factor of 28.64 at 2.5mW and NRZ with 26.03.

As, we are dealing with very long distance we could only differentiate the Q-factor of NRZ and RZ only by difference of ~2. But we could ideally find the high performance Q-factor of RZ in reduced distance than our proposed model. When we analyze for 10Gbps compensated system, RZ which proved less in Quality at 1.8W is raised to high Q value than NRZ when the power is increased, while the view is entirely upside down on dealing with 20Gbps system even with full compensation where RZ entirely drops to Q-value of 3.36 (unacceptable range) while NRZ with 9.34 (appreciated range) at 2.5mW.

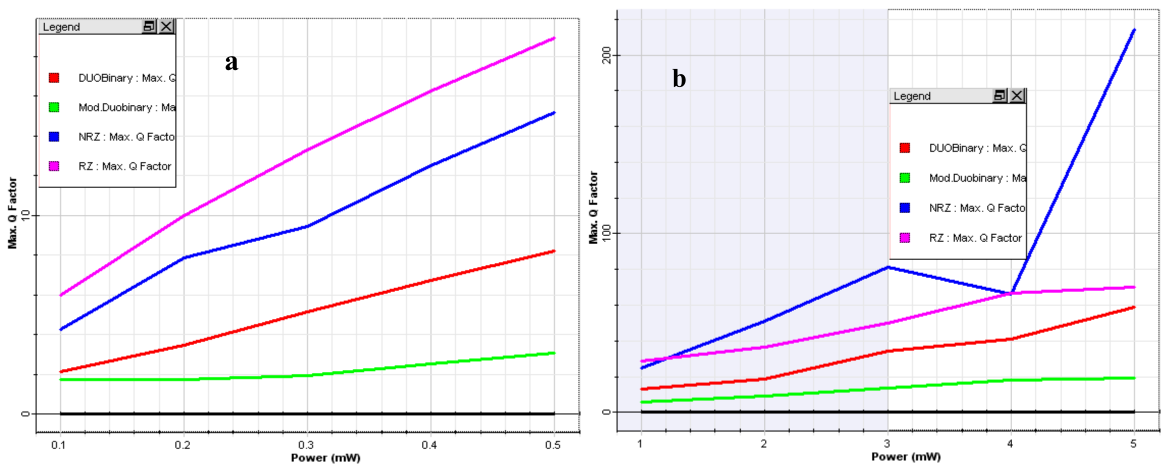


Figure8. Dispersion compensated link with various line codes for a) Lower input power b) higher input power

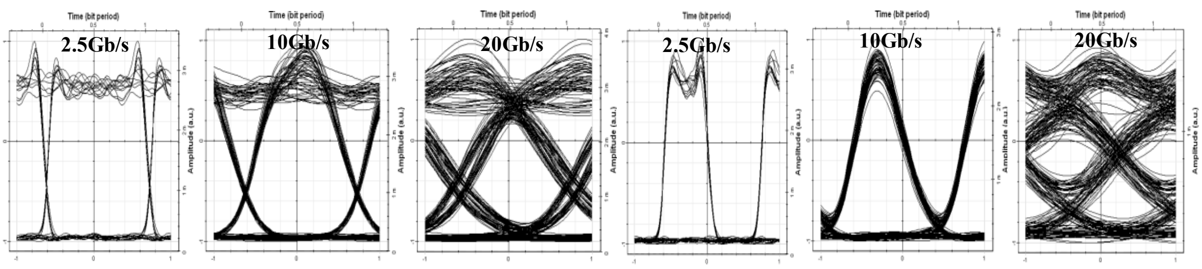


Figure9. Bit Error Rate pattern of NRZ (figures 1, 2 and 3) and RZ (figures 4, 5 and 6) Line Coders.

So, it can be concluded that RZ is very much pronounced to Local Dispersion while NRZ is very much robust towards such Intra-channel Impairments. The logic behind this is RZ with a small pulse width has large spectrum than NRZ which makes it to disperse and interfere easily. Thus RZ suffers high Quality due to the Intersymbol interference.[36,37] Normally it is widely believed that inter-channel impairment is only the consequence of Dispersion, but new factors which are of much importance such as Intra-Four Way Mixing (IFWM) and Intra- Cross Phase Modulation (IXPM). These two terms may be considered as the borrowed concepts from Inter-channel Crosstalk (refer fig.10).

