CHAPTER 2

IMPACT OF FWM ON DWDM NETWORKS

2.1 INTRODUCTION

The performance of DWDM systems can be severely degraded by fiber non-linear effects. Among the consequences of fiber nonlinearity is the generation of optical inter modulation products, an effect commonly known as Four Wave Mixing (FWM) (Agarwal 2001). Unfortunately, these FWM products appear as crosstalk in the transmission bands of the DWDM tributaries, hence degrading the overall transmission performance of the system. The FWM efficiency at any particular wavelength is degraded by the chromatic dispersion of the fiber at that wavelength (Tkach et al 1995). Dispersion shifted fibers with the WDM signal placed near the zero dispersion wavelength are normally used to avoid signal distortion due to dispersion Agarwal (2001). Hence placing the signal wavelengths around the zero dispersion wavelength of the transmission fiber, the condition of phase-matching is nearly satisfied and the FWM efficiency gets improved. In the case of multi-channel systems the FWM generated also gets accumulated along the length of the fiber, (Lichtman 1991). Thus lower dispersion tends to enhance the FWM efficiency and hence a compromise has to be made in the fiber dispersion compensation, (Yu and Mahony 1995).
2.2 LIMITATIONS AND PERSPECTIVES OF FWM

FWM is the third order non-linear phenomenon by which two or more signals propagating simultaneously in a non-linear medium result in the generation of new signals at new wavelengths. The refractive index variation induces shifts in the phase of the signals and leads to the generation of up to \( N(N-1)^2 \) inter modulation products located at the frequencies \( f_{ijk} = f_i \pm f_j \pm f_k \), where \( N \) denotes the number of original signal wavelengths, (Agarwal 1995). This process is called Four Wave Mixing since four photons are involved in the interaction. If there are 2 co-propagating waves, then the number of side bands generated is \( 2(2 - 1)^2 = 2 \) and this is illustrated in the Figure 2.1, (Jose Ewerton et al 1997).

![Figure 2.1 Four wave mixing with two injected frequencies at \( f_1 \) and \( f_2 \)](image)

The FWM component centered at frequency \( f_{ijk} = f_i + f_j - f_k \) where \( i \neq j \neq k \), if lies within the receiver bandwidth of existing channels will cause unwanted interferences. When there are three co-propagating waves, the newly generated frequency component is \( f_4 = f_1 + f_2 - f_3 \), if these frequencies obey the relationship \( \omega_4 + \omega_3 = \omega_1 + \omega_2 \). Thus conservation of energy is satisfied, (Hill et al 1978). In this case, the number of new frequency components generated is \( 3 \ (3 - 1)^2 = 12 \).
Several methods have been proposed in the literature to reduce the FWM crosstalk penalties. In one approach, a de-multiplexer/multiplexer pair and fiber delay lines have been used to randomize the phase of the FWM products, thus increasing the phase mismatch among the various products and co-propagating DWDM tributaries (Inoue 1993). Alternatively, midway phase conjugation can be used to cancel out FWM products generated in either half of a fiber span (Watanabe and Chikama 1994). However, in both cases, the additional optical devices required to suppress FWM products leads to increased path loss and implementation costs. Since FWM penalties are closely related to fiber dispersion characteristics, optimum dispersion maps could be obtained by the alternative placement of fibers with different dispersion characteristics to serve as transmission and dispersion compensating fibers (Nakajima et al 1999) or by using novel optimized fiber designs (Eiselt 1999). These dispersion maps can however be tailored for best performance only in a limited part of the transmission window at any particular time. Chang et al 2000 analyzed the impact of FWM components due to the channels placed in the unequal spacing of the channels. Forghieri et al (1995) studied about the improvement in the system performance when the channels in the WDM systems are unequally spaced.

In WDM systems with equally spaced channels, the newly generated frequency components fall at the channel frequencies giving rise to high level of cross talk. For unequally spaced channel scheme, most of the newly generated frequency components will fall out of the channel frequencies (Nori Shibata et al 1987). Allocation of unequal spaced channel systems in WDM light wave systems has been studied by Kwong and Yong (1995) for suppressing the FWM effect. A Golomb ruler is a set of N integers such that no two distinct pairs of numbers from the set have the same difference Atkinson (1986). Thing et al (2004) introduced the fractional bandwidth allocation algorithm which allows allocating optimal channel
spacing with minimum FWM for eight channels (Thing et al 2003). Phase matching of FWM depends on the relative group velocities of the interacting signals which in turn is determined by the dispersion of the fiber and will be a function of the signal frequencies and their relative polarizations (Billington 1999). Dispersion management and the relationship between FWM suppression and Dispersion is very well discussed by Ekaterina et al (1998). Murakami et al 2002 discussed the impact of higher order dispersion management in the presence of FWM. The performance of the optical system can be improved if the channels are allocated around the zero dispersion wave length region (Suzuki et al 1999).

