Chapter 4

COMBINED EFFECT OF THE SIGNIFICANT FACTORS

4.1 INTRODUCTION

In this chapter the combined effect of major fibre nonlinearities (SRS and FWM) and ASE noise has been studied in a DWDM transmission system. Analysis has been carried out for the estimation of system parameters considering the combined effect of SRS and FWM in the presence of ASE to achieve minimum noise for NZDSF at different data rates. This estimated value of the system parameter is referred to as the optimized value. The novelty of the technique used is that the optimization has been done to maximise the signal to noise ratio (SNR) considering the effects of SRS, FWM and ASE simultaneously.

4.2 COMBINED EFFECT OF SRS AND FWM IN CASCADED AMPLIFIER SYSTEMS

It has been observed that the SRS and FWM effects impose a limit on the maximum allowable power per channel to keep the deterioration of the system performance at a minimum. Also the effect of ASE noise accumulation on the maximum achievable system length has been observed. The combined effect of all the above-mentioned factors is considered in this section.

It has been learnt from the previous chapters that the SRS affects the input power coupled to the channel. Input power of high wavelength channels grows at the expense of the power of the low wavelength channels. ASE and FWM are the sources of noise in the channel. To visualize the combined effect, signal to noise ratio (SNR) has been calculated. To calculate SNR, the modified signal due to SRS has been considered as the signal and the total optical noise (ASE noise and FWM noise combined together) taken as the noise signal as summarized in equation 4.1:

\[
\text{Signal to Noise Ratio (SNR)} = \frac{\text{(Modified Signal due to SRS)}}{\text{(FWM Noise + ASE Noise)}}
\]  

\[\text{---- (4.1)}\]
A program was written in the MATLAB software to calculate the different values as per relations given in the equations 2.3, 2.4, 2.6, 2.7, 2.8 and 2.15. For simulation, a DWDM system with inline optical amplifiers and non-zero dispersion shifted fibre in the anomalous regime (NZDSF\textsuperscript{+}) operating at 1.55\(\mu\)m transmission window has been considered. The values of some important parameters used for the calculations are selected as per specifications of NZDSF and are mentioned below:

- Peak Raman gain coefficient=10.05\(\times\)10\(^{-12}\)cm/W
- Input power per channel=1mW
- Centre wavelength=1.55\(\times\)10\(^{-6}\)m
- Fibre attenuation coefficient at 1.55 \(\mu\)m=0.205 dB/km
- System length=varied; 1000 km, 2000 km, 3000 km, 4000 km, 5000 km
- Effective area of the optical fibre=5.3\(\times\)10\(^{-7}\)cm\(^2\)
- Fibre chromatic Dispersion coefficient at 1.55 \(\mu\)m=3.0 ps/nm-km
- \(dD/d\lambda=0.09\) ps/nm\(^{-2}\)-km
- Third order nonlinear electrical susceptibility \(X=6\times10^{-14}\) m\(^3\)/W
- Rectangular optical bandwidth of an EDFA=30 nm (3.75 THz)
- Population inversion parameter=1.3
- Data rate per channel=2.5 Gbps, 10 Gbps, 40 Gbps
- Refractive index of the fibre=1.45
- Inter-channel separation =varied; 0.4 nm, 0.8 nm, 1.2 nm, 1.6 nm
- Number of channels= varied; 16, 32, 64, 128
- Inter-amplifier separation=varied; 25 km, 50 km, 75 km, 100 km

The variations of total optical noise with wavelength for different values of amplifier separation or channel separation have been evaluated and summarized in Figures 4.1-4.4.

Figure 4.1 represents the noise power/channel (Watts) vs. wavelength (m) for a system length of 2000 km, inter-amplifier separation of 25 km, number of channels 32, inter-channel separation of 0.8 nm and input power/channel to be 1 mW. It can be seen from the figure that the ASE noise power/channel is constant for all the channels, whereas the FWM noise power/channel is more for the central channels and less for the channels at the ends. The behaviour of the FWM noise has been discussed in Chapter 3 (Section 3)
Inter-amplifier separation=25 km, Inter-channel separation=0.8 nm, System length=2000 km, Number of channels=32

Figure 4.1 Noise Power/channel (Watts) Vs. Wavelength (m) in the DWDM transmission system with Inter-channel separation of 0.8 nm, Inter-amplifier separation=25 km, Fibre attenuation coefficient=0.205 dB/km, Effective area of the optical fibre=5.3x10^{-7} cm^2, Dispersion coefficient=3 ps/nm-km and Centre wavelength=1.55x10^{-6} m.
that it increases as the number of neighbouring channels increase. For this set of inputs, it can be concluded from the figure that the FWM noise Power/channel dominates the ASE noise Power/channel. As the FWM noise Power/channel dominates, the total noise power, which is the summation of these two noise powers, follows a trend similar to that for the FWM noise. That means that the total noise has also shown higher values for the central channels.

