SCHOOL OF COMPUTER SCIENCE AND ELECTRONIC ENGINEERING

University of Essex

OPTICAL NON-LINEARITIES AND DISPERSION IN LONG-HAUL WDM FIBRE NETWORKS

(USING VPI PHOTONICS SIMULATION TOOL)

FINAL REPORT

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ABSTRACT

The project undertaken investigates the design of a DWDM optical communication link with the aim of increasing the unregenerated span of fibre while maintaining a good BER for transmission using advanced simulation TCAD tool VPI. Research is done to optimise performance parameters (BER, OSNR) by proper management and eradication of system impairments such as dispersion, non-linear effects and noise. Special emphasis is laid on the correlation and competition between the effects of dispersion and non-linearity in both intra- and inter-channels transmission of the WDM systems. Our analysis and numerical experimentations with the optical links operating at 10 GBps suggest towards having *locally high dispersion* effects (to minimise effect of non-linearities like SPM, XPM, and FWM), but to introduce periodic dispersion compensation (in order to obtain the *low-average dispersion*). The effect of modulation formats (RZ and NRZ) on unregenerated transmission length and BER are also investigated. It was found that in a low-attenuation fibre links the RZ format is considerably more robust to the influence of non-linearities and allows longer unregenerated fibre spans. At the same time large attenuation greatly reduces the fibre span and both RZ and NRZ have equivalent performance. Hence, we have incorporated the power-budgeting of the transmission system to optimise its performance by mitigating penalties caused by mutually-competing factors, such as optical noise, dispersion and non-linearities.

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1. INTRODUCTION

Fibre optic networks form the backbone of communication systems in the present day world. Electronic transmission of data across the globe is an indispensible activity with almost all trade and commerce processes depending on it hugely. The evolution of long distance communication systems indicate at the technological and economic forces which dictate the growth of this industry. History shows that the first long haul transatlantic telegraph cable was successfully installed and implemented in the year 1866.With the passage of time an increase in voice traffic over long distances resulted in laying the Trans Atlantic Telephone cable which was essentially an analog system with co-axial cables and electronic amplifiers. This service system was launched with 36 4 KHz telephone circuits which were frequency division multiplexed over a narrow bandwidth of a few tens of megahertz**.** It was the advent of the internet that spawned the tremendous growth in data traffic and ushered the telecom revolution with fibre optical communication systems taking center stage for intercontinental communication [1][2].

1.1 ***BASIC OPTICAL POINT TO POINT LINK: STRUCTURE AND SYSTEM PERFORMANCE ISSUES***

The deployment of optical communication systems was advantageous from many points-the most striking being the enormous bandwidth provided by such systems. Light wave systems are capable of carrying huge data streams because they operate at much higher frequencies (~200THz) as opposed to electrical systems operating at microwave frequencies (~ 1 GHz).The other advantages include the inherent security of data paths which is a part of the package of light wave systems. Also, keeping in mind factors such as maintenance costs and longevity, optical fibre systems are economically more conducive than electrical systems [3]. A basic point to point optical communication link is shown below:

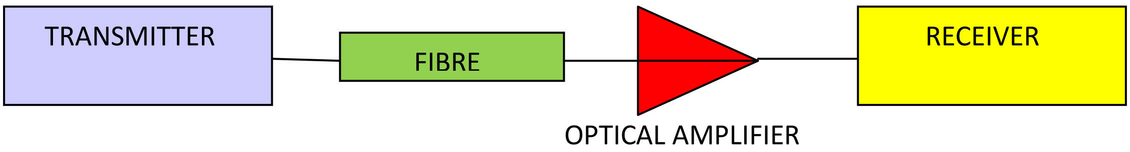
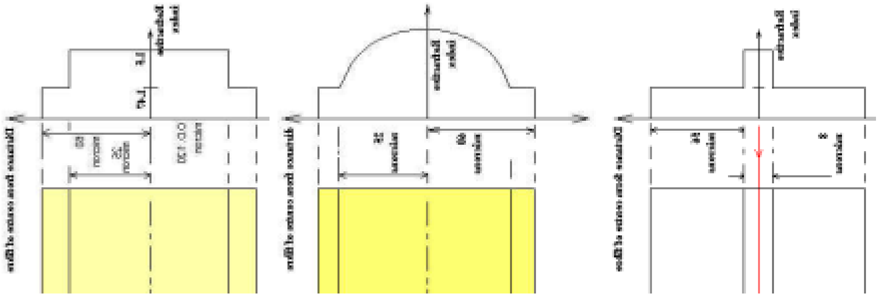


Figure 1. *Optical communication point to point link.*

The major components are the transmitter, the optical fibre, the optical amplifier and the receiver.

The essential components of a transmitter are - a light source and a modulator (internal or external). The basic function of the transmitter is to covert an electrical signal into an optical signal. Light sources in the present age systems are generally high power lasers which emit highly coherent light. This light can be modulated internally by the laser or with an external modulator like the Mach Zehnder modulator. The modulation of light into different formats has a very strong impact on the system performance; this will be discussed in later sections.

The optical fibre constitutes the medium through which light travels from point to point. Optical fibres have a typical structure of an optically denser core and a relatively rarer cladding. This is the key to the reason of light propagation in the fibre – total internal refraction of light. Fibre types are chosen with great care and made specific to the system requirements as this component of the optical communication system is where most signal distortion take place. Broadly, fibre types are of two kinds- step index fibre and graded index fibre. Step index fibre structures have an abrupt change in refractive index at the core cladding interface. With this structure, the problem of different path lengths for light rays does arise with ray angles varying from zero degree along the fibre axis to the maximum acceptance angle offered by the specific fibre type. This problem is done away in single mode step fibres where the core to cladding radius ratio is much smaller. The graded index fibre has a gradually changing refractive index from the rarer cladding to denser core. The paths of the light rays within this fibre are more curved in towards the fibre axis as opposed to the more angular paths traced by the rays in step index fibre. The very obvious advantage of this sort of structure is that most of the light energy is contained within the fibre and losses are minimal.



a) b) c)

Figure2. *Refractive Index profile for a) step index fibre, b) graded index fibre, c) single mode fibre.* [4].

Optical systems got a major boost when cost effective optical amplifiers were introduced to reamplify signals and make up for power losses. Power budgeting is a major area which design engineers have to pay attention to while developing a communication link. Signal power levels have to be sufficiently high for proper detection while at the same time they cannot exceed a certain threshold value. Changing optical intensity in a silica fibre has effects on the refractive index of the fibre material. If the refractive index changes, the behaviour of light within the fibre also changes. This gives rise to distortions in the signal known as non linear effects. Another problem that comes to the surface with the use of optical amplifiers is that of Amplified Spontaneous Emission or ASE noise. Noise is a random process which interferes with the signal propagating and can hinder its proper detection at the receiver [5][6].

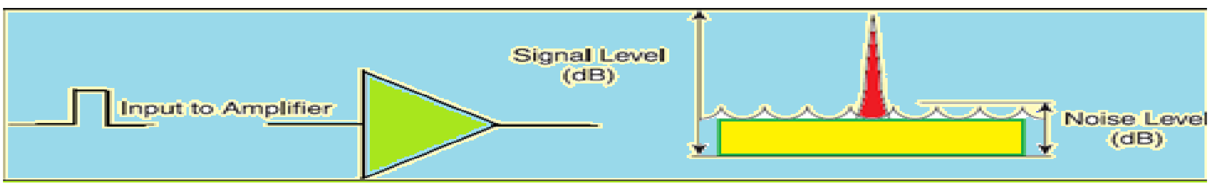


Figure3. *Signal and Noise Level Representation.*

The receiver circuitry is the final block in the point to point optical communication system. The receiver changes the optical signal back into an electrical signal. The main component of the receiver is the photodiode which converts the incident optical intensity into corresponding electrical signal value. Before reaching the receiver the signal undergoes many degradation processes such has dispersion, non linear behavioural distortions, noise etc. These have a major impact on the detection process. There are a number of ways in which such undesirable effects can be mitigated. These are addressed in later sections. Any system's performance is measured in terms of system performance parameters: OSNR-Optical Signal to Noise Ratio, BER- Bit Error Rate and ISI – Inter Symbol Interference. These performance parameters determine and indicate accurate signal detection at the receiver. The signal power level should be above the photodiode threshold level and this is achieved if the signal OSNR value is sufficiently high. Similarly a low BER and ISI value indicate distortion free signal waveform.

1.2 ***DWDM SYSTEMS***

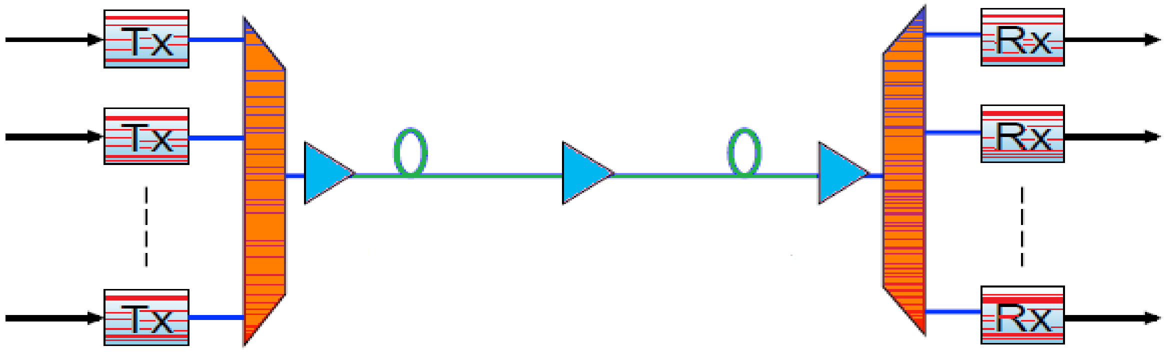


Figure4. *Elements of WDM system.*

The knowledge that at some frequencies the fibre loss is extremely low brought a revolution in the optical communication research. The need for higher capacities paved way for intelligent multiplexing techniques. WDM (Wavelength Division Multiplexing) and TDM (Time Division Multiplexing) both provide ways to increase system capacity.

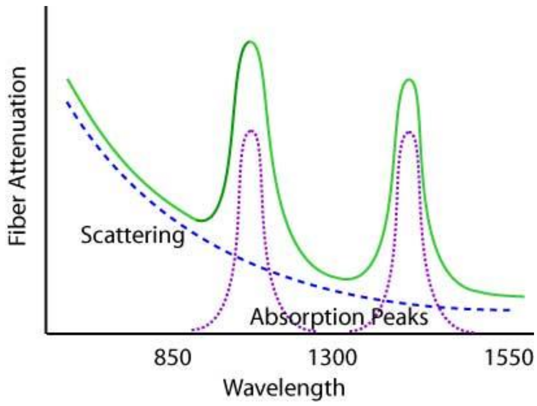


Figure5. *Fibre Attenuation vs operating wavelengths, indicating low loss windows at 1300nm and 1500nm.* [7]

In TDM systems the lower bit streams are multiplexed (interleaving) in a way so as to provide a higher bit stream. These systems had to be regenerated every 50-60Km because of the fibre attenuation suffered and hence were not conducive for long haul communication [8][9]. On the other hand, wavelength division multiplexed systems have many wavelengths multiplexed onto the same fibre at the same bit rate. WDM systems became even more popular commercially with the advent of the Erbium Doped Fibre Amplifier (EDFA) which gave amplification to all wavelengths simultaneously without significant crosstalk. EDFA also leveraged several nano meters of optical bandwidth over thousands of kilometres. Moreover, with advances in optoelectronics high bit rates of 10GBits/s and 40GBits/s were achieved for single channel which when combined in a multichannel system promised capacity in terabits. However, accurate transmission of tremendous amounts of data has several technical hurdles along the way. The key impairments suffered by a WDM system are pulse broadening due to dispersion, signal distortion due to non linear behaviour of light in optic fibre and power attenuation. These problems in transmission and their rectification methods to obtain proper transmission are discussed in detail in the subsequent sections.