In this chapter, the Unequal Spacing Channel (USC) allocation using Optical Orthogonal Coding (OOC) technique and Genetic algorithm based channel allocation technique to reduce the FWM effect have been studied. The number of inter-modulation products falling on the desired channel for the equal and unequal channel spacing is analyzed. The performance of OOC based channel allocation towards reducing the effect of FWM is analyzed for SSMF, NZDSF and DSF fibers. Moreover, the impact of FWM in SSMF is also studied using a very basic experimental set-up and by simulations using the OPT Simulation package. To compute the error probability it is necessary to calculate probability density function of the received current where the sample space is the set of all possible bit patterns in all the channels.

2.3 GENETIC ALGORITHM BASED CHANNEL ALLOCATION

In this section, a Genetic Algorithm based WDM channel allocation is considered with the objective function of reducing FWM. The general steps involved in a GA based optimization are found in (Haupt 1995). In order to apply GA based approach in optimizing the WDM channel allocation
problem, the chromosomes are defined as an array of parameters to be optimized. Genes are the basic building block of Genetic algorithm. A gene is a binary encoding of a parameter. A chromosome is an array of genes. In our algorithm we predict large list of random chromosomes. The cost function of each is evaluated and ranked from the most to the least fit with respect to their cost function. Unacceptable chromosomes are discarded leaving a superior species - subset of the original list. Genes that survive become parent chromosomes and reproduce to offset the discarded chromosomes. Mutation introduces small random changes in a chromosome. Cost functions are evaluated for the mutated chromosome and the process is repeated.

The algorithm uses binary sequences called genes for channel allocation. Bit 1 corresponds to the allocation of a channel in that slot and 0 corresponds to the channel not being considered for allocation. In our case, the cost function is decided by the maximum FWM power falling on the in-band channels of the WDM system, considering the channel allocation as per the bit pattern of the corresponding chromosome.

The chromosomes are then ranked from best to worst in terms of minimizing the maximum FWM power and the ones giving lower value are preferred and others are discarded and then paired for mating and new offspring are formed by pair-swapping genetic material. The stopping criterion is fixed as the maximum average FWM power level acceptable in the system. The flow chart for the genetic algorithm is shown in Figure 2.2. The parameters used in the simulation are tabulated in Table 2.1.
Table 2.1 Parameters used in the simulation

<table>
<thead>
<tr>
<th>S.No</th>
<th>Parameter</th>
<th>Unit</th>
<th>SMF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Attenuation coefficient (α)</td>
<td>dB/km</td>
<td>0.2</td>
</tr>
<tr>
<td>2.</td>
<td>Chromatic Dispersion (D_c)</td>
<td>ps/nm km</td>
<td>16</td>
</tr>
<tr>
<td>3.</td>
<td>Dispersion slope</td>
<td>s/m²</td>
<td>80</td>
</tr>
<tr>
<td>4.</td>
<td>Nonlinearity coefficient (γ)</td>
<td>1/W km</td>
<td>1.3</td>
</tr>
<tr>
<td>5</td>
<td>Effective core area (A_{eff})</td>
<td>µm²</td>
<td>80</td>
</tr>
</tbody>
</table>

Figure 2.2 Flow chart of the genetic algorithm

The 16 channels selected out of 40 available channels for allocation as a result of the above optimization is given by their channel numbers as, {1, 2, 4, 6, 10, 12, 14, 17, 20, 22, 27, 29, 30, 37, 38, 40}, (Ramprasad and Meenakshi 2007).
2.4 OPTICAL ORTHOGONAL CODES BASED CHANNEL ALLOCATION

An Optical Orthogonal Code (OOC) is a family of (0, 1) sequences with good auto- and cross-correlation properties (Chung et al 1989) i.e., the autocorrelation of each sequence exhibits the “thumbtack” shape and the cross correlation between any two sequences remains low throughout. Its study has been motivated by its application in code division multiple-access scheme in a fiber optical channel (kitayama et al 1999). The efficiency of four wave mixing depends on fiber dispersion and channel spacing, (Ekaterina et al 1998). In a Unequal spacing channel USC scheme the signal waves and newly generated waves have different wavelengths. Since the dispersion varies with wavelength, the group velocities of the signal waves and generated waves are different. This destroys the phase matching of the interacting waves and lowers the efficiency with which power is transferred to newly generated frequencies.

