Abstract— Focus on development of broadband optical communication systems is incredible since it offers combination of wide bandwidth and low losses unmatched by any other transmission medium. One of the most important changes in fiber-optic communication systems brought about by EDFAs is the expansion of regenerator spacing up to transoceanic distances. However, a new problem has arisen, that is, the accumulation of fiber nonlinearities along the links with the increase in optical power levels. In optical communication systems, the input signal to the fiber is usually a composite optical signal modulated with information bit streams. When all the input signal frequencies interact due to fiber nonlinearities, the output bit stream may behave in a complicated way giving adverse effects on system performance. In wavelength-division-multiplexing (WDM) systems, interference due to fiber nonlinearities may limit the system performance significantly. While the other two conventional limiting factors in designing optical communication systems, namely, fiber loss and dispersion, are relatively well understood, and can be easily overcome by optical amplifiers and dispersion compensation, fiber nonlinearities have not been fully analyzed and understood despite a rich collection of literature dealing with fiber nonlinearities. Therefore, it is crucial to understand fiber nonlinearities and their effects on fiber-optic communication systems. The main motivation of this work was to study theoretical and simulation studies of broad band optical communication systems due to fiber nonlinearities. Here, we investigate power effects on simulation of optical communication systems with self phase modulation (SPM) and cross phase modulation(XPM). by using the parametric run feature in OptSim .By increasing the power, SPM grows and depletes the signal, and the measured power actually decreases with the increasing of the transmitted power. The eye diagram highlights the conversion due to the SPM and XPM. Specifically the eye opening decreases with increasing transmitted power.

Keywords—Eye diagram, Optsim , SPM, XPM, Kerr effect

I INTRODUCTION

Civilizations have advanced as people discovered new ways of exploiting various physical resources such as materials, forces and energies. In the twentieth century, information was added to the list when the invention of computers allowed complex information processing to be performed outside human brains. We are moving towards a society which requires that we have access to information at our finger tips when we need it, where we need it, and in whatever format we need it. The information is provided to us through our global mesh of communication networks, whose current implementations, e.g. today’s Internet; do not have the capacity to support the huge bandwidth demands. Fiber-optic technology can be considered as ideal choice for meeting our above needs because of its potentially limitless capabilities, like large information-carrying capacity, immunity to interference & crosstalk , small size & weight and potentially low cost. Nowadays, optical fiber is considered as a medium of transmission for future networks. In fiber-optic technology, wavelength-division multiplexing is being used, which multiplexes multiple optical carrier signals on a single optical fiber by using different wavelengths of laser light to carry different signals. It allows for multiplication in capacity, in addition to enabling bidirectional communication over optical fiber. The overall capacity of WDM transmission system is governed by available bandwidth and achievable spectral efficiency .Limits to the spectral efficiency is due to modulation, detection techniques and various non-linear impairments which arise due to Kerr effects. For long haul transmission with number of WDM channels, the accumulated nonlinear effects lead to waveform distortion and cross talk between channels[1]. “As fibers are not vacuum”, so impairments do arise due to high power,more wavelengths, faster rates and longer signals. Fiber impairments can be categorized into linear and nonlinear effects. Linear effects correspond to attenuation and dispersion (chromatic and polarization).With the advent of Erbium-doped fiber amplifiers (EDFAs), the attenuation limits on transmission distance have been overcome and also dispersion can be reduced using different dispersion-cancellation techniques. So we can say, that linear effects can be compensated but non-linear effects get accumulated. These effects arise as optical fiber data rates, transmission lengths, number of wavelengths, and optical power levels are increased Non linear effects correspond to scattering phenomenon and Optical Kerr effects. These nonlinearities have become critical issue in the advancement of optical communication systems and set an upper limit to the amount of information that can be transmitted in optical fiber[2].

II OPTICAL KERR EFFECT

The general equation for the refractive index of the core in an optical fiber is:

\[ n = n_0 + n_2 \cdot P/A_{eff} \]

where,\( n_0 \) = the refractive index of the fiber core at low optical power levels.

\( n_2 \) = the nonlinear refractive index coefficient
P = the optical power in Watts. 
\( A_{\text{eff}} = \) The effective fiber core area in square meters.