2. SIMULATION TCAD TOOL- VPI PHOTONICS

Photonic simulation is a necessity in today's day and age of high speed, exponentially growing world of optical communication systems [10]. In the past, communication systems were limited by attenuation or loss , dispersive behaviour of signal along propagation and efficiency of transmitter and receiver devices. It was the foray into the use of optical amplifiers, which dramatically increased the distance over which data could be successfully transmitted, that predicting non linearities along the transmission made numerical modelling an essential tool for design analysis. Then again, simulations aid the organized storage and transfer of design captures to be reused, copied, discussed or modified by engineers within an organization or across organizations. Another very strong reason why simulators are necessary are the fact that one can keep the specified design parameters fixed as an entity whose value can be altered as is the requirement of the customer [11]. This is true for individual component models, a section of the system (comprising only a few components) and the system as a whole as well. This is beneficial because it means that standard design rules can be applied repetitively without any problem by teams who may not be design experts themselves.[12]

The software tool used is for simulations in this project is a commercial package called VPI which has two main components: the VPI transmission maker capsule which contains the component maker; the other useful tool is the VPI analyzer. These are the virtual spaces used to design, develop, analyze and investigate photonic circuitry and system design and operation. The software is capable of providing PDA tools for both building up a circuit from scratch with individual models to using various templates available. The analyzer has provisions for effectively displaying scope outputs in both time and spatial domain. Also, the software is fully equipped to for estimating the bit error rate. It has not only the algorithms for such numerical modelling but also various display options such as eye diagrams to show the designer the results in totality. All in all it is a complete photonic transmission design suit. With the current version of the VPI software one can not only analyze attenuation, dispersion, device operation but also make it possible to assemble complex topologies very quickly and with definite accuracy which can be visually verified. The two main parts of the software are the VPItransmissionMaker and the VPIAnalyzer. The VPItransmissioMaker has four main subdivisions:-

1) TC Modules : these contain all the individual components such as transmitters, optical sources, optical amplifiers, filters, modulators, fibres, receivers etc. It also has numerical and mathematical analyzers which are essential to process a signal.
2) Active Photonic Demos : which contains templates which can show laser and filter characteristics in different assemblies, signal processing techniques and formats, optical sources such as tuneable lasers, ultra short sources and fully working templates of systems

such as BER estimations for aperiodic boundary conditions, directly modulated NZR system etc.

3) Optical Amplifiers Demos : this contains templates of hybrid amplifiers, Raman amplifiers in different configurations, dopes fibre and doped waveguide amplifiers. It also has a section which gives a perspective on modelling the amplifier from scratch.
4) Optical systems demos : this contains advanced network system templates such as long haul, WDM and TDM systems, modulation templates and testing and measurement templates.

In the numerical modelling of many optical components, the VPI software makes use of the well founded transmission line theory. This encompasses imagining the functioning of optical devices, such as lasers, akin to the travelling of waves on a transmission line. Depending on the specific workings of the device, impedance mismatches can create reflections which are analogous to the way the carriers would move inside a semiconductor device.

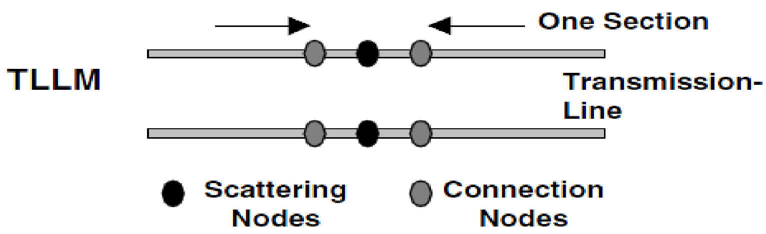


Figure 6. *TLM used in laser functioning.* [13]

Also, the VPI software has a graphical user interface which makes it possible to model at various levels of abstraction, be it wiring together of individual components or putting together large network parts together. Signal representation is hugely responsible to enable the simulator to have many modules interact and getting unique solutions while expounding upon the evident faults in the design. There are two modes in which signals are transferred from point to point within a simulation: sample mode and block mode.

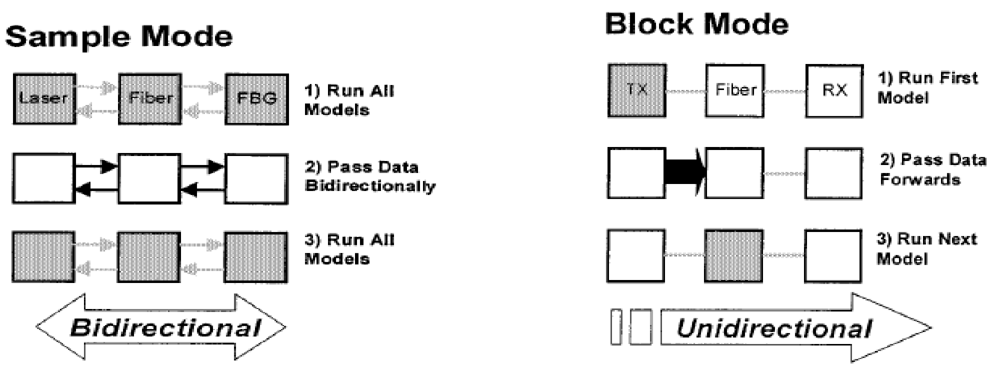


Figure 7. *Signal Flow Representations in VPI Photonics*. [13]

In *sample mode* all the modules which are to be simulated are always powered up. This is because the passage of data is a two way process- *a bidirectional simulation* and all modules should be active to provide the latest data to its neighbour. During one iteration, the signals are represented as a complex envelope of data, transmitted over the whole bandwidth, to closely spaced modules to carry out simulations of complex interactions. On the other hand, the Block mode follows unidirectional transfer of data. Unidirectional transfer of data is made possible because data is transmitted as arrays or blocks of complex envelop of optical field. Hence biderctionality is impossible for modules which are spaced by one or more block spaces. Hence, data is transferred one by one to each module at a time[10][12].

3. DISPERSION IN DWDM SYSTEMS

According to Maxwell's theory of electromagnetism, any dielectric material will respond to the presence of an electromagnetic field. Optical fibres made with silica are no exeption. Although the change exhibited in material properties when subjected to EM fields in silica is not that pronounced, however, in an optical fibre waveguide like structure this response is inevitable. Hence arises a signal distorting effect known as dispersion. Dispersion is essentially a phenomenon where different spectral frequencies of a light pulse travel with different speeds within the fibre and result in pulse broadening. Needless to say, pulse broadening is undesirable as this would lead to overlapping with adjacent bit pulses and make detection at receiver highly inaccurate. [14]

3.1 ***DISPERSION - INTERMODAL AND INTRAMODAL***

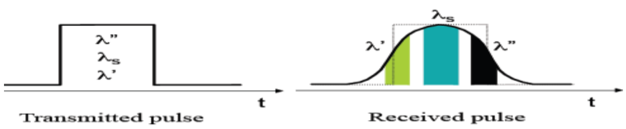


Figure 8. *Effect of Dispersion on a pulse.* [4]

The type of dispersion that a system will suffer from is predetermined by the type of fibre employed for transmission. In multimode fibres, many different modes of a light ray can travel. Each mode has a corresponding mode index (group velocity) associated with it and this difference in speed causes pulse broadening.From the perspective of geometric optics, non paralle light rays injected into the fibre core follow different paths resulting in a delay of collective signal at the receiver end and pulse broadening. This sort of dispersive behaviour is called intermodal dispersion and limits the performance of a WDM system severly in terms of transmission distance covered and capacity carried. Single mode fibres are used instead and they do away with the problem of intermodal dispersion as only one mode transfers the energy of the injected pulse.However, the problem of dispersion still lingers; this is attributed to the frequency dependence of the refractive index of the fibre and its waveguide structure. This is called intramodal or Chromatic dispersion. The velocity of any wave travelling in a fibre with refractive index n can be expressed as:

$$v = \frac{c}{n(\lambda)}$$

where c is the speed of light and $n(\lambda)$ is the wavelength dependent refractive index of material [14]. Even though, in a single mode fibre only one frequency travels, the light signal that is transmitted is modulated appropriately. Any modulated signal will have a non zero spectral width and a data bandwidth encompassing a range of frequencies which numerically are almost equal to the bit rate. These different spectral components have different velocities in the fibre and lead to pulse broadening in single mode fibre. This is highly undesirable as in intensity modulated data streams such broadening can limit the bit rate from going to higher values which is a chief objective for WDM long haul systems. Also, chromatic dispersion accumulates linearly over distance and increases quadratically with the bit rate. This quadratic dependence can be explained on two accounts- first, if the bit rate is made two times more, the Fourier transformed frequency spectrum will double and have more spectral components thereby making the dispersion scenario worse. Second, doubling the bit rate halves the data time slot in the time domain and this makes the system more sensitive to dispersion caused pulse spreading. Hence, for long haul WDM systems with both large distance transmission and huge capacity with high bit rates chromatic dispersion is a major obstacle to overcome.[15]

3.2 ***DI SPERSION COMPENSATION TECHNIQUES***

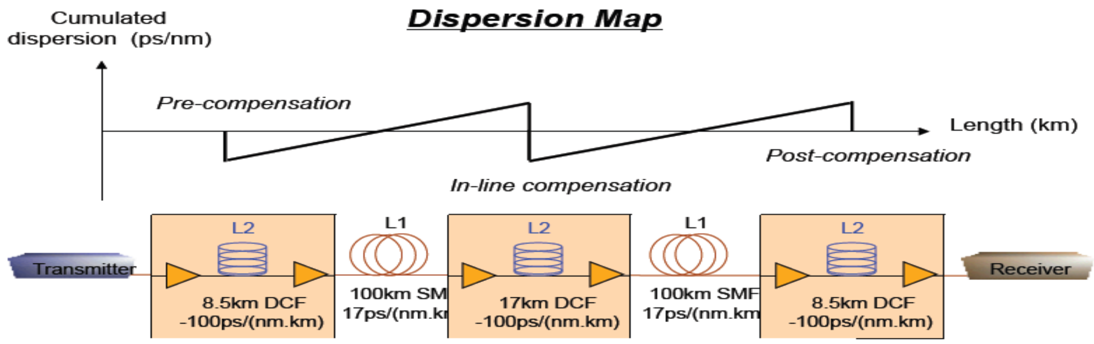


Figure 9. *Dispersion Compensation in an optical link.* [4]

Chromatic dispersion can be attributed to material dispersion and waveguide dispersion in a fibre. Material dispersion occurs because the refractive index of silica is frequency dependent and when considering different spectral components the refractive index can be assigned a group refractive index n_g. It is seen that the material dispersion D_M is dependent on how the group refractive index of the material changes for different spectral components or the slope of the refractive index over a certain window of wavelengths.

We have $D_M = c^{-1} (\frac{dng}{d\lambda})$ where c is the speed of light. Hence, it can be ascertained that

D_M=0 when $\frac{dng}{d\lambda}$ will be zero. This is called zero dispersion wavelength and it is around 1.276μm for silica. Now, waveguide dispersion is due to structural inaccuracies of the shape of the fibre and depends on fibre parameters such as radius of the core and the difference of refractive index between the core and cladding. Hence, it is possible to manufacture fibre such that the zero dispersion wavelength is shifted to the low loss operational wavelength like the 1.55μm. Such fibres are called dispersion shifted fibres .It is also a possibility to construct fibres which have zero dispersion over a band of operating frequencies, these fibres are known as dispersion flattened fibres. This is one way to overcome chromatic dispersion in systems, but there are limitations to use these fibres in long haul systems. Although such fibres provide low overall dispersion they are more susceptible to optical non-linear effects which will be discussed later [14].