2.4.1 Illustration of a 16 Channel Assignment

A 16 channel intensity modulated direct detection DWDM system spanning \( f_1 - f_{16} \) is considered. The bit rate per channel is set at 40 Gbits/s. The minimum channel spacing of 0.02 THz is selected for ESC and 0.02 THz for USC. Table 2.2 illustrates Equal and Unequal channel frequency allocations for a 16 channel DWDM system (Ramprasad and Meenakshi (2006). The band width expansion factor is approximately equal to 2.
Table 2.2 Unequal and Equal channel frequency allocations for a 16 channel DWDM system

<table>
<thead>
<tr>
<th>Channel Number</th>
<th>Equal spacing in (THZ)</th>
<th>Unequal spacing in (THZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>192.95</td>
<td>192.5</td>
</tr>
<tr>
<td>02</td>
<td>193</td>
<td>193</td>
</tr>
<tr>
<td>03</td>
<td>193.05</td>
<td>193.052</td>
</tr>
<tr>
<td>04</td>
<td>193.1</td>
<td>193.1075</td>
</tr>
<tr>
<td>05</td>
<td>193.15</td>
<td>193.165</td>
</tr>
<tr>
<td>06</td>
<td>193.2</td>
<td>193.2675</td>
</tr>
<tr>
<td>07</td>
<td>193.25</td>
<td>193.2875</td>
</tr>
<tr>
<td>08</td>
<td>193.3</td>
<td>193.9975</td>
</tr>
<tr>
<td>09</td>
<td>193.35</td>
<td>193.42</td>
</tr>
<tr>
<td>10</td>
<td>193.4</td>
<td>193.49</td>
</tr>
<tr>
<td>11</td>
<td>193.45</td>
<td>193.565</td>
</tr>
<tr>
<td>12</td>
<td>193.5</td>
<td>193.637</td>
</tr>
<tr>
<td>13</td>
<td>193.55</td>
<td>193.717</td>
</tr>
<tr>
<td>14</td>
<td>193.6</td>
<td>193.805</td>
</tr>
<tr>
<td>15</td>
<td>193.65</td>
<td>193.887</td>
</tr>
<tr>
<td>16</td>
<td>193.7</td>
<td>193.997</td>
</tr>
</tbody>
</table>

2.5 STUDY OF FWM CROSS TALK

2.5.1 FWM Power Estimation

The FWM power $P_{ijk}$, generated by three continuous-wave channels of input powers $P_i$, $P_j$, $P_k$ at frequencies $f_i$, $f_j$, $f_k$, at the output of a fiber with attenuation $\alpha$ and length $z$, is given by (Antonella Bogoni and Luca Potti 2004),

$$P_{ijk} = d_{ijk} \gamma^2 L_{eff} P_i P_j P_k e^{-\alpha z}.$$  \hspace{1cm} (2.1)
where $d_{ijk}$ is the degeneracy factor, taking a value of one or two for degenerate ($i = j$) and non-degenerate ($i \neq j$) terms, respectively; $L_{\text{eff}}$ the effective length; $\gamma$ the nonlinear coefficient; and $\eta_{ijk}$ the efficiency.

\[
\gamma = \left( \frac{2\pi n_2}{A_{\text{eff}} \lambda_0^2} \right)^2
\]  

(2.2)

where $n_2$ is the fiber nonlinearity index, $\lambda_0$ the comb central wavelength and $A_{\text{eff}}$ the effective core area. $\Delta \beta_{ijk}$ represents the phase matching coefficient. The efficiency $\eta_{ijk}$ and the phase matching coefficient are approximated, for long enough fiber spans as,

\[
\eta_{ijk} = \frac{\alpha^2}{\alpha^2 + \Delta \beta_{ijk}}
\]  

(2.3)

\[
\Delta \beta_{ijk} = \frac{2\pi c}{\lambda_0^2} D_c \Delta \lambda_{ik} \Delta \lambda_{jk}
\]  