This equation shows that refractive index of the fiber has intensity dependent component and the index of refraction is related to the optical intensity by the non-linear coefficient \( n_2 \). Thus, the refractive index may exhibit non-linear behavior if the contribution of the \( n_2 \) term is large.

The nonlinear refractive index causes an induced phase shift that is proportional to the intensity of the pulse. The intensity dependence of the refractive index of a non-linear medium is manifested through phase modulation of the signal propagating through the media. The phase modulation occurs when the power across the pulse is non-uniform; as a result the various spectral components of the pulse experience different intensity, this in turn causes the refractive index, as determined by each component, to vary and consequently the components of the signal travel with different velocities. This mechanism of light propagation induces a non-linear phase shift across the pulse. The varying phase implies that the instantaneous optical frequency across the pulse differs from the central frequency. This frequency difference can be viewed as a frequency chirp. This implies that new frequency components are generated and as a result the optical spectrum of the pulse is broadened. The degree of broadening depends on a number of factors such as the length of the fiber, the fiber dispersion and the pulse shape. Depending on the shape of the input signal, the Kerr nonlinearities manifest itself by different effects such as Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM), and Four-Wave Mixing (FWM) [3]. These nonlinear effects are induced by high powers and long distances enabled by Erbium-doped fiber amplifiers (EDFA) at high bit rates. These lead to attenuation, distortion and cross channel interference. These limit the maximum power on any channel and also limit the maximum bit rate. In WDM system, the total optical power of carrier in the fiber is the sum of the optical intensity of each and every sub-carrier channels that have been multiplexed. Furthermore, in long haul transmission, EDFAs are used to amplify the signal to counteract the attenuation of the fiber, thus the contribution of the non-linear coefficient \( n_2 \) becomes significant. Therefore the non linearity effects are enhanced in the system [4].

Minimizing the amount of power \( P \), launched and maximizing the effective area of the fiber, \( A_{\text{eff}} \) can reduce the non-linearities produced by refractive index.

### III OVERVIEW OF SPM & XPM

Self-phase modulation (SPM) is a nonlinear optical effect of light-matter interaction. An ultra short pulse of light, when travelling in a medium, will induce a varying refractive index of the medium due to the optical Kerr effect [5]. This variation in refractive index will produce a phase shift in the pulse, leading to a change of the pulse's frequency spectrum. Self-phase modulation is an important effect in optical systems that use short, intense pulses of light. For an ultra short pulse with a Gaussian shape and constant phase, the intensity at time \( t \) is given by:

\[
I(t) = I_0 \exp \left( -\frac{t}{\tau} \right)
\]

Where, \( I_0 \) is the peak intensity, and \( \tau \) is half the pulse duration. If the pulse is travelling in a medium, the optical Kerr effect produces a refractive index change with intensity:

\[
n(I) = n_0 + n_2(I)
\]

Where \( n_0 \) is the linear refractive index and \( n_2 \) is the second-order nonlinear refractive index of the medium. As the pulse propagates, the intensity at any one point in the medium rises and then falls as the pulse goes past. This will produce a time-varying refractive index. This variation in refractive index produces a shift in the instantaneous phase of the pulse:

\[
\phi(t) = \omega_0 t - 2 \pi \int_{-\infty}^{t} n(\tau) \, d\tau
\]

Where \( \omega_0 \) and \( \lambda_0 \) are the carrier frequency and \( m \) wavelength of the pulse, and \( L \) is the distance the pulse has propagated. The phase shift results in a frequency shift of the pulse. The instantaneous frequency \( \phi(t) \) is given by:

\[
\phi(t) = \omega_0 + \phi(t)
\]

where \( \alpha(t) = \frac{d\phi}{dt} = 4 \pi L n_2 I_0 \)