Another way is to compensate the pulse broadening with pulse shrinking process. This is achieved using a optical fibre with dispersion value of opposite polarity than that of the single mode fibre used. Say the system under question is using a single mode fibre with positive dispersion value + D ps/nm.Km and the length of the fibre for which dispersion is to be compensated is L Km (this distance is limited by the bit rate the system operates on), then the total accumulated dispersion is going to be DL ps/nm. To compensate this, we choose a fibre with negative dispersion value say –D' and have the signal pass through it over a distance l' such that the product is equal in magnitude to DL, that is, D'l' = DL. To implement this concept over thousands of kilometers dispersion maps are made for careful and correct estimation. [16]

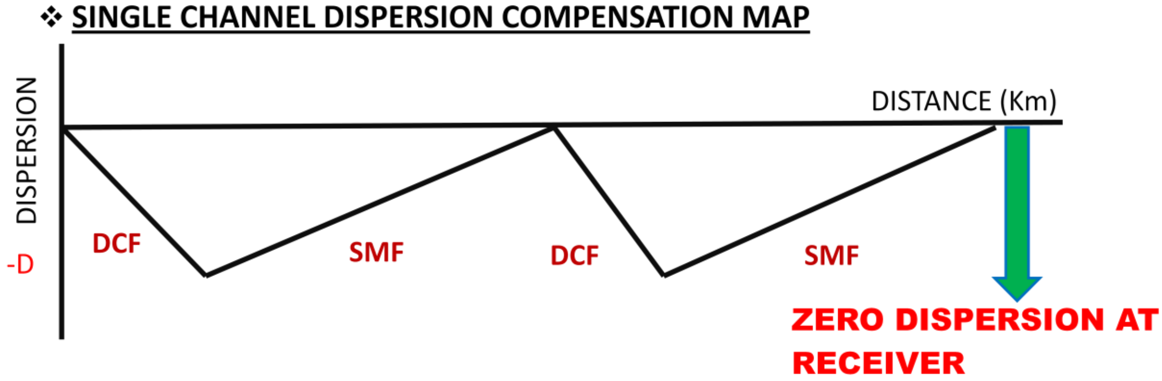


Figure 10. *Dispersion Map for Single Channel.*

Dispersion maps with alternate positive –negative dispersion fibres for compensation give very accurate results for a single channel with the achievement zero dispersion at the receiver end. Another use of dispersion maps is in multichannel systems where only the central frequency is able achieve zero dispersion [23]. This essentially means that only one optical channel can be completely compensated. A phenomenon of residual dispersion arises with the longer wavelengths showing a negative residual dispersion and the shorter wavelengths showing positive residual dispersion as shown below:

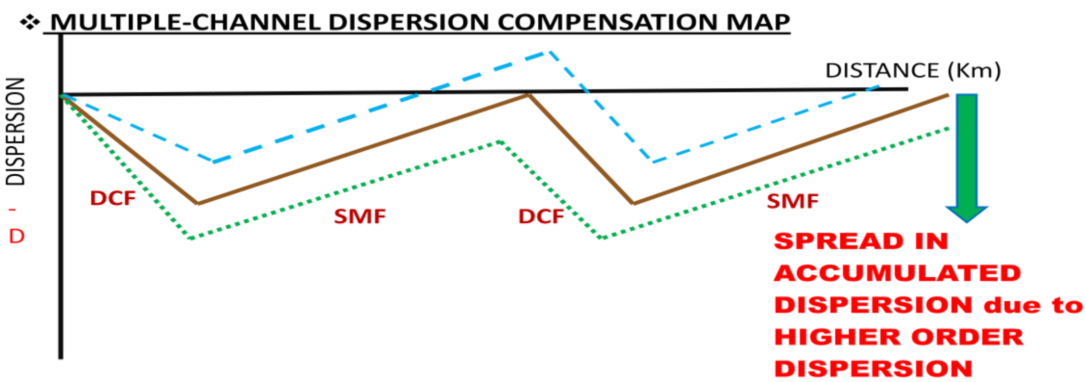


Figure11. *Dispersion Map for Multiple Channels.*

As can be seen in the figure above, a result of higher order dispersion is a spread in accumulated dispersion over multiple channels. The problem of residual dispersion can be eliminated with *fixed dispersion slope management.* Dispersion slope of a fibre refers to the change in dispersion values with wavelength. Dispersion slope management entails matching the dispersion slope of the compensating modules (here the dispersion compensation fibre) with the transmission fibre. Even this procedure does not completely eliminate the channel dispersion spread across wavelengths completely, however, it squashes together the dispersion compensation mapping diagrams together to show almost equal compensation for all channels propagating. Also, the aforementioned fixed dispersion slope management is not always the best solution for compensation of dispersion along in a network. Tuneable dispersion management is a better and more dynamic alternative with a number of factors supporting it – (a) Accurate level of channel dependent residual dispersion not be know and maybe susceptible to change with temperature etc. (b) In a full-fledged network different fibre types may be used according to requirements and exact matching of slopes may become difficult. (c) Slope values are seen to change in a reconfigurable network with distance. Hence, slope compensation is not a trivial issue, manufactures of dispersion compensation fibres have to ensure that the ratio of the fibre dispersion to the dispersion slope is equal to that of the transmission fibre. This ratio is used as a figure of merit (FOM) while designing any compensation plan[15][17].

4. OPTICAL NON LINEAR EFFECTS IN FIBRE

It is a well known fact that the influx of Erbium Doped Fibre Amplifiers (EDFAs) completely changed the scene of WDM systems. Regenerator spacings have started reaching a few thousand kilometres now. However, this has brought new problems to the surface namely optical fibre non-linearities. As mentioned before, most dielectrics respond to electromagnetic waves and if the medium is a non-linear function of an electric and magnetic field, non-linear phenomenon occurs. Optical fibre non-linearities are broadly classified as non-linearities due to stimulated scattering and non-linearities due to intensity dependent refractive index of fibre. Stimulated scattering effects are essentially inelastic scattering of photons in a medium which lead to unequal energy sharing between channels on a WDM system. The non-linear scattering effects are identified as the Stimulated Raman Scattering (SRS) effect and the Stimulated Brilluoin Scattering (SBS) effect. The second type of non-linear effects comes into play due to the non-linear dependence of refractive index of fibre on injected power. The refractive index(n) of silica fibre increases with optical power as follows:

$$n = n_0 + n_2 \frac{P}{A_{eff}}$$

Where n_0 is the linear refractive index at lower powers, P is the injected power, A_{eff} is the effective area of optical mode in fibre and n_2 is the non-linear coefficient which typically has a value of $2.6 \times 10^{-20} m^2 /W$ [18][19].

The non-linear behaviour of any wave propagating in a medium is given by the non-linear Schrodinger wave equation:

$$\frac{\partial u}{\partial z} + \frac{i}{2}\beta_2 \frac{\partial}{\partial t}\left(\frac{\partial u}{\partial t}\right) + \frac{\alpha}{2} u = i\gamma |u|^2 u$$

where

u: pulse amplitude; $|u|^2$: optical power

β_2 : chromatic dispersion of single mode fibre; α : fibre loss;

γ : fibre non-linear coefficient;

This equation describes the factors which interplay to give rise non-linearities in optical systems. What is most striking about this equation is that we can clearly see that non-linear intensity dependent distortion is a product of the interactions between non-linear refractive index response of fibre and the fibre chromatic dispersion. The extent of and the nature of such an interaction is hugely dependent on the magnitude and sign of the fibre chromatic dispersion. In fact dispersion plays a pivotal role in containing fibre non-linearities [14].

There are three major intensity dependent refractive index fibre non-linearities- self phase modulation, cross phase modulation and four wave mixing.

1) SELF PHASE MODULATION (SPM)

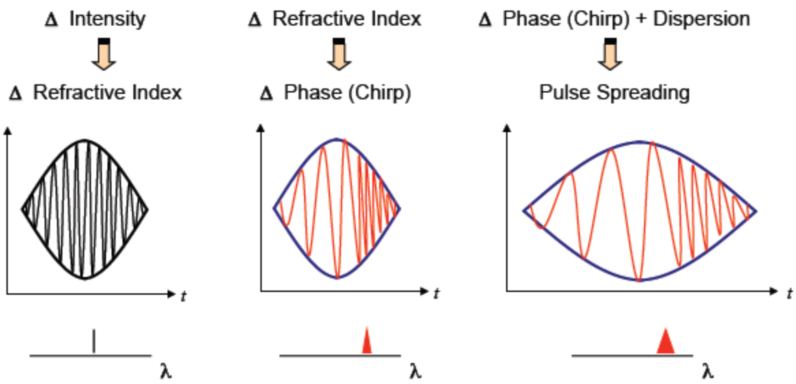


Figure12. *Self Phase Modulation.* [4]

The non-linear dependence of the refractive index leads to a phase change Φ in the propagating light pulse.

$$\Phi = \gamma P L_{eff} \quad \text{and} \quad \gamma = \frac{2\pi n_2}{\lambda A}$$

Even though the nonlinear coefficient n_2 is not a very big value ($2.6 \times 10^{-20} m^2 /W$), the use of powerful amplifiers like EDFA makes the lengths achieved and powers operated at have a significant effect on the role that the nonlinear coefficient plays in WDM systems. The non-linear behaviour of the refractive index makes the peak of a light pulse travel more slowly accumulating 'chirp' or phase shift along the way. The fore end of the pulse moves quickly and this called the 'red shift' while the rare end more slowly called the 'blue shift'. This broadens the pulse. Dispersion plays a role in reducing this effect. Positive dispersion or increasing group delay over distance will make the red shifted wavelengths travel more slowly and make the trailing edge , blue shifted, wavelengths move faster thereby narrowing the pulse and counteracting the effect of SPM [19].

2) <u>CROSS PHASE MODULATION (XPM)</u>

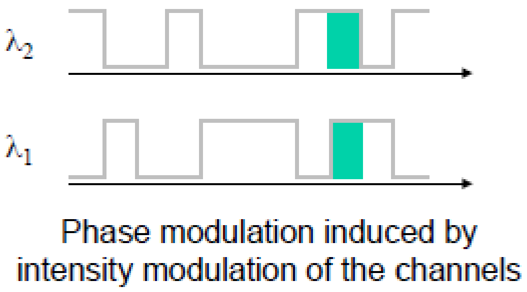


Figure13. *Cross Phase Modulation.* [4]

Cross phase modulation non-linearity arises when the phase of signal in one WDM channel is affected or changed by other intensity fluctuations in another channel. With respect to self phase modulation, this is a more damaging distortion and till date remains one of the major factors causing penalty in long haul systems. The mechanism with which this frequency chirp occurs is similar to that of self phase modulation with pulses being subjected to broadening because of the red shift and blue shift, however, it has a greater impact as there are many high intensity channels in a system and their collective effect on each other can be tremendous. Once again chromatic dispersion emerges as the only means to restrict this problem due to velocity mismatch [19].