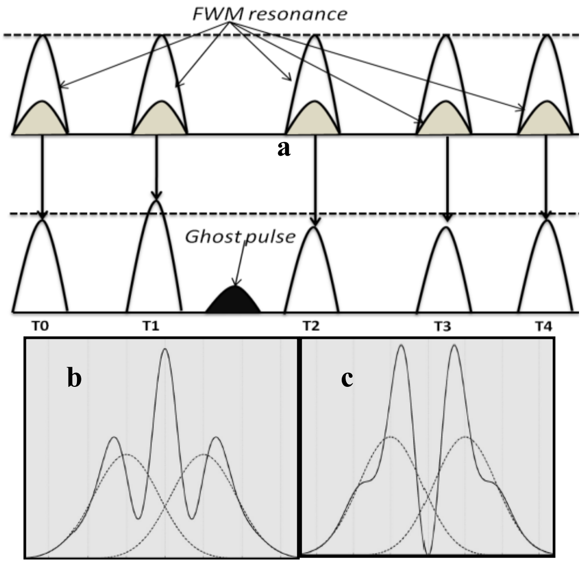
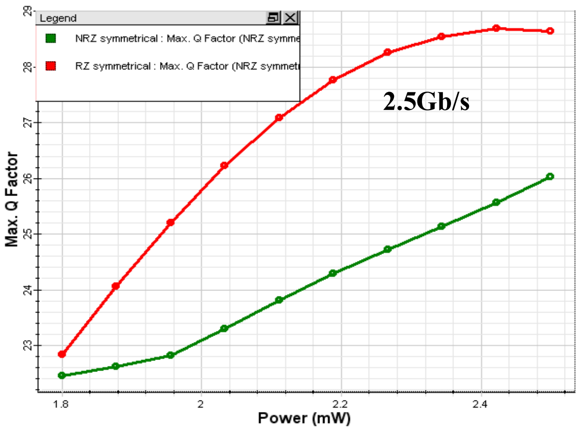
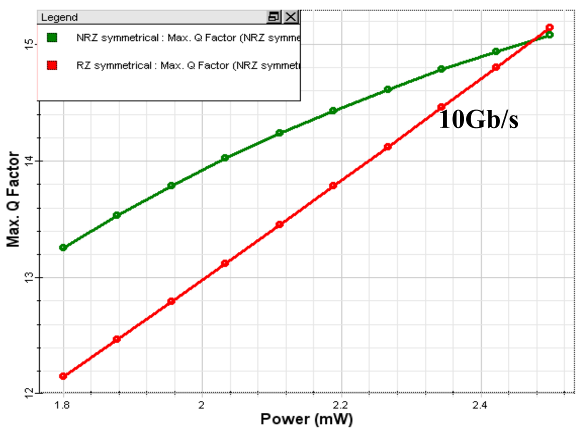


Figure10. (a)Demonstration of Intrachannel Four Wave Mixing (b)Formation of Ghost pulse (c) Suppression of Ghost pulse





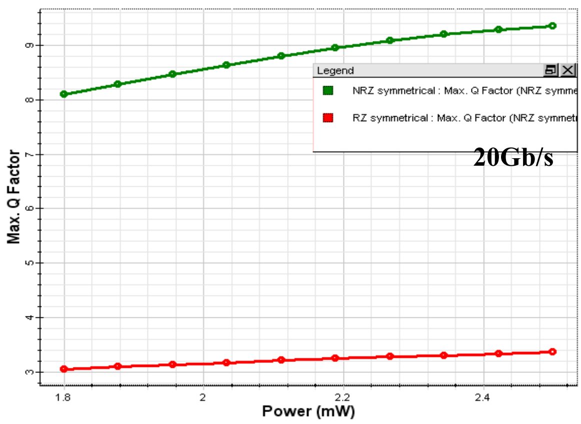


Figure11. Comparative analysis of NRZ and RZ schemes for different bitrates

RZ format with large bandwidth is very highly pronounced to IFWM and IXPM in high bitrates due to severe dispersion. Normally the dispersion leads to the concept of IFWM where the energy of adjacent pulses are transferred to form a "Ghost Pulse" which can be pictured in fig.10(a) where the pulses in upper row show original pulse intensity and pulses in lower row shows the dispersed pulses. The coherent mixing of frequency from adjacent pulses is shown in lower row. On speaking the reality, when there is a '0' bit surrounded by two 1's, due to dispersion, overlapping of pulses at the midway(Constructive interference) leads to generation of 1'bit in the place of 0 bit which forms the ghost pulse and reduces the Eye height. Moreover, overlap between center of one pulse and tail of other pulse leads to shift in the peak of original pulse (in fig.10(b)). So, the ISI can be avoided by inverting the adjacent 1's by phase of 180^{o} where the overlapping of adjacent pulse leads to destructive interference and overlapping of tail and midway of pulses too can only shift the peak from center but the eye pattern is saved (in fig.10(c)). This basic principle forms the idea in Duobinary and AMI coding.