The noise power/channel (Watts) vs. wavelength (m) plots for a system length of 2000 km, inter-amplifier separation of 25 km, number of channels 32, inter-channel separation of 1.6 nm and input power/channel to be 1 mW have been compiled in Figure 4.2. In this figure, the ASE noise power/channel comes out to be slightly greater than the FWM noise power/channel. This may be attributed to the decrease in the FWM noise power and increase in the ASE noise with the increase in the channel spacing as has been explained in the preceding chapter. However the total noise power/channel follows a behaviour similar to that of the FWM noise.

Figure 4.3 shows the variation of noise power/channel (Watts) with wavelength (m) for a system length of 2000 km, inter-amplifier separation of 50 km, number of channels 32, inter-channel separation of 1.6 nm and input power/channel to be 1 mW. It can be visualized that the ASE noise power/channel dominates the FWM noise power/channel for these values. The ASE noise power/channel has shown considerable increase over the FWM noise power/channel. Although the total noise power/channel still follows a trend analogous to that for the FWM noise power/channel, however the variation in total noise power/channel with wavelength is not that pronounced in comparison with those reported in Figure 4.1 and Figure 4.2. Comparing these three figures, it can be concluded that as the ASE noise power/channel is increasing in comparison with the FWM noise power/channel, the total noise power/channel is becoming almost same for all the channels. It can be inferred that the total noise power/channel is more for the central channels if the FWM noise dominates the system. On the other hand, it remains almost constant for all the channels if the ASE noise dominates.

The variations of different powers/ channel and SNR with wavelength have been shown in Figure 4.4 for a system of length 1000 km, inter-amplifier separation 25 km, number of channels 32 and inter-channel separation 0.8 nm. The curve showing Psrs refers to the
modified signal power due to SRS/ channel (dbm), whereas the NPtotal curve to the total noise power/channel (dbm) and SNR curve for the signal to noise ratio (db). The SNRcurve shows lower values for the channels in the centre and higher values for the channels on the sides. The channel with the highest wavelength gives a maximum value of SNR. This may be explained by the fact that the signal power of higher wavelength channels grows at the expense of the power of the low wavelength channels due to SRS, whereas the total noise Power/channel shows dip at the higher and lower wavelength channels remaining constant for the central channels. Therefore, channel with highest wavelength have maximum modified signal power and minimum total noise power resulting in a maximum SNR. Similarly, the channel number 3 shows the worst performance in terms of SNR due to the higher value of the total noise power and lower value of signal power.

4.3 PULSE WALKOFF EFFECT

The analysis reported so far has considered the SRS effect without taking into account the pulse walk off effect. Further analysis has been carried out to incorporate the pulse walk off effect so that the effect of different data rates can be studied.

When pulses in each channel travel at different group velocities due to dispersion, the pulses slide past each other while propagating. Figure 4.5 illustrates how two isolated pulses in different channels collide with each other. When the faster travelling pulse has completely walked through the slower travelling pulse, the crosstalk effect becomes negligible. The relative transmission distance for two pulses in different channels to collide with each other is called the walk-off distance, \( L_w \) (Agrawal, 2001):

\[
L_w = \frac{T_o}{v_g^{-1}(\lambda_1)-v_g^{-1}(\lambda_2)} \approx \frac{T_o}{|D\Delta\lambda|} \quad (4.2)
\]

Where \( T_o \) is the pulse width
\( v_g \) is the group velocity
\( \lambda_1, \lambda_2 \) are the centre wavelength of the two channels
\( D \) is the Dispersion coefficient
and \( \Delta \lambda = (\lambda_1 - \lambda_2) \)
Inter-amplifier separation=25 km, Inter-channel separation=1.6 nm, System length=2000 km, Number of channels=32