3) <u>FOUR WAVE MIXING (FWM)</u>

Very high capacity systems over long distances with high bit channels and implementation of optical amplifiers give rise to a third order non-linearity of four photon mixing or four wave mixing. This non-linearity produces crosstalk in a system and degrades the system quality. The generation of new waves is similar to the intermodulation distortion encountered in electrical systems.[21] Essentially, if three components propagate together with frequencies f_i, f_j and f_k, then a third frequency f_{ijk} comes into being such that

$$f_{ijk} = f_i + f_j - f_k$$

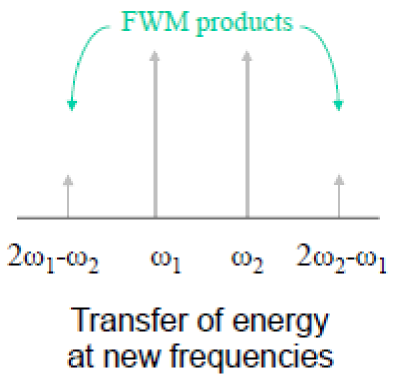


Figure14.*Four Wave Mixing Products.* [4]

If this new frequency resulting from interactions of the other frequencies falls close to or is exactly the same as a frequency operating in the WDM system will cause penalties which will make the interference noise (caused by this new wavelength) fall within the detection bandwidth of the receiver. There are a couple of techniques to mitigate this effect. One is to use fibre with high local dispersion and the other is to employ clever unequal channel spacing.This can be understood better by analysing the FWM efficiency equation:

Efficiency of FWM – $\eta = \left|\frac{1-\exp\left(-[\alpha+\Delta\beta]L\right.}{(\alpha+\Delta\beta)L}\right|^2$

Where α is fibre loss; $\Delta\beta$ is difference in propagation constant of waves

It can be inferred from the above equation that the FWM efficiency will be minimum when $\Delta\beta$ is maximum and phase matching between channels is low. This indicates towards having high positive dispersion in the fibre. Also, with unequal spacing between channels, no FWM waves will emerge at any channel frequencies and as a result of which crosstalk will be reduced in the system. All discussions above reiterate one thing – dispersion is a necessary evil for long haul propagation in a WDM system. It takes on the role of a rectification process for most intensity produced non-linearities. Keeping all factors in mind it is easy to come to a conclusion that for having long unregenerated transmission distances it is useful to design a system with high local dispersion and low average dispersion [19][22].

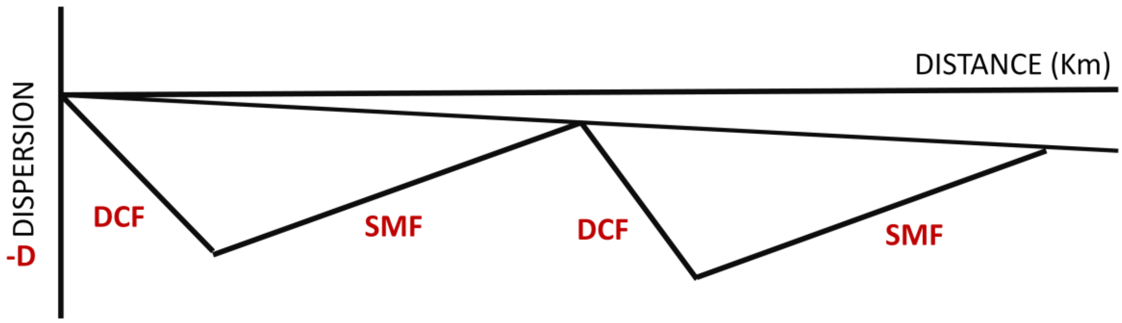


Figure15. *Dispersion map with high local dispersion and low average dispersion.*

5. SIMULATIONS AND RESULTS

As mentioned before, it was the influx of EDFA that made WDM systems extremely popular for commercial use. EDFA ensured proper power levels for long distance transmission. Now what is of interest is to ensure maximum spans at a good bit error rate without any regeneration of signal. This is possible by careful dispersion management and mitigation of nonlinear effects. The following simulations investigate these effects and their interplay further.

5.1 DISPERSION ANALYSES

INVESTIGATION : To visualise the time delay of a pulse in time domain after propagating through dispersive fibre and see what a dispersed pulse would appear to the receiver.

EXPERIMENT SETUP: One line from the transmitter goes directly to the channel analyser providing the original pulse while the other take the generic route through the dispersive fibre.

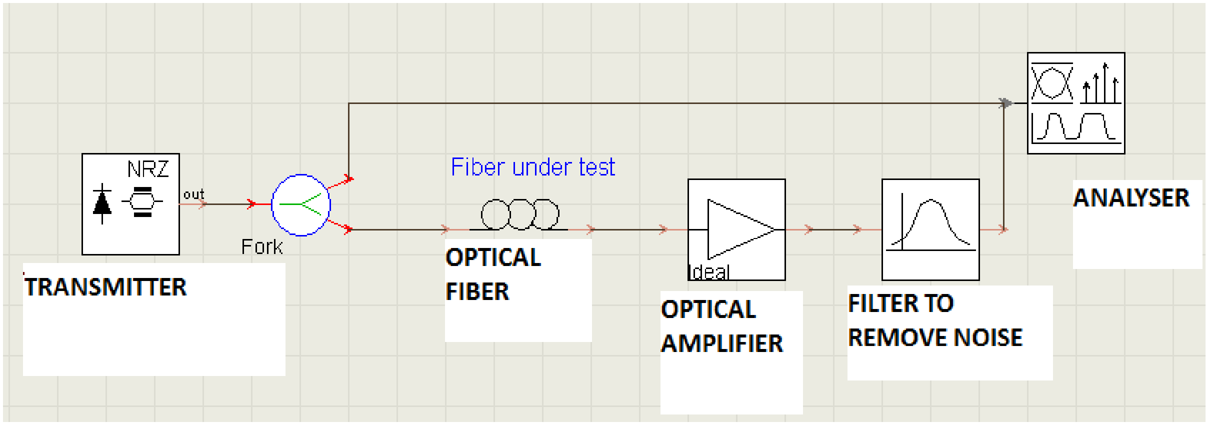


Figure 16. *Circuit for dispersion time delay analysis.*

RESULTS:

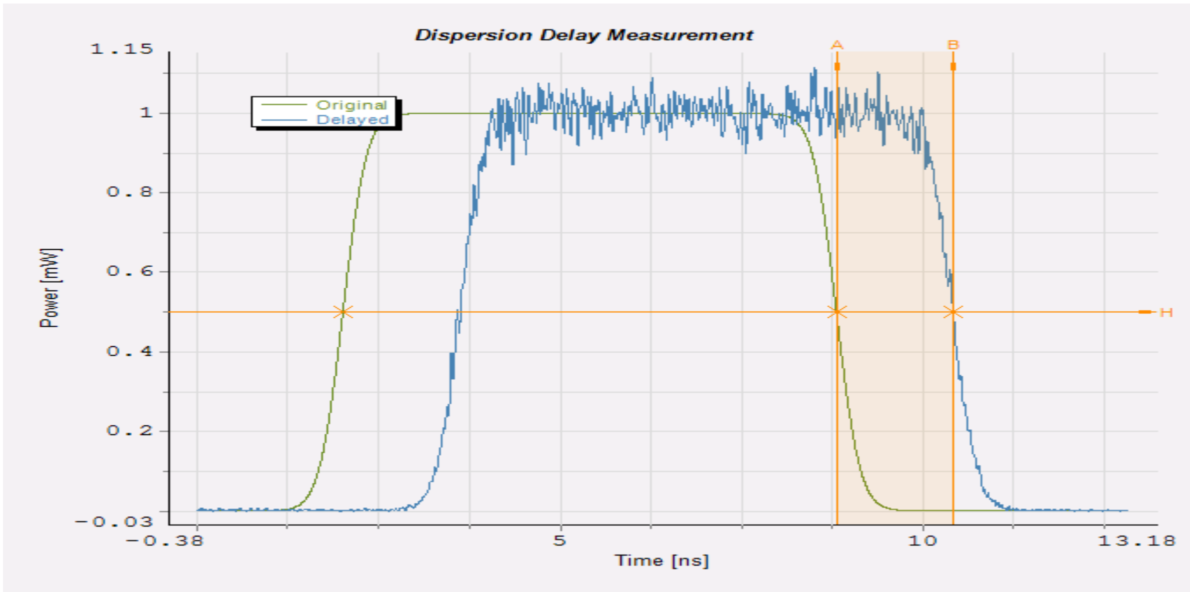
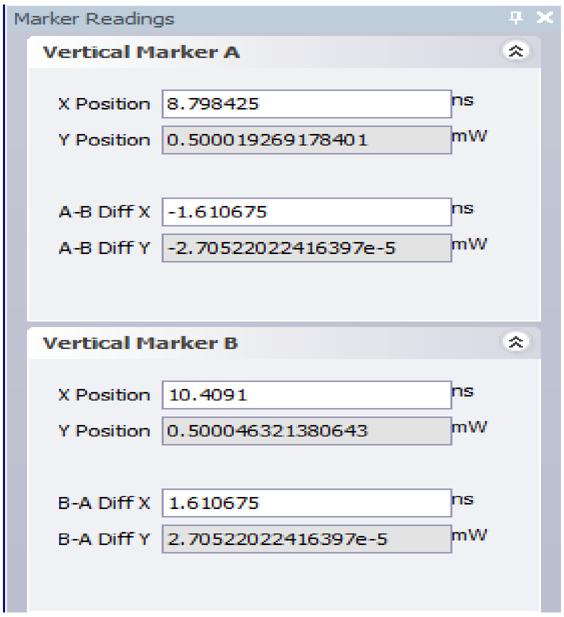


Figure 17. *The time delayed pulse due dispersion caused pulse broadening.*



The figure above shows the delay in time at which a pulse reaches the receiver after propagation through a dispersive fibre. The table below gives accurate values of the time delay, which for this particular fibre is 1.61ns.

Figure 18. *Tabular findings of the delayed pulse with the X and Y axis positions.*

5.2 DISPERSION COMPENSATION WITHOUT ATTENUATION

INVESTIGATION: The simulation experiment tries to delve into dispersion compensation techniques using DCF and SMF fibre spans alternately. Pre-compensation dispersion mapping has been used as a guide line in this compensation scheme. The motivation behind this experiment is to achieve maximum unregenerated distance at good BER levels like10^{-12}. Having no dispersion compensation would distort the signal and make detection at the receiver very inaccurate thereby lowering the bit error rate.

SETUP: The transmitter is transmitting at 10Gbps at a single wavelength of1550nm. The signal then enters a dispersion compensation fibre with dispersion value of -100ps/nm.km. The single mode fibre span has a dispersion value of 17ps/nm.km and is 60Km in length, which is the dispersion limited length for 10Gbps. For accurate dispersion management with net zero dispersion the dispersion-length product for the DCF and SMF spans should be equal. This gives a DCF span of10.2 Km .The receiver has a threshold of 1mW. In this setup we do not consider_fibre losses(signal attenuation). The non-linear index of fibre spans in this experiment is non zero.

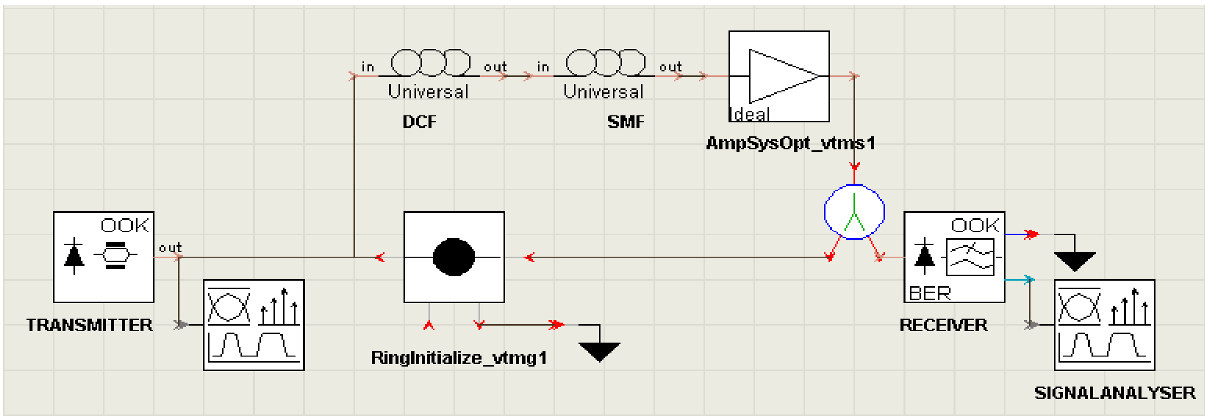


Figure 19: *Circuit for Dispersion Management.*

Also a comparison is made between NRZ and RZ modulation formats. The maximum achievable distance at a target bit error rate of 10^{-12} is compared.