On considering IXPM it the intensity based consequence i.e., recalling the different speeds of frequency with respect to the refractive index depending upon intensity. To be very clear, when overlapping pulses are considered, the intensities of the overlapping tails of interfering pulses also affect the instantaneous-frequency shifts across the considered pulse, which results in the shift in the mean frequency of the considered pulse. Due to the dispersion, the shift in the mean frequency causes the interfered pulse to travel at a speed different from that of an isolated pulse, hence leading to timing jitter. The frequency shift of interacting pulses can be given as, $\frac{d\Delta f_{XPM}}{dz} \sim F(x) = \frac{\exp(-2/x^2)}{x^3}$ where x is the ratio between the pulse width and the pulse separation. Unlike IFWM, IXPM does not depend on the phase matching of pulses, where IFWM forms strong transfer of energy at coherent matching of phase of the pulses. IXPM disturbs only the phase and not the amplitude similar to the impairment due to interchannel XPM[30].

5.2 Multichannel Systems

In this section, at first the proposed model is analyzed with 100% Compensation with different powers to analyze the effect of non-linearity under Compensation and secondly the multichannel system with highest power is compensated to different compensation percentages (variation in Compensation is done by adjusting the Dispersion slope of proposed DCF in DCM) and the effect of over Compensation on Non-Linearity is studied. The performances of NRZ and RZ with 100% compensation at 6, 12, 18, 24 and 30mW powers are plotted in fig.12 and BER pattern of best performed channels at respective powers are shown in fig. 13.

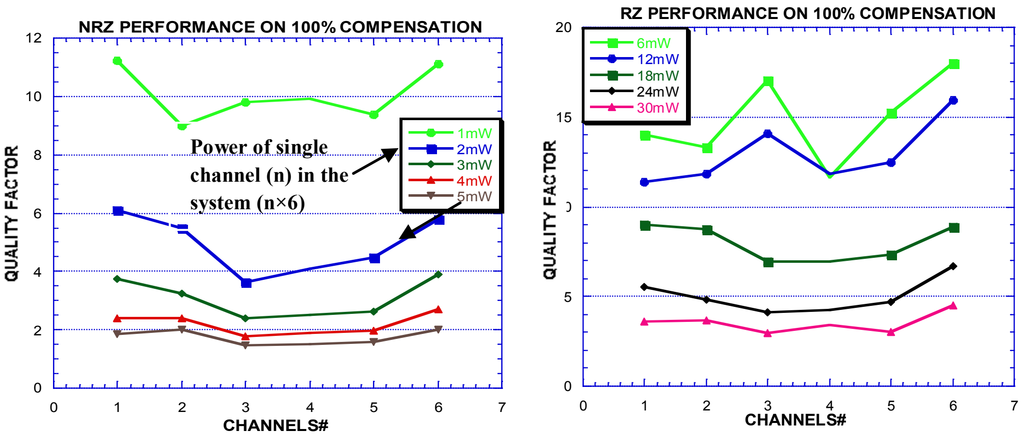


Figure12. Multichannel analysis of proposed link with 100% Compensation for various Powers

From fig.12, on comparing slope Compensation between NRZ and RZ, at 6mW (each channel with 1mW power) the RZ performs well with Q-value of compared to NRZ (refer appendix). Even when the power is increased to very high range 18mW the RZ performs well with Q-value above ~7 but NRZ severely suffers to yield Q-value even above 4. The NRZ format which performs well in Single Channel System now degrades making RZ superior in Multichannel Systems. From the BER pattern in fig.13 it could be pictured out that even at 30mW the dispersion of RZ is unaffected with 100% Slope compensation but NRZ proves to be worst even form 12mW.

Although NRZ is superior to RZ in Single Channel Systems, it suffers a lot due to interchannel non-linearities. Because, as the pulse width of NRZ is large compared to RZ it has more interaction times with the other pulses in the fiber[36, 37]. The pulses in time domain interact efficiently with the pulses of other wavelength in due to more interaction times for NRZ. But on looking RZ, its precise short pulse width makes it more efficient in interaction times. Due to shorter width of RZ pulses, these pulses could "Walk-off" easily thus preventing more interaction times.