Plotting \( \phi(t) \) shows the frequency shift of each part of the pulse. For the central portion of the pulse (between \( t = \pm \tau/2 \)), there is an approximately linear frequency shift (chirp). It is clear that the extra frequencies generated through SPM broaden the frequency spectrum of the pulse [6]. It is due to the power dependency of the refractive index of the fiber core. It interacts with the chromatic dispersion in the fiber to change the rate at which the pulse broadens as it travels down the fiber. As an optical pulse travels through the fiber, the leading edge of the pulse causes the refractive index of the fiber to rise, resulting in a blue shift. The falling edge of the pulse decreases the refractive index of the fiber causing a red shift. These red and blue shifts introduce a frequency chirp on each edge which interacts with the fiber's dispersion to broaden the...
pulse. Increasing fiber capacity demands require increasing WDM channel count and channel data rates. This can lead to decreased transmission performance in fiber because of nonlinear effects due to fiber propagation. One particular effect is known as cross phase modulation (XPM). As SPM refers to the phenomenon that occurs when a phase modulation occurs across a pulse due to its own intensity variations thus broadening the optical spectrum of the pulse[7]. XPM is also similar to SPM as it is also due to the nonlinear behavior of the refractive index on the optical intensity and it led to broadening of optical spectrum. However, in this case the total induced nonlinear phase shift on a given channel is due to the combined intensities or power variations of all transmitted channels, since the index of refraction of the fiber depends on the total optical power of all channels, which can result in cross talk among WDM channels. XPM is a nonlinear optical effect where one wavelength of light can affect the phase of another wavelength of light through the optical Kerr effect[8]. In XPM, two pulses travel down the fiber, each changing the refractive index as the optical power varies. If these two pulses happen to overlap, they will introduce distortion into the other pulses through XPM. Cross-phase modulation is used as a technique for adding information to a light stream by modifying the phase of a coherent optical beam with another beam through interactions in an appropriate non-linear medium. [9]

Cross-phase modulation can also be relevant under different circumstances:

- It leads to an interaction of laser pulses in a medium, which allows e.g. the measurement of the optical intensity of one pulse by monitoring a phase change of the other one (without absorbing any photons of the first beam). This is basis of a scheme for quantum non demolition (QND) measurements.
- The effect can also be used for synchronizing two mode-locked lasers using the same gain medium, in which the pulses overlap and experience cross-phase modulation.
- Cross-phase modulation is also sometimes mentioned as a mechanism for channel translation (wavelength conversion), but in this context the term typically refers to a kind of cross-phase modulation which is based on changes in the refractive index via the carrier density in a semiconductor optical amplifier[10].

IV SIMULATION SOFTWARE & SET UP

OptSim is an advanced optical communication system simulation package designed for professional engineering and cutting-edge research of WDM, DWDM, TDM, CATV, optical LAN, parallel optical bus, and other emerging optical systems in telecom, data comm, and other applications. It can be used to design optical communication systems and simulate them to determine their performance given various component parameters. OptSim is designed to combine the greatest accuracy and modeling power with ease of use on both Windows and UNIX platforms.

SIMULATION SET UP FOR SPM

Here, the transmitter section consists of data source, electrical driver, optical filter, laser source and amplitude modulator. The data source is in NRZ format at 10Gb/s bit rate. The electrical driver generates the desired data transmission format and converts the logical input, a binary sequence of zero and one into electrical signal. The single pole low pass filter is used as electrical filter. The output of the modulator is fed to the optical splitter through EDFA amplifier. One output of the optical splitter is given to optical fiber link, consisting of optical fiber and optical amplifier. The second output of the optical splitter is fed to optical spectrum analyzer and the optical power meter. Optical power meter evaluates the power, defined as the mean square value of an optical signal. The third output of the optical splitter is fed to the photo detector through optical filter. Photo-detector converts the optical signal into electrical signal. Output of the photo-detector is given to electrical filter and electrical splitter. It splits the input electrical signal into two parts. At the output of the electrical splitter is connected oscilloscope for electrical signal and Q estimator to measure the Q value. In this work a 10 Gb/s NRZ signal is sent over 2 fiber spans of 50 km each. Input power values have been varied from 10 to 17 dBm through the parametric run feature. The dispersion at the fiber input for each span has been set to 0.4ps/nm/km. EDFA noise has been turned off. By increasing the optical power, SPM grows and depletes the signal, therefore causing the measured power to decrease as the transmitted power increases.
In this set up, two WDM channels are launched over two DS fibre spans of 100 km, each. The transmitter section consists of data source, electrical driver, laser source and amplitude modulator. The data source is in NRZ format at 10 Gb/s bit rate. The electrical driver generates the desired data transmission format as it converts the logical input, a binary sequence of zero and one into electrical signal. CW-laser is considered as the light source. In the continuous wave (CW) mode of operation, the output of a laser is relatively constant with respect to time. The population inversion required for lasing is continually maintained by a steady pump source. Two WDM channels are considered. The lower power, probe channel is sent along the link together with the stronger power, pump channel. Both the probe and pump channels are modulated by digital NRZ signal at 10Gb/s. Optical modulators are used to convert electrical signals representing data or voice into modulated optical signals. An optical modulator may be used for generating the required optical power by changing optical parameters such as the transmission factor, refractive index, reflection factor, degree of deflection and coherency of light in the optical system according to the modulating signal. The dispersion parameter to each span is varied from 0 to 6 ps/nm/km, by using the parametric run feature in OptSim. EDFA noise has been turned off in order to simplify the analysis. The output from two channels is combined amplified and fed to the fiber spans each consisting of optical fiber, grating and pre-amplifier. Output is fed to the filter and the receiver through optical-splitter. Simulation results are seen by using spectrum analyser and oscilloscope displays.