(2.4)

where $\Delta_{ik}$ and $\Delta_{jk}$ are the wavelength spacing between channels $i$ and $k$, and $j$ and $k$, respectively. This approximation is valid for the SMF and NZDSF fibers in the C-band. In the case of channels arranged on an equally spaced grid, as the ITU grid, $\Delta \beta_{ijk}$ takes the discrete values,

\[
\Delta \beta_n = n \left( \frac{2\pi c}{\lambda_0^2} \right) D_c \Delta \lambda^2
\]  

(2.5)

and hence the efficiency becomes,

\[
\eta_n = \eta \left( \Delta \beta_n \right),
\]  

(2.6)
where \( n = |i-k| |j-k| \) is the efficiency order, \( \Delta \lambda \) is the selected ITU grid resolution, typically being a multiple of 0.2 nm and \( \eta \) is the efficiency of individual channel.

The number of crosstalk components falling on the desired channels and the overall number of inter modulation products generated due to FWM for an Equal spacing channel (ESC) scheme are shown in Figures 2.3 and 2.4. Figure 2.4 shows that there are nearly 3500 inter modulation frequency components falling on the channel frequency \( 1.942 \times 10^{14} \) Hz, however this is not an allotted channel frequency. Figures 2.5 and 2.6 show the corresponding results for the USC scheme based on OOCs. It is noted from the figures that though a large number of inter modulation components are generated, none of them actually fall on the desired channel frequency. This implies that though FWM is not eliminated it's impact on the desired channels has been removed by the use of OOC based USC scheme. The total bandwidth occupation for ESC is given by \( B_{\text{ESC}} = (n-1) \times \text{channel spacing} = 15 \times 50 \text{ GHz} = 0.75 \text{ THz} \), where \( n \) is the number of channels, 16 in this case. The corresponding bandwidth occupation for USC is \( B_{\text{USC}} = (193.9975-192.5) \text{ THz} = 1.4975 \text{ THz} \). The bandwidth expansion factor \( B_{\text{USC}} / B_{\text{ESC}} = 1.4975 / 0.75 \sim 2 \).

The 16 channels selected out of 40 available wavelengths for allocation as a result of optimization using genetic algorithm is given by their channel numbers as, \{1, 2, 4, 6, 10, 12, 14, 17, 20, 22, 27, 29, 30, 37, 38, 40\}. The corresponding FWM power obtained are shown in Figure 2.7. It is observed from the figure that after optimization and channel allocation, maximum FWM power is occurring at the 8th and the 9th channels, it’s strength being -6 dBm. However from Figure 2.5 it is noted that the number of FWM components falling on the desired channels is zero for OOC based allocation and hence the FWM power on desired channels is zero. Thus the impact of FWM crosstalk power on desired channels in a DWDM optical
system is found to be less when the channel spacing is unequally allotted based on Optical Orthogonal Coding technique as compared to the Genetic algorithm technique, (Ramprasad and Meenakshi 2007).

Figure 2.8 illustrates the FWM power versus the power per channel in mWs. The parameters taken for estimation are as follows: Fiber length 17.5 km, Nonlinear refractive index 2.68e-20, core effective area 50 \( \mu \text{m}^2 \), frequency allocation = [193.0, 193.1, 193.2, 193.3] THz. This cross talk power is calculated using the Equations (2.1) to (2.4). It is seen that the FWM power increases with the increase in the channel power.

![Figure 2.8 Illustration of FWM power versus channel power](image)

**Figure 2.8** Number of cross talk components falling on the desired channels in ESC scheme
Figure 2.4  Overall number of inter modulation components generated due to FWM in ESC scheme

Figure 2.5  Number of cross talk components falling on the desired channels in USC scheme
Figure 2.6  Number of Inter modulation products generated due to FWM in USC

Figure 2.7  FWM power under optimal allocation using GA
2.5.2 Experimental Study

In a standard single mode fiber, a very low value of crosstalk power is expected because FWM efficiency at any wavelength is degraded by the chromatic dispersion at that wavelength. This is experimentally verified using a partially degenerate FWM set up. The schematic arrangement for this is shown in Figure 2.9 and the photograph of the same is shown in Figure 2.10.

![Graph showing FWM noise versus Power per channel](image)

**Figure 2.8** FWM noise versus Power per channel

![Diagram of experimental setup](image)

**Figure 2.9** Experimental setup to observe FWM using SMF
As shown in Figure 2.9, continuous wave outputs from two narrow line width lasers are combined using a 3db coupler multiplexer and the output is coupled to a single mode fiber (SMF-28) of 15 Kms length and the output of the SMF is studied on an optical spectrum analyzer.