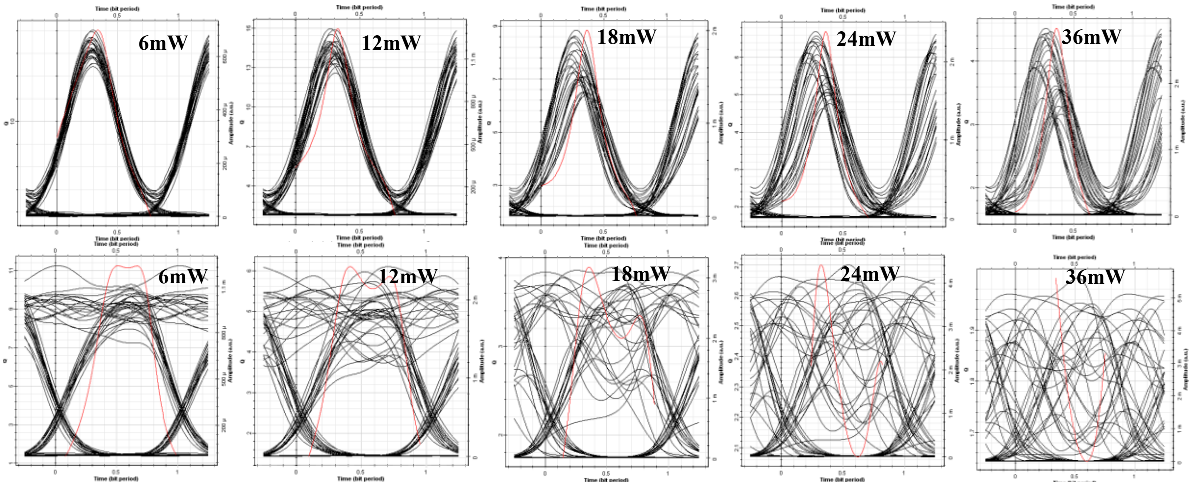


Figure13. BER analyzed pattern of best channels of RZ (Upper row) and NRZ (Lower row) at different Powers

Moreover, as discussed earlier the high dispersion of RZ pulse proves to be beneficial now in considering multichannel systems. Because, when the dispersion is high, the pulse height is reduced which favours RZ to work under controlled manner with intensity dependent non-linearities. Also, average power of RZ pulse is high when compared to NRZ making it to reach a long distance with reduced transmitting power once again proving its efficiency[34, 35].

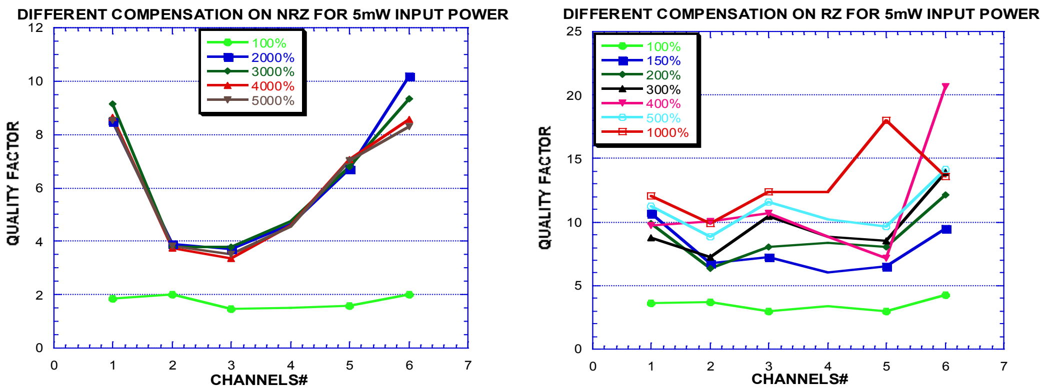


Figure14. Comparative analysis of NRZ and RZ with various % of compensation at 30mW multichannel Systems

In order to analysis the effect of Dispersion Compensation at high non-linearities, the multichannel system with 30mW power is compensated with very impractical range and the results are shown in fig.14 and the values are tabulated in the appendix. From figure it is clear that the RZ with low performance at such high power has shown an average channel Q-factor of above 8 at 200% compensation and an average channel Q-value of ~13 at 10% Compensation. But NRZ has consistently three to four impaired channels even at 5000% of Compensation. Fig.15 states that the worst performed channels in RZ have Q-value even more than the best performed NRZ channels.