Figure 4.2 Noise Power/channel (Watts) Vs. Wavelength (m) in the DWDM transmission system with Inter-channel separation of 1.6 nm, Inter-amplifier separation=25 km, Fibre attenuation coefficient=0.205 dB/km, Effective area of the optical fibre=5.3x10^{-7} cm^2, Dispersion coefficient=3 ps/nm-km and Centre wavelength=1.55 x10^{-6} m.
Inter-amplifier separation=50 km, Inter-channel separation=1.6 nm, System length=2000 km, Number of channels=32

Figure 4.3 Noise Power/channel (Watts) Vs. Wavelength (m) in the DWDM transmission system with Inter-amplifier separation of 50 km, Inter-channel separation=0.8 nm, Fibre attenuation coefficient=0.205 dB/km, Effective area of the optical fibre=5.3x10⁻⁷ cm², Dispersion coefficient=3 ps/nm-km and Centre wavelength=1.55 x10⁻⁶ m.
Inter-amplifier separation=25 km, Inter-channel separation=0.8 nm, System length=1000 km, Number of channels=32, Data rate= 2.5 Gbps

Figure 4.4 Power/channel (dbm for $P_{SRS}$ and NPtotal, db for SNR) Vs. Wavelength (m) in the DWDM transmission system with Fibre attenuation coefficient=0.205 dB/km, Effective area of the optical fibre=5.3x10^{-7} cm$^2$, Dispersion coefficient=3 ps/nm-km and Centre wavelength=1.55 x10^{-6} m.
Figure 4.5 Illustration of walk-off distance (Lee, 2000)
When dispersion is significant, the walk-off distance is relatively short, and the interaction between the pulses will not be significant.

When input is in the form of pulses, the Raman interaction decreases because the pump and stokes pulses separate as they propagate at different group velocities. Energy transfer between two pulses occurs only when they spatially overlap. The pulse walk off phenomenon has the effect of reducing the interaction length $L_{\text{eff}}$ to the propagation distance over which one pulse passes through the other. The most important feature is the group-velocity mismatch that limits the SRS process to a duration during which the pump and Raman pulses overlap (Agrawal, 2001). The walk-off length ($L_w$) can be written as:

$$L_w = \frac{T_o}{v^{-1}_{gp} - v^{-1}_{gs}}$$  \hspace{1cm} (4.3)

Where $T_o$ is the pulse width
$v_{gp}$ is the group velocity of pump
and $v_{gs}$ is the group velocity of stokes

The influence of the pulse walk off effect on the SRS and hence different powers/ channel and SNR has been reported in Figure 4.6 which has been plotted for a system of length 1000 km, inter-amplifier separation 25 km, number of channels 32, inter-channel separation 0.8 nm and data rate of 2.5 Gbps. It can be seen from the figure that the tilt in the power due to the SRS ($P_{\text{SRS}}$) has reduced after considering the walk off effect. The curve of NPtotal remains unchanged and resembles that of Figure 4.4. The SNR curve has shown the trend similar to that of Figure 4.4, however the tilt of this curve has also decreased corresponding to the decrease in the $P_{\text{SRS}}$. SNRmin has also been plotted in this figure which gives the minimum value of SNR. It
can be concluded from Figure 4.4 and Figure 4.6 that the minimum value of the SNR has increased as the pulse walk off effect in the SRS is incorporated.

Figure 4.7 illustrates the variation of different powers/channel with wavelength for same system parameters as considered for the previous case (Figure 4.6) except the data rate of 10 Gbps. As the data rate is increased the pulse walk off effect gets aggravated resulting in decrease in the effect of SRS. It is clear from the figure that the modification in the input signal power per channel due to the SRS has decreased. Total noise power per channel has shown no change as compared to the earlier case plotted in Figure 4.4. It may be due to the fact that the FWM is basically bit rate independent and the ASE noise taken for one channel remains same irrespective of the data rate, although total ASE noise of the system changes with the data rate. The SNR has shown improvement with the data rate and the minimum value of the SNR has also registered an increase. It may be ascribed to the decrease in the SRS effect.