The wavelengths of the two sources are $\lambda_1 = 1549.00 \text{ nm}$ and $\lambda_2 = 1550.12 \text{ nm}$ with an input power of the order of 2 mW. The output spectrum obtained for the partially degenerate FWM using SMF is shown in Figure 2.11. Since the single mode fiber used for the experiment has more chromatic dispersion at 1550nm window ($D_C = 16 \text{ ps/nm km}$), a very small cross talk power of the order of $5 \mu\text{W}$ is obtained. This is due to phase mismatch between the two wavelengths caused by dispersion.
Figure 2.11 Output spectrum obtained for the partially degenerate FWM using SMF of length 5 km

As shown in Figure 2.11 the output spectrum shows FWM power measured in dBm along the y-axis and input wavelength of operation in the x-axis. Since there is insufficient vertical magnification of the spectrum analyzer which is used to measure the power of the output spectrum, a distinct FWM of stokes and anti-stoke wavelengths is not seen.

2.5.3 Simulation Study

In the preliminary experiment it was seen that in single mode fibers, a very low value of crosstalk power is generated. However using dispersion shifted fiber (DSF) and operating with the signals close to or at the zero dispersion wavelength results in increased phase matching and hence higher FWM efficiencies (Agrawal 2001). If the power generated in the sidebands due to FWM is sufficient, these sidebands can further mix, giving
rise to multiple sidebands (Bosco et al 2000). This concept can be used in the design of a multi-wavelength source for wavelength division multiplexed systems. Since cost of DSF is very high, it was not possible to verify them by experiment and therefore a computer simulation is carried out in our work to observe the FWM products using DSF for 2 channels (partially degenerate FWM) and 16 channel WDM transmission systems. Computer simulation allows various scenarios to observe FWM products and to calculate FWM cross talk power. The simulation begins by creating an electric field for each channel including laser line-width as a random walk of the phase. The parameters of the DSF (Cartaxo 1999) used in the simulation set up are shown in Table 2.3.

Table 2.3 Parameters of the DSF used in the simulation

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Length</td>
<td>50 km</td>
</tr>
<tr>
<td>2</td>
<td>Attenuation Constant</td>
<td>0.25 dB/km</td>
</tr>
<tr>
<td>3</td>
<td>Input coupling efficiency</td>
<td>1 dB</td>
</tr>
<tr>
<td>4</td>
<td>Output coupling efficiency</td>
<td>0.022dB</td>
</tr>
<tr>
<td>5</td>
<td>Group delay constant</td>
<td>49,00,000 ps/km</td>
</tr>
<tr>
<td>6</td>
<td>GVD constant</td>
<td>4.5 ps/nm/km</td>
</tr>
<tr>
<td>7</td>
<td>Dispersion slope constant</td>
<td>0.072 ps/nm²/km</td>
</tr>
<tr>
<td>8</td>
<td>Birefrigence constant</td>
<td>6.25 rad/m</td>
</tr>
<tr>
<td>9</td>
<td>Effective area constant</td>
<td>72 micron²</td>
</tr>
<tr>
<td>10</td>
<td>Non-linear co-efficient</td>
<td>2.128</td>
</tr>
</tbody>
</table>

Here continuous wave outputs from 2 CW lasers, made to operate at a wavelength of 1.54 µm and 1.5405 µm are combined using 2x1 multiplexer. The wavelength separation between the 2 sources is 0.5 nm. Input power is set for both the sources as 8 dBm (6mW). The multiplexed light output is sent through a 50km long DSF and the output of the DSF is studied on an optical spectrum analyzer. Similarly the simulation model for a sixteen channel WDM system is also setup as shown in Figures 2.12, to observe in-band FWM products. Figure 2.13 shows the
spectrum of signal at the input of the Dispersion Shifted Fiber for the simulation done for 2 channels WDM and Figure 2.14 shows the spectrum of signal at the output of the Dispersion Shifted Fiber. It is seen that, the input signals spectral widths are widened due to their propagation through the fiber. The partially degenerate FWM components can also be observed with the separation between new frequency and input frequency being equal to the separation of the 2 input frequencies. Here partially degenerate FWM means that $f_1$ is not equal to $f_2$ but they are nearly equal. Similarly the separation between the new wavelength and input wavelength both on the left hand side and the right hand side is equal to 0.5 nm. The DSF used has a zero dispersion wavelength of 1544 nm and a dispersion slope of 0.072 ps/km-nm². The value of $n_2$ used is $2.4 \times 10^{-20}$ and degeneracy is 3.