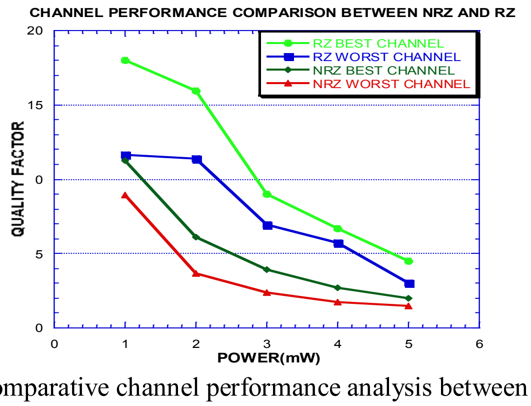


Figure15. Comparative channel performance analysis between RZ and NRZ

Practically, Non-linearity is common to any type of format, but the fact is that the tolerant characteristics of format are to be studied. The change or rise in Q-factor at 30mW power due to the over compensation do not represents the adjustment or control in non-linearity. It represents the fact that when the dispersion is controlled very highly, the improvement in dispersion have resulted in total system performance enhancement but non-linearity is not under control. It is evident from fig.14 at 5000% Compensation the channels are degraded and there is exchange or gain in powers of adjacent channels.

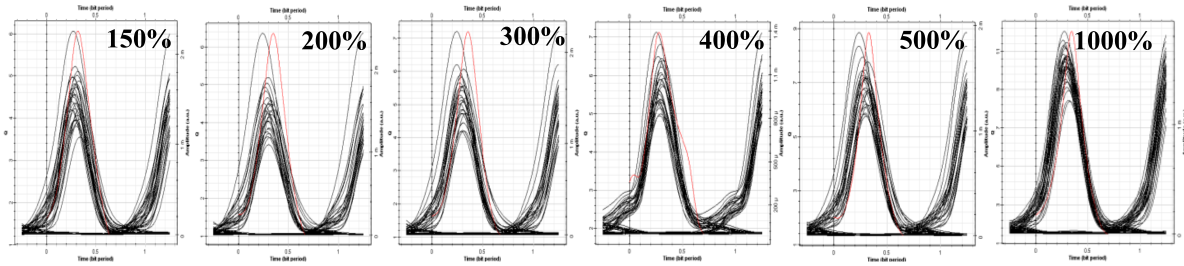


Figure 16.BER pattern of Best performed RZ channels at different Compensation for 30mW multichannel System

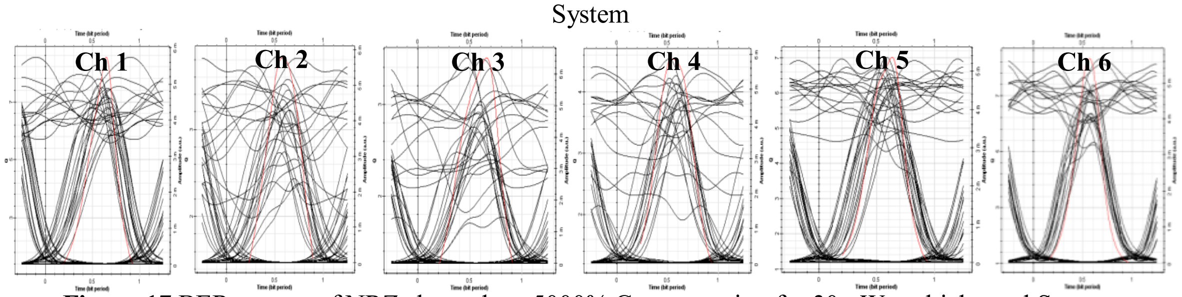


Figure 17.BER pattern of NRZ channels at 5000% Compensation for 30mW multichannel System

Even in RZ we could see the gain in adjacent channels due to non-linearity. Also practically overcompensation results in channel impairments, because as discussed earlier mixing efficiency FWM is not only inversely proportional to channel spacing but also dispersion. So, considered amount of dispersion is always needed for effective communication with good receiving range. The work is mainly to select out the perfect line coding format under inter-channel impairments, so such impractical range of Compensation is carried out.