RESULTS:

5.2.1 RESULTS WITH NRZ MODULATION FORMAT

Shown below are the visualisations for the transmitted NRZ signal's waveform and eye diagram as seen at the transmitter terminal.

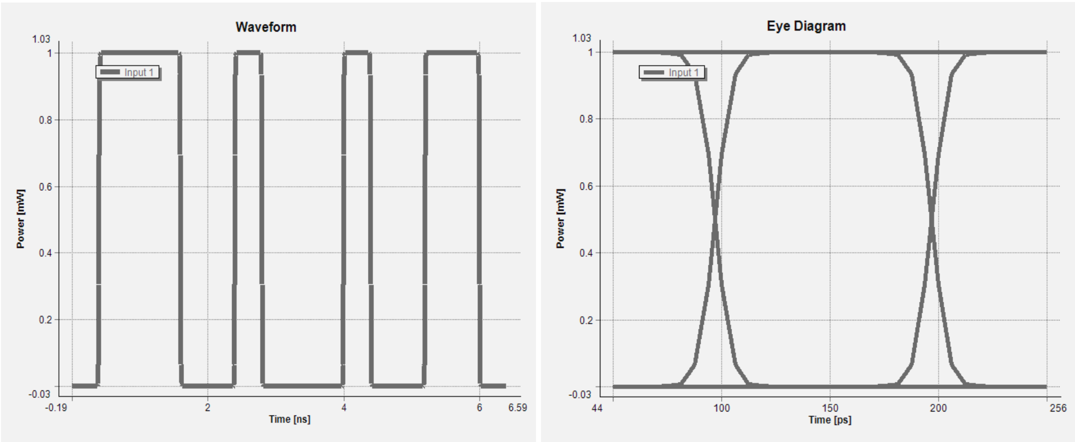


Figure 20. *Transmitted NRZ waveform (left) and eye diagram (right).*

The corresponding NRZ signal at the receiver has some distortion in the shape of the signal at the receiver end as is seen on the waveform on the left below. This distortion is attributed to the non zero non-linear index of the fibre spans. Also, the figure on the right below shows the eye diagram of the NRZ signal at a bit error rate of 10^{-12}. The distortion in shape in the waveform at the receiver can also be seen if the eye diagrams of the transmitted signal and the received signal are compared.

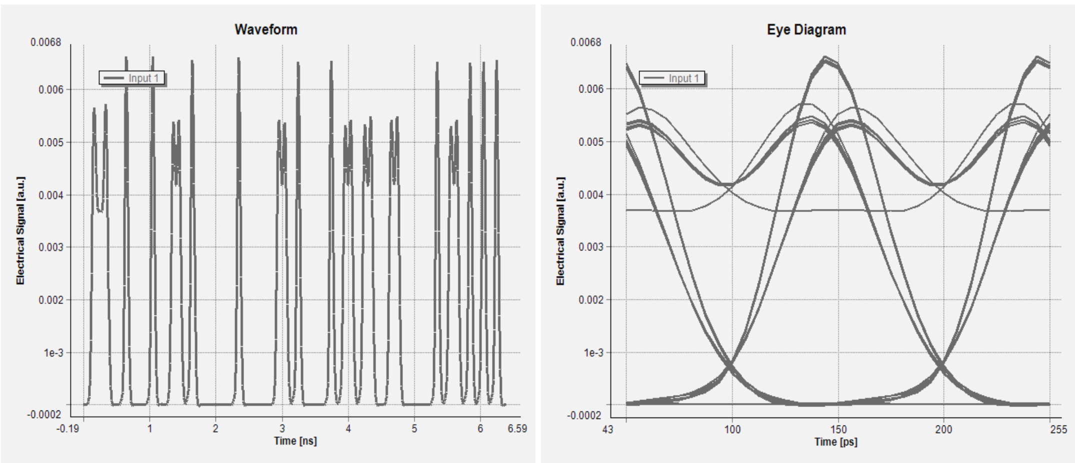


Figure 21. *Received NRZ waveform (left) and eye diagram (right).*

The maximum achievable distance with NRZ modulation format with non zero nonlinear index and no attenuation is 280 Km. The change of BER with distance is shown in the graph below:

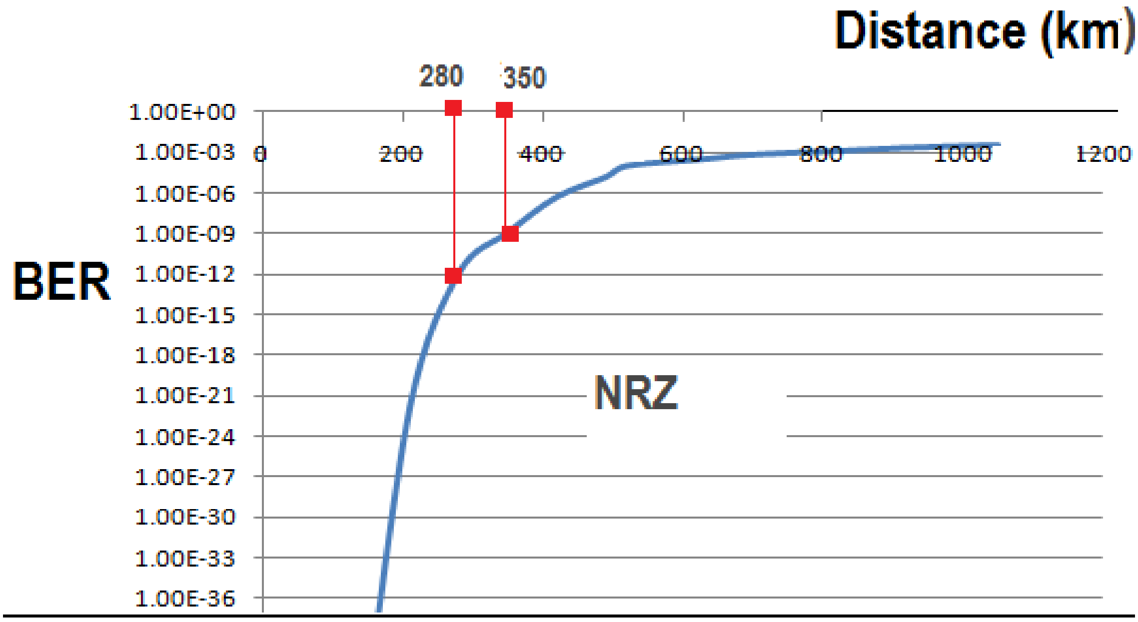


Figure 22. *BER vs transmitted distance for NRZ modulation.*

The relationship between the bit error rate and the distance covered is logarithmic and after reaching the critical distance which in this case is 280Km, the decay in the signal accuracy and performance with distance is rapid.

5.2.2 RESULTS WITH RZ MODULATION FORMAT

RZ modulated waveform is shown below, the narrow mark space ratio is apparent in the waveform when compared to the NRZ modulation shown previously.

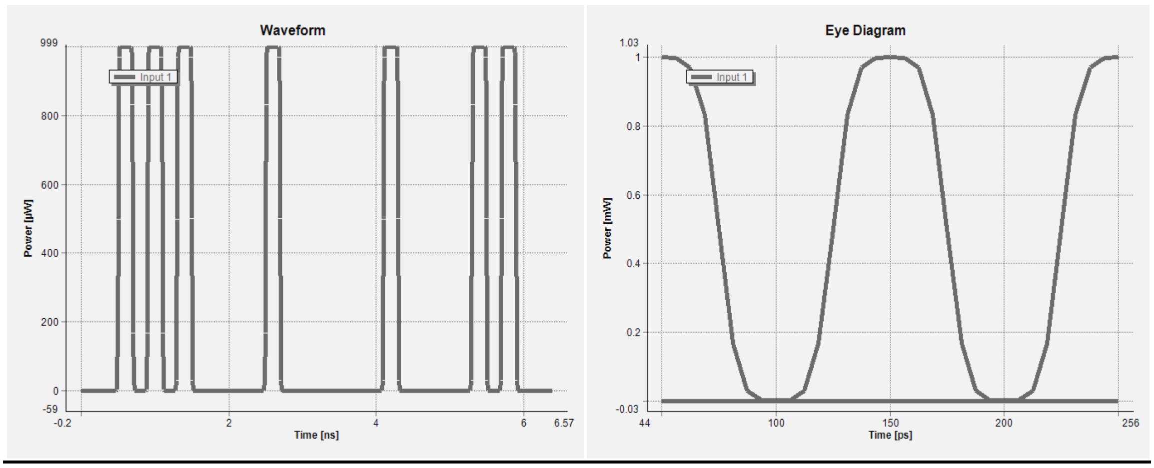


Figure 23. *Transmitted RZ waveform (left) and eye diagram (right).*

The detected signal at the receiver and its corresponding eye diagram are shown below. On careful analysis of the eye diagram, it can be seen that the shape of the signal is not as distorted as was in the case of the NRZ modulated pulse. We can draw an important conclusion from this that RZ modulation format is more resistant to non-linear distortion than NRZ format and hence would be better suited for long distance transmission. This is proven as well – the critical distance for a target BER of 10^{-12} in a RZ modulation format scheme is 700 Km as opposed to the 280 Km in the NRZ modulation scheme.