The simulation results for the 16 channel WDM transmission system are shown in Figures 2.15, 2.16 and 2.17. Figure 2.15 shows the spectrum of signal at the input of the Dispersion Shifted Fiber for the simulation done for unequally spaced 16 channels WDM and Figure 2.16 shows the spectrum of signal at the output of the Dispersion Shifted Fiber.
Figure 2.12 Simulation model for 16 channel WDM
Figure 2.13  2 channel WDM signal spectrum at the input of DSF

Figure 2.14  Partially degenerate FWM Spectrum at the output of DSF 50km
Figure 2.15 16 unequal channel WDM spectrum at the input of DSF

Figure 2.16 FWM cross talk components in unequal spacing
The comparison of the input and output spectrum (before and after DSF) clearly shows the generation of in-band FWM products and their pronounced strength at the centre wavelength of operation. Also, FWM products generated in equally spaced channels are seen to have high amplitude compared to original transmitted signal. Comparing the Figures 2.16 and 2.17 the cross talk components fall on the desired channel and hence are not visible in the case of ESC as seen in Figure 2.17. The input frequency power level measured in the simulation power meter is 0.55 mW and the new frequency power level is 5 mW.

Figure 2.17 Spectrum at the output of DSF for 16 ESC channel WDM transmission systems

2.5.4 Analysis of FWM Cross Talk Power

Antonella Bogoni et al (2003) simulated and made a comparative study of the system spectral occupation and signal to cross talk ratio versus channel input power for the equal channel spacing and the proposed three channel code techniques, channel detuning and channel suppression
techniques. Also signal to cross talk ratio has been reported for NZDSF, SM and DS fibers using Three channel coding (TCC) and Equal spacing channel.

In our model the FWM cross talk generated by multiplexing channels are examined and its power can be estimated using the expression for the FWM based on Equation (2.6) (Inoue et al 1994),

\[
P_{\text{FWM}} = \left[ \frac{1024 \pi^6 (D_L)^2}{n_0^4 \lambda^2 c^2} \right] \times \frac{P_p P_q P_r}{A_{\text{eff}}} e^{-\alpha L} \times \left[ \left\{ \sum_{m=1}^{M} \exp \left( \frac{-\alpha + i \Delta \beta^{(m)} L_0}{\alpha - i \Delta \beta^{(m)}} \right) \right\} \times \exp \left( -\alpha + i \Delta \beta^{(m)} L_0 \right) \right]^2
\]

(2.6)

\( A_{\text{eff}} \) is the effective mode area, \( P_p, P_q, P_r \) are the input powers of the sources, \( M = 5 \) number of sections, \( n = 3 \) is the number of fibers in one section, \( L_0 \) is the length of one fiber, \( \alpha \) is the fiber loss coefficient, \( n_0 \) is the refractive index, \( \Delta \phi \) is phase difference coefficient, \( c \) is the light velocity, \( D \) is the degeneracy factor. The parameters taken in the calculations are \( L_0 = 10 \) Km, the number of spans \( N = 50 \), repeater span \( L = 100 \) Km, fiber loss = 0.2 db/km, third order nonlinear susceptibility \( \chi = 4 \times 10^{-8} \) esu, the zero dispersion wavelength = 1550nm, Chromatic dispersion (\( D_c \)) and Dispersion slope are set corresponding to the fiber type.

The FWM crosstalk power is analyzed for all the three fibers. An accurate analysis of the four wave mixing impact on DWDM system is carried out for different types of fibers. Unequally spaced channel allocation is carried out with the optical spreading code and the performances are compared for various fiber types. Table 2.4 lists some of the important parameters of the three primary fiber types, namely, SMF, DSF and NZDSF. Single mode fiber has more chromatic dispersion and also a high value of non-linearity coefficient.
Table 2.4  Comparison between three primary fiber types: SMF, DSF and NZDSF, Wiley series (Agrawal 2002)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>SMF</th>
<th>DSF</th>
<th>NZDSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attenuation coefficient (α)</td>
<td>dB/km</td>
<td>0.2</td>
<td>0.22</td>
<td>0.23</td>
</tr>
<tr>
<td>Chromatic dispersion (Dc)</td>
<td>ps/(nm km)</td>
<td>16</td>
<td>-0.7</td>
<td>3</td>
</tr>
<tr>
<td>Dispersion slope (S)</td>
<td>s/m³</td>
<td>80</td>
<td>70</td>
<td>50</td>
</tr>
<tr>
<td>Nonlinearity coefficient (γ)</td>
<td>1/(W km)</td>
<td>1.3</td>
<td>0.3</td>
<td>1.8</td>
</tr>
<tr>
<td>PMD coefficient (Dp)</td>
<td>ps/√km</td>
<td>0.2</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Effective core area (A_{eff})</td>
<td>µm²</td>
<td>80</td>
<td>50</td>
<td>72</td>
</tr>
</tbody>
</table>