VI. Conclusions

The Model of Dispersion Compensation fiber and Enhanced- Large Effective Area Fiber was designed with practical values with respect to various vendors' specification. The proposed model with the aim of DCM insertion loss avoidance is successfully achieved by having reduced length low loss DCF with Dispersion of -170 ps/nm-Km with the length of 2 Km with the combination of NZ-DSF(E-LEAF) fiber of Dispersion Coefficient ~4ps/nm-Km. Thus a long haul Symmetric Dispersion Compensated link with 1700 Km E-LEAF and DCF of 40 Km has yielded an acceptable range of Q-factor and Bit Error Rate (BER) with both NRZ and RZ formats at 10Gbps, while NRZ yielded Q-value of 8.091 at 1.8mW input power in 20Gbps Single Channel Systems. Thus the proposed design also seems to be very qualitative in multichannel systems where RZ could transmit 30Gbps at an average channel Q-value of ~13. By the analysis the suitable formats for proposed model have been discussed and their range of powers and various parameters are tabulated.

From the analysis of our model it is very clear that RZ forms very qualitative for Interchannel impairments while NRZ is very much robust to intra-channel impairments. The effect of non-linearity is discussed with the aid of various percentage of Compensation. The non-linearity behavior is studied for the proposed model and impacts are noted which states dispersion compensation cannot have control over Non-linearity. The nonlinearity can be only controlled with low power channels and RZ is the better solution for our proposed model.

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Appendix

LINE CODE FORMAT	POWER(mW)	DATA RATE (Gb/s)					
		2.5		10		20	
		Q-Factor	BER	Q-Factor	BER	Q-Factor	BER
RZ	1.8	22.83	8.3×10^{-116}	12.15	2.1×10^{-34}	3.05	1.1×10^{-3}
	2.5	28.64	6.8×10^{-183}	15.19	1.6×10^{-52}	3.36	3.8×10^{-4}
NRZ	1.8	22.46	3.8×10^{-112}	13.25	8.9×10^{-52}	8.09	2.8×10^{-16}
	2.5	26.03	7.5×10^{-150}	15.07	1.7×10^{-40}	9.34	4.2×10^{-21}

Table1. Line Coding analysis for Single Channel System.

LINE CODE FORMAT	POWER (mW)	BEST PERFORMED CHANNEL		WORST PERFORMED CAHNNEL	
		Q-Factor	Bit Error Rate	Q-Factor	Bit Error Rate
RZ	6	18.03	2.9×10^{-73}	11.62	8.9×10^{-32}
	12	15.95	6.9×10^{-58}	11.38	1.5×10^{-30}
	18	8.97	8.2×10^{-20}	6.93	1.0×10^{-12}
	24	6.69	5.4×10^{-12}	4.08	9.3×10^{-6}
	30	4.52	1.4×10^{-6}	2.98	5.9×10^{-4}
NRZ	6	11.24	7.9×10^{-30}	8.97	7.3×10^{-20}
	12	6.09	3.4×10^{-10}	3.64	6.3×10^{-5}
	18	3.89	2.6×10^{-5}	2.39	3.6×10^{-3}
	24	2.70	1.8×10^{-3}	1.76	1.6×10^{-2}
	30	2.00	1.1×10^{-2}	1.45	3.0×10^{-2}

Table2. Line Coding analysis with 100% Symmetric Compensation in multichannel system.

LINE CODE FORMAT	% OF COMPENSATION	BEST PERFORMED CHANNELS		WORST PERFORMED CAHNNELS	
		Q-Factor	Bit Error Rate	Q-Factor	Bit Error Rate
RZ	150	10.72	2.3×10^{-27}	6.77	6.7×10^{-12}
	200	12.16	1.2×10^{-34}	6.36	4.4×10^{-11}
	300	13.91	1.5×10^{-44}	7.20	1.4×10^{-13}
	400	20.63	3.6×10^{-95}	7.12	2.5×10^{-13}
	500	14.15	4.9×10^{-46}	8.86	1.7×10^{-19}
	1000	17.98	7.9×10^{-73}	9.87	1.3×10^{-23}
NRZ	2000	10.17	6.2×10^{-25}	3.71	4.6×10^{-5}
	3000	9.32	2.5×10^{-21}	3.70	3.8×10^{-5}
	4000	8.64	1.3×10^{-18}	3.63	6.3×10^{-5}
	5000	8.53	3.4×10^{-18}	3.50	1.0×10^{-4}

Table3. Performance of Line Coding with various percentage of Compensation in multichannel system