### Table 4.2 : Parameter Table

<table>
<thead>
<tr>
<th>Name of component</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser</td>
<td>CW-lorentzian</td>
<td>Center frequency 1550nm,(193.4THz)</td>
</tr>
<tr>
<td>Amplitude modulator</td>
<td>Sine square</td>
<td>3db excess loss</td>
</tr>
<tr>
<td>Driver</td>
<td>NRZ</td>
<td>-2.5, +2.5 as levels</td>
</tr>
<tr>
<td>Electrical filter</td>
<td>PIN</td>
<td>Responsivity 875</td>
</tr>
<tr>
<td>Optical filter</td>
<td>Raised cosine type</td>
<td>-</td>
</tr>
<tr>
<td>Optical fiber</td>
<td>Two spans of 50 km each</td>
<td>Dispersion 0.4ps/nm/km</td>
</tr>
<tr>
<td>Preamplifier</td>
<td>Gain(dbm)</td>
<td>25 dbm</td>
</tr>
<tr>
<td></td>
<td>Dispersion(pm/nm/km)</td>
<td>Varied from 0 to 6 Ps/nm/km by parametric run feature in OptSim</td>
</tr>
<tr>
<td></td>
<td>Pump power(dbm)</td>
<td>10 dbm</td>
</tr>
<tr>
<td></td>
<td>Probe power(dbm)</td>
<td>-20 dbm</td>
</tr>
</tbody>
</table>

## V SIMULATION RESULTS

### SIMULATION RESULTS FOR SPM:

![Eye diagram for Run1 and Run2](image1.png)

![Eye diagram for Run3 and Run4](image2.png)

![Superimposition of all the signals](image3.png)
VI CONCLUSION

The behaviour of SPM versus the optical power for two spans amplified system has been investigated. A 10 Gb/s NRZ signal is launched over two DS fiber spans (D=0.4 ps/nm/km) of 50 km, each. The power at the input to each span is varied from 10 to 17.5 dbm by using the parametric run feature in OptSim. EDFA noise has been turned off in order to simplify the analysis of SPM. By increasing the power, SPM grows and depletes the signal, and the measured power actually decreases with the increase of the transmitted power. Specifically the eye opening decreases with increasing transmitted power. Cross-phase modulation (XPM) is a nonlinear optical effect where one wavelength of light can affect the phase of another wavelength of light through the optical Kerr effect. The behavior of XPM for two spans amplified system has been investigated. Two WDM channels are launched over two DS fiber spans of 100 km, each. The dispersion parameter to each span is varied from 0 to 6 ps/nm/km, by using the parametric run feature in OptSim. In order to focus on XPM, lower power probe channel is sent along the link together with the stronger power, pump channel. Both the probe and pump channels are modulated by digital NRZ signal at 10Gb/s. EDFA noise has been turned off in order to simplify the analysis. Impact of cross phase modulation (CPM) by varying the dispersion parameter can be seen by the results.

REFERENCES