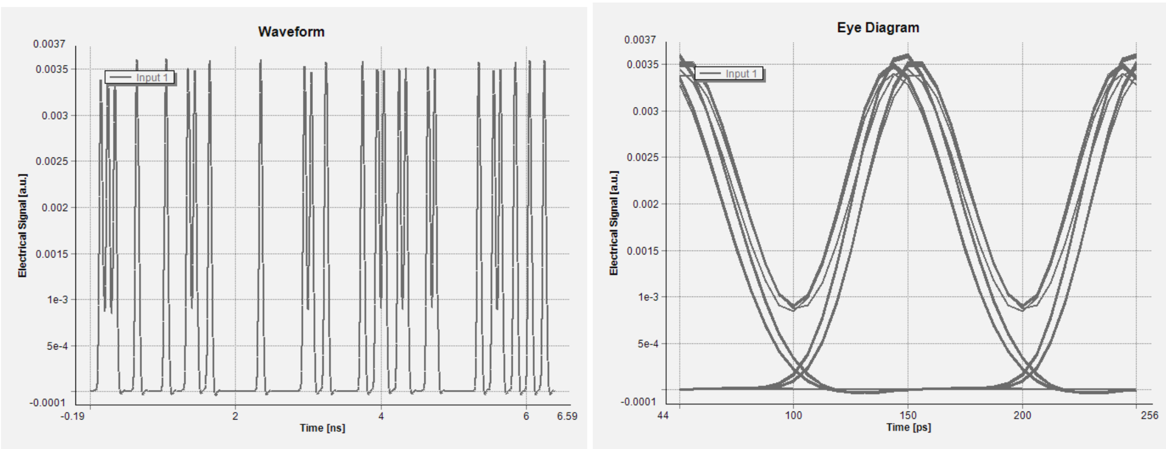


Figure 24. *Received RZ waveform (left) and eye diagram (right).*

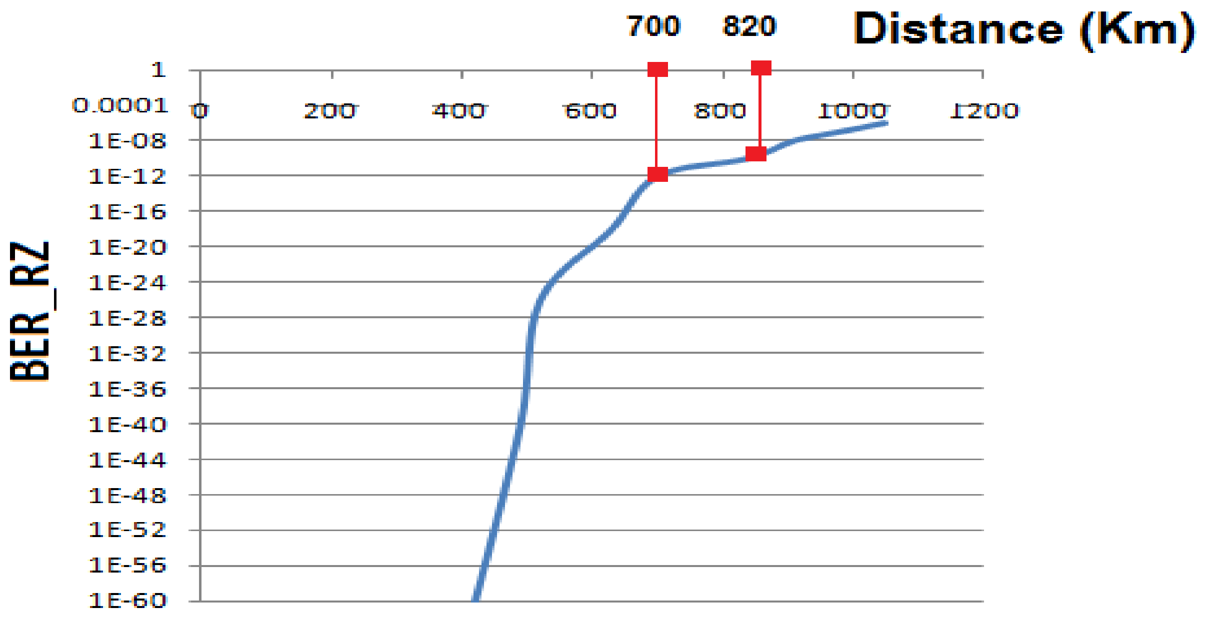


Figure 25. *BER vs transmitted distance for RZ modulation.*

5.2.3 ADDITION OF ATTENUATION

One of the main benefits of using a CAD software is that it enables the user to analyse different aspects of a system design separately. After analysis of each issue separately, one can club all design issues together and further analyse system performance. In the previous simulations , fibre losses in the DCF and SMF spans were ignored. This is not the case in a real world situation. Power budgeting is a very important issue, especially when dealing with fibre nonlinearities over large transmission distances. Now attenuation values are added in the both spans of the system , for the DCF span attenuation is 0.5dB/Km and the SMF span the attenuation value is 0.2dB/Km. Not surprisingly, signal is attenuated very fast and also by the data given in the graphs below , it can be seen that even modulation formats cannot do much to increase the transmission distance.

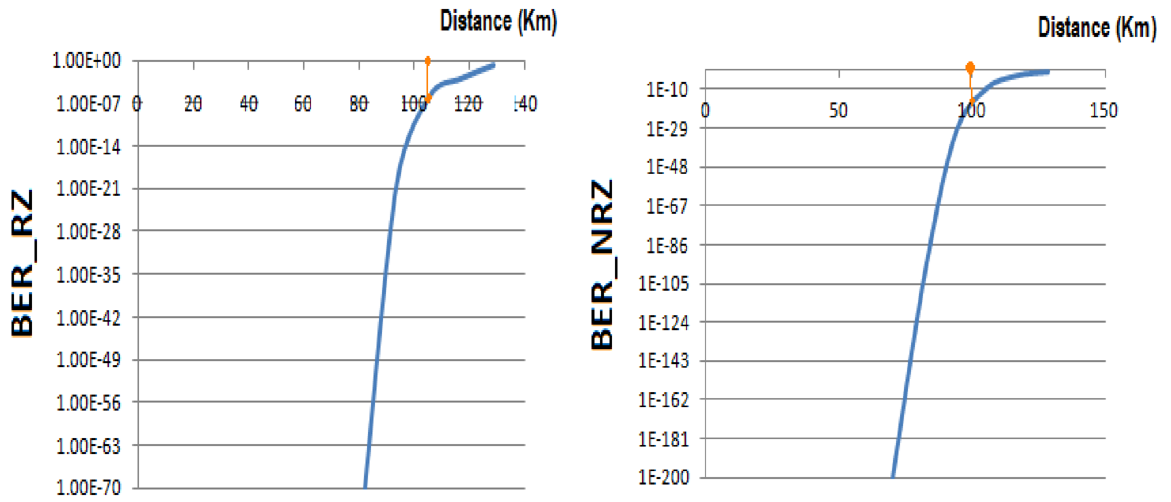


Figure 26. *Comparison between BER vs transmitted distance graphs for NRZ and RZ modulation formats.*

5.3 DISPERSION COMPENSATION WITH ATTENUATION MANAGEMENT

With the major drop in transmission distance while maintaining target BER of 10^{-12}, it is absolutely essential to compensate for fibre loss. For one collective span of DCF and SMF, the attenuation is seen to be of 17dB (0.5*10 + 0.2*60). The launch power into the circuit in DB is that of -24dB. An important point of consideration while employing the use of EDFA is that the signal cannot be amplified to any desired value because of the intensity dependent refractive index of the fibre which might trigger non-linear effects like intrachannel SPM, XPM and FWM. Moreover, amplifiers introduce ASE(Amplified Spontaneous Emission) noise into the system and at each amplification stage this noise value will also be amplifies along with the actual signal . This is highly undesirable as this leads to inaccurate detection at the receiver and degrades the BER and system performance on the whole. Hence it was seen that having amplifier gain of 15dB was the right trade off which would keep the OSNR levels sufficient high for proper detection at the receiver while also keeping non-linear effects in the channel at acceptable levels.

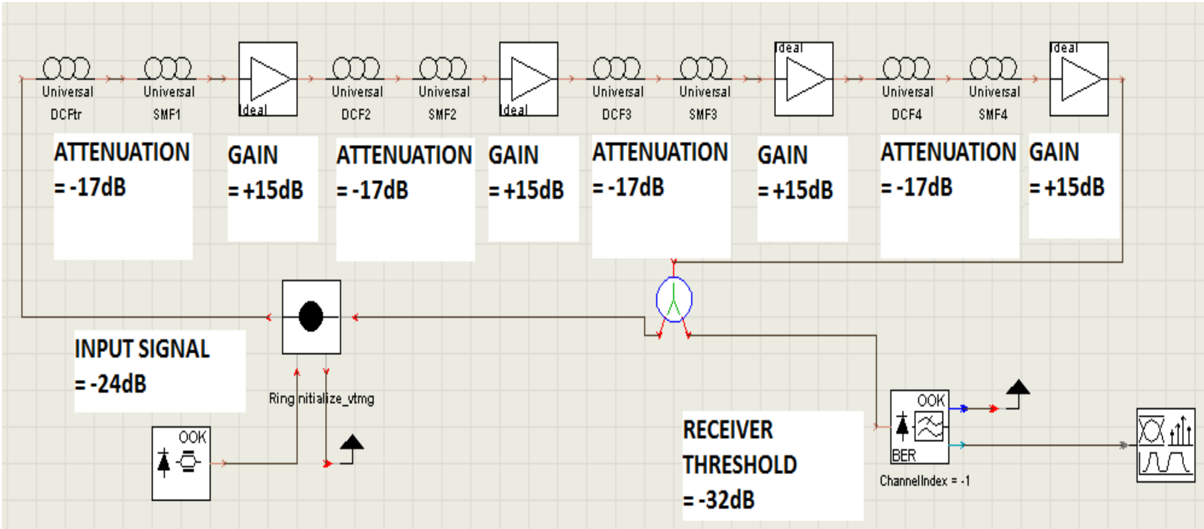


Figure 27. *Circuit for attenuation management with EDFA.*

The circuit above shows only four spans of such attenuation management. However, VPI simulation software provides a looping element where the simulation can be performed over many iterations. The graph of BER vs Distance below shows the results of simulations and it is seen that with this attenuation management scheme, amplified distances reach a maximum of 1600 Km roughly without any regeneration for both RZ and NRZ modulation formats. Again, it is noticeable that at smaller distances of a few hundred kilometres the performance of RZ modulation is better than NRZ modulation due to its better tolerance to non linear effects. This performance margin can be useful at later stages.

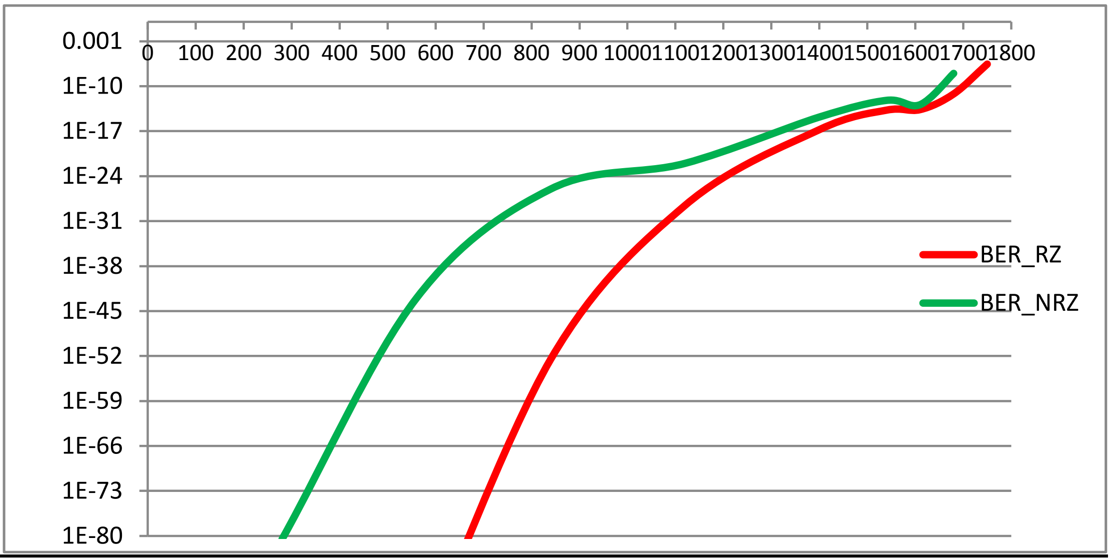


Figure 28. *BER vs transmitted distance for NRZ and RZ modulation formats for system with attenuation management.*

These results were for single channel propagation. It was important to do this analysis thoroughly to understand the dynamics that would come into play in a multichannel WDM system.

The next set of simulation results will look into the workings of a multichannel system with special emphasis on non-linear impairments and the role of dispersion in mitigating these effects over long distances.

5.4 MULTICHANNEL DISPERSION MANAGEMENT

In the following investigation, we analyse a system with eight channels at spacing of 50GHz with a central reference frequency at 193.1THz (1550nm). In the first setup, the channels transmitting at 10Gbps are multiplexed and passed through a single mode fibre with zero dispersion and analysed.