A comparison of the FWM crosstalk power as a function of channel frequencies for single mode fiber, Dispersion shifted fiber and Non-zero dispersion shifted fiber for the same fiber length and the input power is shown in Figure 2.18.

Figure 2.18  Comparison of crosstalk power for the SMF, DSF and NZDSF under USC
The Unequal channel spacing allocated using spreading codes is considered for all the three fiber transmissions. A comparison of maximum FWM crosstalk power under the USC scheme for the three fiber types is shown in Table 2.5. The dispersion shifted fiber has a maximum crosstalk power of about 2.8 mW and the single mode fiber has about 5µW, (Ramprasad and Meenakshi 2006).

The Non-zero dispersion shifted fiber occupies a place in between single mode fiber and dispersion shifted fiber possessing a crosstalk power of about 0.125mW. The reduced dispersion of Non-zero dispersion shifted fiber (NZDSF) with less FWM crosstalk power makes this fiber a suitable candidate for deployment in multi-channel WDM systems.

Table 2.5  Comparison of maximum crosstalk power for SMF, DSF and NZDSF for USC scheme

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Fiber Type</th>
<th>Crosstalk Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Single mode fiber</td>
<td>5 µW</td>
</tr>
<tr>
<td>2.</td>
<td>Dispersion Shifted fiber</td>
<td>2.8 mW</td>
</tr>
<tr>
<td>3.</td>
<td>Non-Zero Dispersion Shifted fiber</td>
<td>0.125 mW</td>
</tr>
</tbody>
</table>

A plot of FWM efficiency versus Δβₙ (phase constant for various wavelengths) for NZDSF is shown in Figure 2.19. FWM efficiency is plotted for the discrete values of Δβₙ with Δλ = 0.2 nm and z =100 km. The penalty induced by FWM is more pronounced if Δβ is too low or Pᵢⱼₖ (hence Pᵢ, Pⱼ, or Pₖ) exceed a certain threshold level. The phase matching condition (Δβ=0) is easily achieved if the chromatic dispersion of the fiber is low and/or the frequency spacing between the co-propagating signals is reduced. Hence FWM efficiency is inversely proportional to dispersion and channel spacing
and therefore high FWM efficiency is obtained when the phase mismatch is low. This affects the design of DWDM systems by limiting transmit power and number of channels. The pump powers being low, the effects of SPM and XPM could be neglected (Song et al 1999).

![Figure 2.19 FWM efficiency versus phase matching co-efficient for NZDSF](image)

**2.5.5 FWM Noise Statistics**

Performances of an optical transmission system are measured in terms of the Optical Signal to Noise Ratio (OSNR), the Q factor and the Bit Error Rate. In optical transmission systems, the optical noise entering the receiver dominates the electrical noise generated in the receiver. An optical noise is produced by EDFA and the preamplifier prior to the receiver. Other parameters that affect the performance are the sampling time and the decision level used to differentiate between the mark and space levels. The BER is usually estimated from the probability density function of the sampled
electrical currents corresponding to the Mark and the Space state. Monte carlo simulations are used to obtain histograms of the currents in the Mark and the Space states where different samples corresponds to different realization of the random variables in the system.

Considering a sixteen channel WDM in which one of the multiplexed light wavelengths is selected by an optical filter in the receiver, the light amplitude $E$, at the selected signal frequency is given by the following equation Inoue (1994),

$$E = B_s (P_s)^{1/2} e^{j\theta_s} + \sum_{pqr} B_p B_q B_r (P_{pqr})^{1/2} e^{j\theta_{pqr}}$$  \hspace{1cm} (2.7)