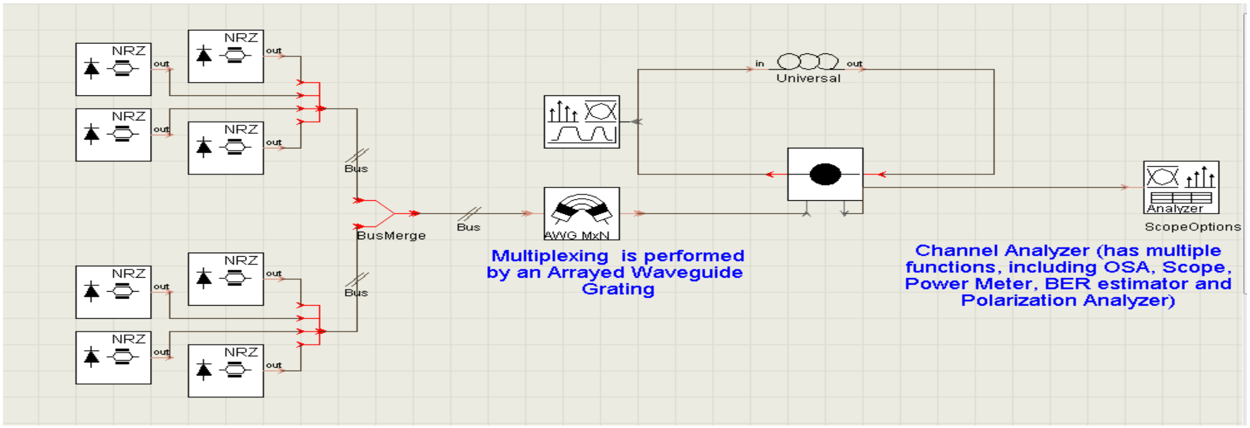


Figure 29. *8 channel WDM system.*

At the end of a few kilometers, we get the following spectral representation of the eight channels. The results of four wave mixing are very clear with reduced individual channel power and the emergence of sidebands. SPM and XPM are not that apparent, but if carefully analysed, pulse broadening of specific channels has led to a broadening of their individual frequency bands.

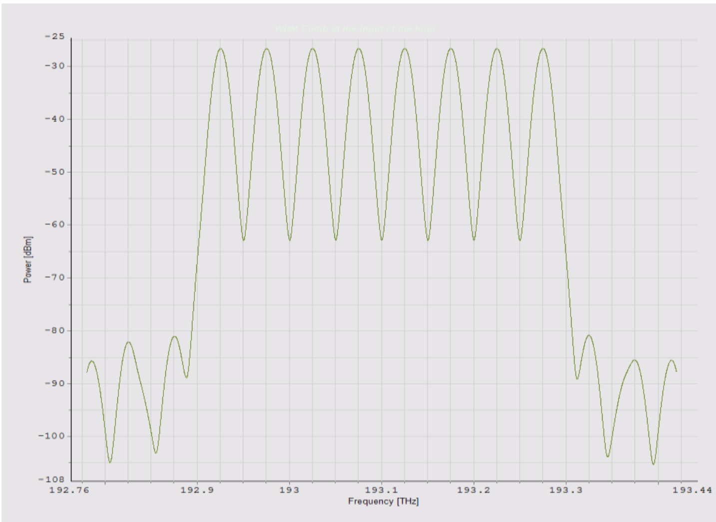


Figure 30. *Four Wave Mixing in 8 channel WDM system.*

If the transmission distance is increased further, the spectrum is further degraded as shown below with most of the channel energy lost to non-linear effects and creation of sidebands. The corresponding eye diagrams of individual channels also reflect this state and it is seen that if signals with eye diagrams with such level of interference are detected at the receiver, errors will be rampant.

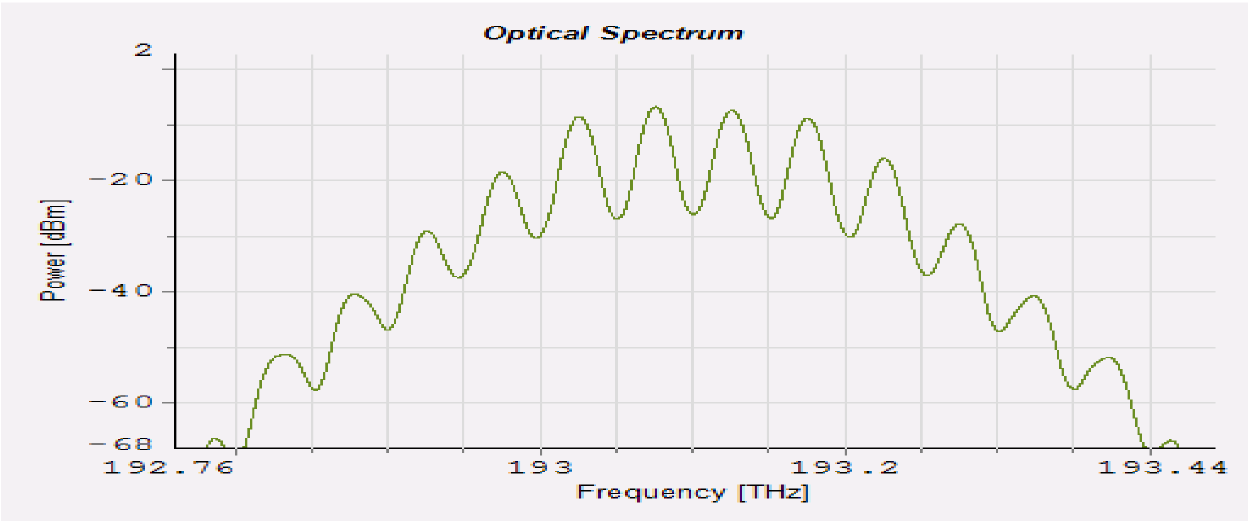
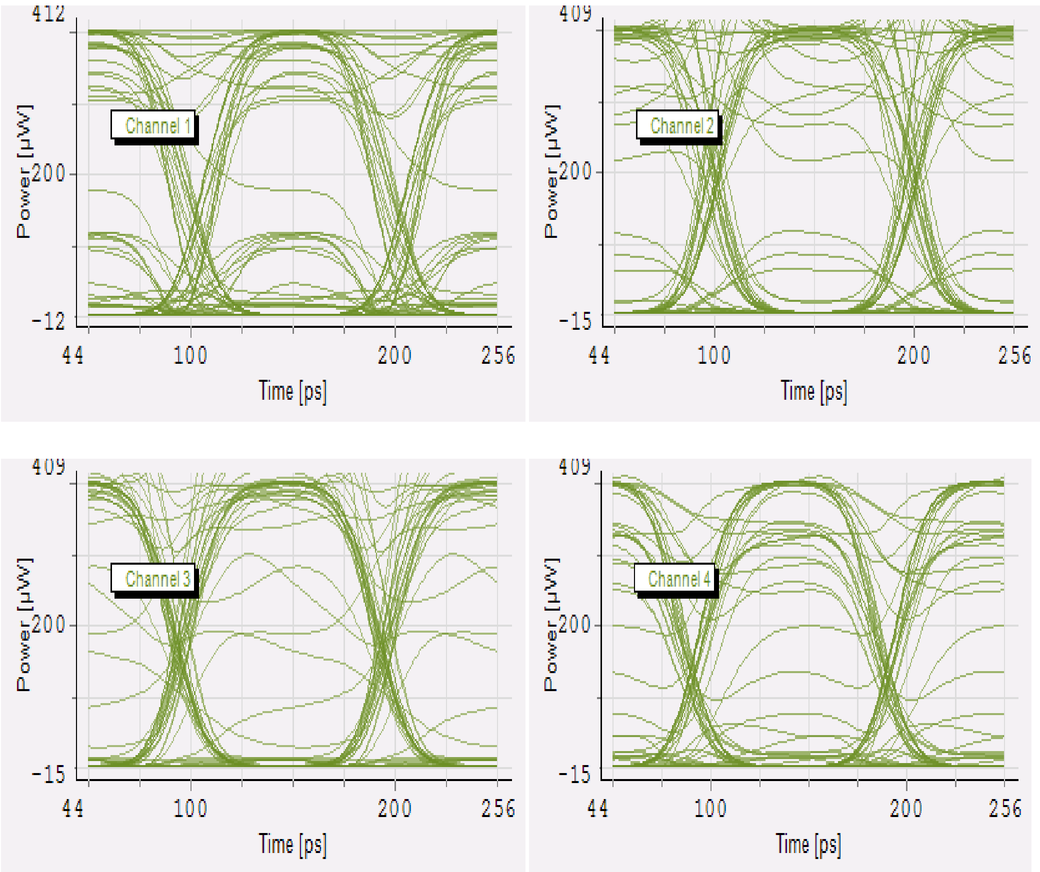


Figure 31. *(above)Complete distortion of 8 channel WDM system due to FWM generated waves, (below) Eye diagrams of first four channels of system showing eye closure due to interference by FWM generated waves.*



These are the eye diagrams of the signal with the first four channels at spacing of 50GHz. As is evident , there is a lot of interference by adjacent channels which may be linked with the non linear effects like XPM and SPM and also by the new channels formed because of four wave mixing.The growth of the four wave mixing product can be tracked over a certain distance. The graph below shows how the power of a signal lessens over distance as the different sidebands emerge and gain powerfrom the original signal.

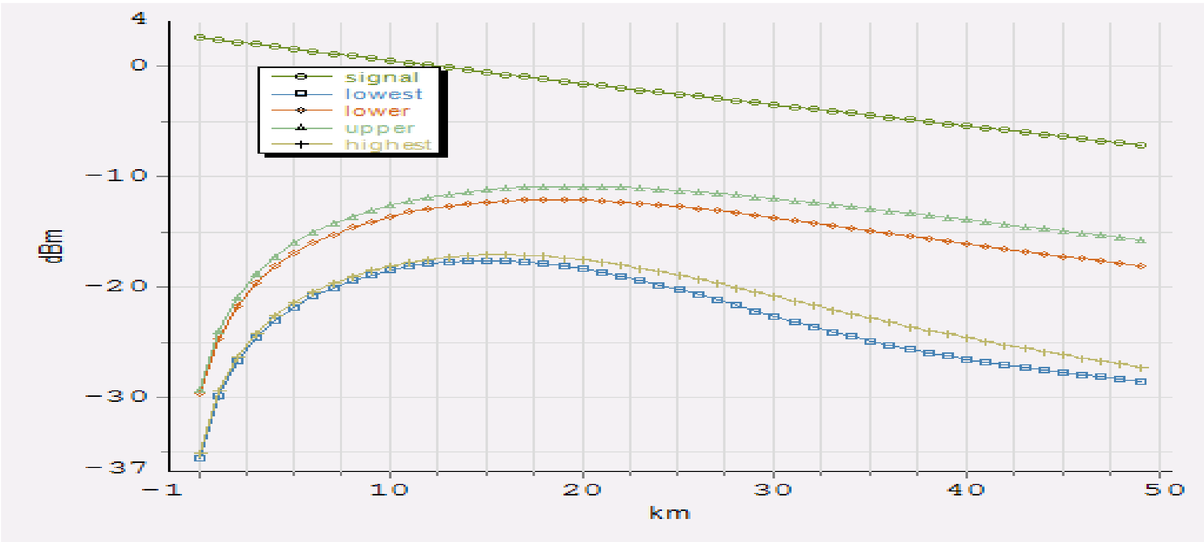


Figure 32. *Graph showing the increase in power of sidebands as FWM generated waves grow along transmitted distance, while the signal power is reduced due to distribution of energy from main signal to sidebands.*

Now to rectify these distortions, we introduce dispersion into the single mode fibre with its typical value of 17ps/nm.Km and also compensate this dispersion by using a black box mode for dispersion compensation which has the DCF and SMF spans along with amplifiers spaced every 80 Km.

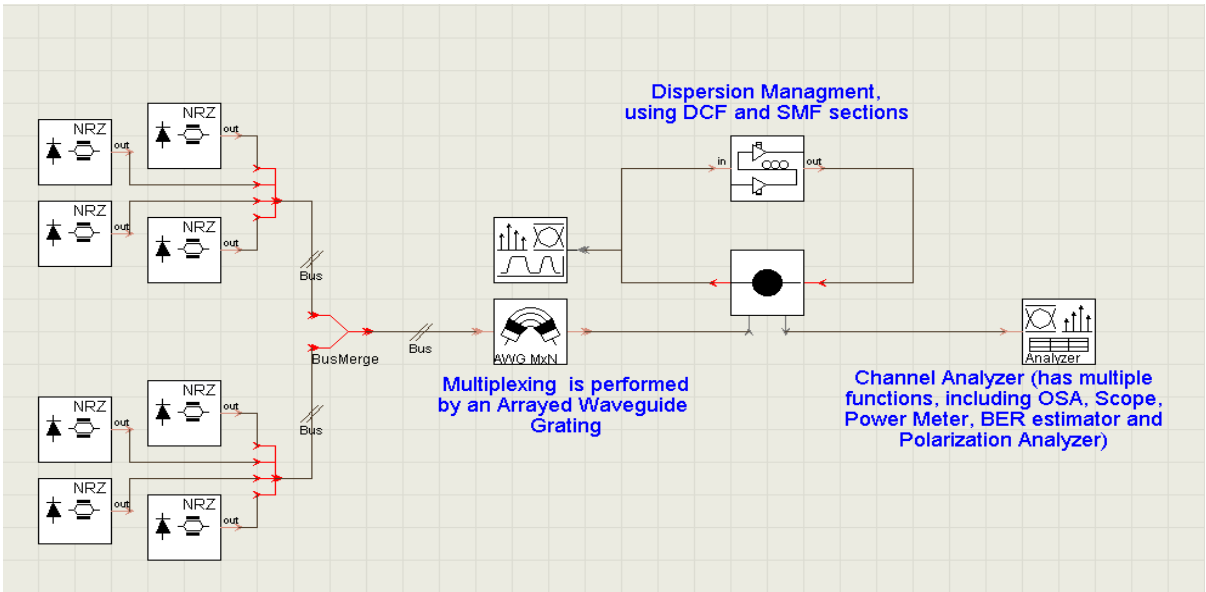


Figure 33. *8 channel system with dispersion compensation module.*

The results begotten by this process are as per what is written in theory and expected. The optical spectrum of the of the eight channels show the disappearance of the FWM produced side bands and also an increase in optical power of individual channels.

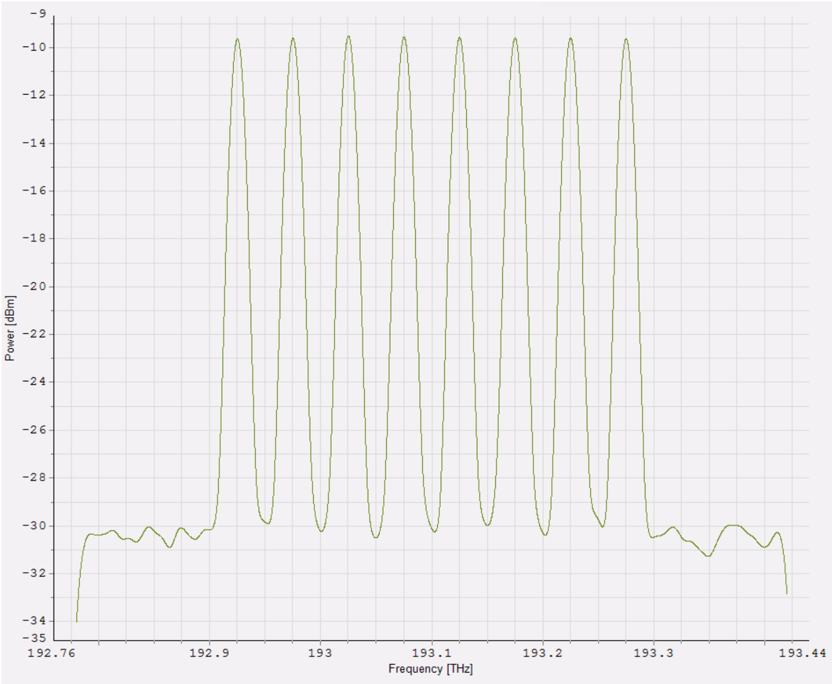


Figure 34. *Dispersion rectified signal-visible reduction in sidebands created by FWM.*

The accumulated chromatic dispersion (GVD:Group Velocity Dispersion) management is shown below and is in tandem with the dispersion scheme employed by the black box model used in the circuit diagram.

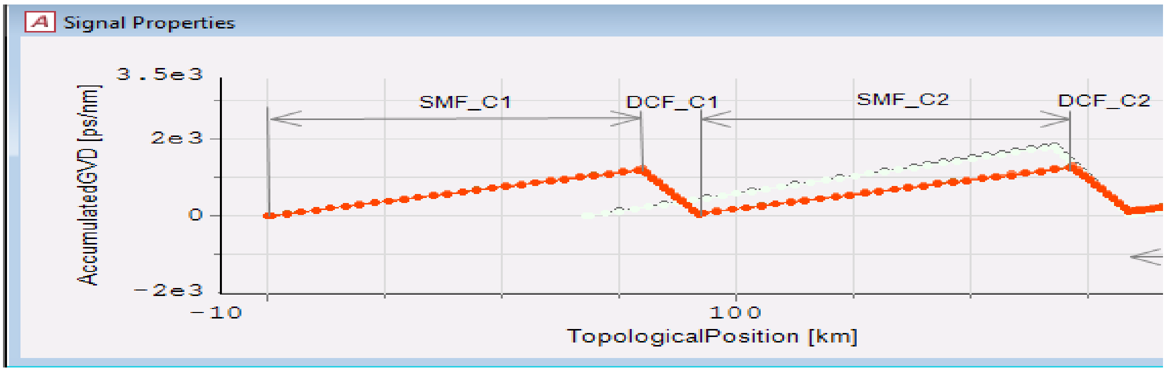


Figure 35. *Dispersion mapping of WDM system.*

The phase shift (increase in phase) caused by SPM is shown to be contained by dispersion over the same distance in the figure below:

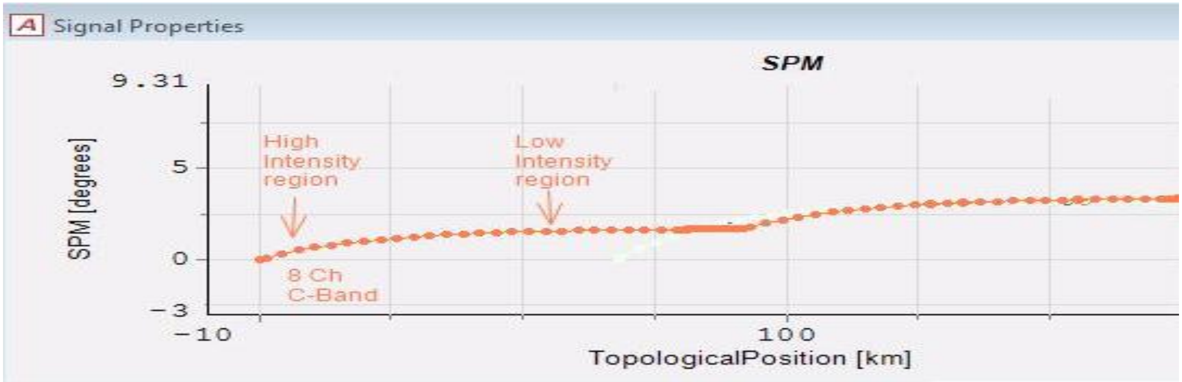


Figure 36*. Variation of SPM along transmitted distance.*

Also, OSNR values for a particular channel in the system are shown to indicate proper power /attenuation management in the 8 channel WDM system. It can be noticed that the power decrease gradient is more steep where we have the DCF span which has a higher attenuation value than the SMF span.

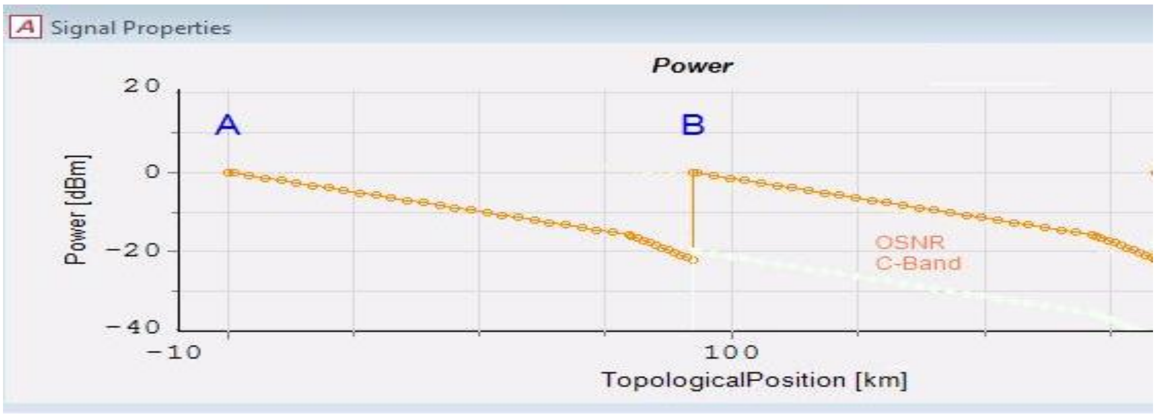


Figure 37*. OSNR along transmitted distance.*

6. CONCLUSIONS AND FUTURE RESEARCH

WDM systems promise a lot of capacity and have the potential to deliver on that account. From the perspective of having cost effective systems it is important that for long haul operation regenerator spacing are maximised. Regenerators essentially are optoelectronic devices which reconstruct a signal by converting from optical to electrical and back to optical domain. This is a costly mechanism and therefore efforts are made to increase signal quality and transmission distances. EDFAs are capable of having very high gain and have made it possible for signals to be amplified so that they can traverse large distances. Now what has to be tackled for error free accurate transmission are the optical impairments that the system suffers.

Pulse broadening due to dispersion of optical signals is a major impediment in long haul transmission. This undesirable problem leads to inter-symbol interference(ISI) which in turn makes the signal more prone to error thereby increasing the BER of the system. Other than that the phenomenon of optical non-linearities occurs which severely distorts the shape of the pulse. However, for signals transmitted over long distances these major impairments are seen to work together to nullify the other's effects.

The project investigations carried out have delved deep into issues regarding chromatic dispersion prevalent in single mode fibre and its very effective compensation with the use of alternating DCF and SMF spans. This investigation has yielded positive results in achieving good BER of magnitude 10^{-12} for distances as large as 1600Km. This result is comparable to what has been achieved in the real world scenarios as well. A comparison between modulation formats non return to zero NRZ and return to zero RZ has also been carried and it has been found that RZ is more robust to optical non-linearities and is better suited for long haul transmission in a WDM system. Second, the issue of power budgeting as been addressed and is of paramount importance because long haul systems have major intensity dependent impairments while at the same time it becomes necessary to have a good optical signal to noise ratio (OSNR value) for accurate detection at the receiver with respect to the threshold value of the photodiode in the receiver circuit. Lastly, optical non-linearities arising due to the non-linear response of the optical transmission medium which is the silica glass fibre have been investigated. The effects are called the Kerr Effects like SPM, XPM and FWM have been studied and efforts have been made to eliminate them. It has been found that having high local dispersion and low average dispersion help to contain non-linear behaviour, hence making dispersion a necessary evil for long haul operation in WDM networks. All these investigations and results facilitate the deployment of amplified unregenerated spans in capacity intensive WDM systems.

Further research in this field can be made in areas of modulation formats such as CRZ, DPSK and QPSK modulation formats and algorithms for forward error correction. This is because data encoding makes the signal operation more resilient to errors. Non-linear effects due to the stimulated scattering of light SRS and SBS and the ways to mitigate them by transmitting with unequal channel energies also need investigation Also, unequal gain spectrum of EDFA and its equalisation can be further investigated.

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