where $P_s$ and $\theta_s$ are the peak power and the phase respectively of the selected light signal. $P_{pqr}$, $\theta_{pqr}$ are the peak power and the phase respectively of FWM generated from a combination of p, q and r th channels that satisfy $p + q - r = s$ and $B_i = 1$ or 0, when the $i$ th channel is Mark or Space, respectively. The summation term in equation (2.7) accounts for all channel combinations satisfying $p + q - r = s$. The channel combinations are further classified into three categories; (i) the case where all the channels including the selected channels are different ($p \neq q \neq r \neq s$), (ii) when p, q and r channels are different but the r th channel is identical to the selected channel ($p \neq q \neq r = s$) and (iii) when p and q channels are identical ($p = q \neq r$) but are different from r th channel. These are expressed as,

$$\sum_{pqr} = \sum_{pqr \neq rs} + \sum_{pqr = rs} + \sum_{p = q \neq r} = \sum_{I} + \sum_{II} + \sum_{III}$$  \hspace{1cm} (2.8)

where summation I, II and III denote summation for $p \neq q \neq r \neq s$, $p \neq q \neq r = s$ and $p = q \neq r$ cases, respectively. At the receiver the photocurrent is proportional to the optical power and hence to $|E|^2$, where $E = E^{(m)}$ or $E^{(s)}$. For
large distance $L$, $\exp(-\alpha L) \ll 1$. Hence in our analysis we have assumed a single fiber span without optical amplification and all other receiver noises assumed negligible. This is justified for high input powers.

The photocurrent obtained from Inoue (1994) for the Mark and space state at the detector is used for the study of its statistical behavior. In the current research work, a random simulation to study the nature of FWM noise is carried out and the pdfs of $I_m$ and $I_s$ are computed by Monte Carlo simulations, (Ramprasad and Meenakshi 2006).

The other parameters used for the simulation are fiber length $L$ = 150 km having an EDFA for a span of 75 kms to compensate for the attenuation of 0.22 dB/km. The power in each channel is set to 10 mW, minimum channel spacing is taken to be 20 GHz, dispersion slope 0.06 ps/km.nm$^2$, effective core area is 50 $\mu$m$^2$, non-linear refractive index is $2.69 \times 10^{-20}$ m$^2$/W, number of channels 16, number of spans is 2, allocated bandwidth is 800 GHz. Figure 2.20 shows the pdf of the mark state receiver current $I_m$ obtained from the random experiments. Similarly Figure 2.21 is plotted for the space current pdf.
It is found from the random simulation experiments that the probability distribution of the mark state current is nearly Gaussian distributed and the space state current exhibits a pdf that is almost exponential in nature.
2.6 SUMMARY

In this chapter, the limitation imposed by FWM components on DWDM systems has been studied. To summarize, a simple and effective method to observe new wavelength generation due to partially degenerate FWM has been shown practically using ordinary single mode silica fiber. A computer simulation was carried out for different types of fibers for 2 channel and 16 channel WDM fiber optic transmission system to observe FWM products under ESC and optical orthogonal code based USC. The comparison of ESC and USC scheme in terms of FWM generation shows that the unequally spaced channel scheme applicable for any fiber type allowed the DWDM system to have almost nil FWM crosstalk power. A comparable performance with equally spaced channel scheme can be obtained at the cost of transmission length of the fiber and the bit rate / channel.

An USC allocation based on the Genetic algorithm technique, which is a powerful mathematical optimization technique, was also carried and the FWM power generation obtained. The impact of FWM crosstalk power on DWDM optical systems is found to be less when the channel spacing is unequally allotted based on Optical orthogonal coding technique as compared to the Genetic algorithm technique. In addition to this, an analysis of FWM impact on DWDM optical system is carried out for different types of fibers and a comparison is made on the generated FWM crosstalk power.

This approach consists in optimizing channel allocation by considering not only the total in-band FWM crosstalk but also the number of inter-modulation products falling into the channel band width. The numerical results which are obtained shows that there is more FWM crosstalk power of 2.8 mW generated for the dispersion shifted fibers which are employed to reduce the dispersion at the operating wavelength 1550nm, a less crosstalk
power of 0.125 mW is generated by the non-zero dispersion shifted fibers which are currently employed because of their minimum dispersion and loss at the operating wavelength and a very minimum value of crosstalk power of 5 μW has been generated in the case of ordinary single mode silica fibers because of their high value of dispersion at the operating wavelength.

The statistical behavior of the Four wave mixing noise has been analyzed and the probability density function for the Mark state (one state) and Space state (zero state) of the detector current in the multi-channel system are plotted separately. The FWM noise in the receiver photocurrent of the DWDM multiplexed systems with N=16 channels is determined and it is found that the distribution is nearly Gaussian distributed for the Mark state current and has an exponential decay for Space state current.