Variation of power/channel with wavelength for data rate of 40 Gbps has been described in Figure 4.8. It has been learnt from the figure that the pulse walk off effect is further pronounced and the SRS effect has reduced at higher data rate. The SNR and SNR min have registered improvements as compared to the corresponding values in the proceeding case (Figure 4.7). It can be seen that the improvement in the SNR in this case is not that prominent as was in Figure 4.7. It may be ascribed to the less variation in the SRS due to the corresponding less increase in the pulse walk off factor. Comparing Figure 4.6, Figure 4.7 and Figure 4.8, it can be inferred that the SNRmin gets increased with increase in the data rate due to the corresponding decrease in the SRS effect.
Inter-amplifier separation=25 km, Inter-channel separation=0.8 nm, System length=1000 km, Number of channels=32, Data rate=2.5 Gbps

Figure 4.6 Power/channel (dbm for $P_{\text{SRS}}$ and $N_{\text{Ptotal}}$, db for SNR) Vs. Wavelength (m) in the DWDM transmission system with pulse walk off effect at Data rate of 2.5 Gbps, Fibre attenuation coefficient =0.205 dB/km, Effective area of the optical fibre=$5.3\times10^{-7}$ cm$^2$, Dispersion coefficient=3 ps/nm-km and Centre wavelength=$1.55\times10^{-6}$ m.
Inter-amplifier separation=25 km, Inter-channel separation=0.8 nm, System length=1000 km, Number of channels=32, Data rate=10 Gbps

Figure 4.7 Power/channel (dbm for P_{SRS} and NPtotal, db for SNR) Vs. Wavelength (m) in the DWDM transmission system with pulse walk off effect at Data rate of 10 Gbps, Fibre attenuation coefficient=0.205 dB/km, Effective area of the optical fibre=5.3x10^{-7} cm^2, Dispersion coefficient=3 ps/nm-km and Centre wavelength=1.55 x10^{-6} m.
Inter-amplifier separation=25 km, Inter-channel separation=0.8 nm, System length=1000 km, Number of channels=32, Data rate=40 Gbps

Figure 4.8 Power/channel (dbm for $P_{SRS}$ and NPtotal, db for SNR) Vs. Wavelength (m) in the DWDM transmission system with pulse walk off effect at Data rate of 40 Gbps, Fibre attenuation coefficient= 0.205 dB/km, Effective area of the optical fibre=5.3x10^-7 cm², Dispersion coefficient=3 ps/nm-km and Centre wavelength=1.55 x10^-6 m.
4.4 OPTIMIZATION OF SYSTEM PARAMETERS BASED ON SNR

During the process of the optimization of the system parameters, a minimum value of SNR corresponding to the worst affected channel has been considered in the current study. Subsequently, the SNR was calculated for the different values of the parameter to be optimized. Thereafter, a graph was plotted between the SNR and the parameter to be optimized. From the plot, the value of the concerned parameter corresponding to a maximum value of SNR was noted. This value has been suggested to be the optimized value of that particular parameter for the given set of inputs. In the proposed program, some of the system parameters such as input power, receiver sensitivity, refractive index of the fibre, population inversion, fibre chromatic dispersion have been selected as constant, whereas the system length, number of channels, inter-channel separation and inter-amplifier separation have been considered as variables.

Various steps of the methodology used for the optimization of the system parameters have been shown in Figure 4.9. The simulation system parameters are same as had been used in the section 4.2.

Figure 4.10 shows the variation of signal to noise ratio vs. Inter-amplifier separation considering the pulse walk off effect for different values of system length, data rate of 2.5 Gbps, inter-channel separation of 0.8 nm and number of channels to be 32. It is obvious that the optimized value for the Inter-amplifier separation for all the three sets of inputs, differing only by system length, is 50 km. However the signal to noise ratio (SNR) corresponding to the optimized value for these three sets of inputs comes out to be different, that is 18 db for the system length of 1000 km, 13 db for the system length of 2000 km and around 8 db for the system length of 3000 km. It has been discussed in the Chapter 3 that the Inter-amplifier separation has opposite effects on the noise generated due to the fibre nonlinearities and ASE noise accumulation, hence it was expected that the optimized value will be near the central value.

The same optimized value has been obtained from Figure 4.11 for data rate of 10 Gbps and Figure 4.12 for data rate of 40 Gbps. The SNR increases for data rate of 10 Gbps but decreases for 40 Gbps as compared to 10 Gbps although SNR corresponding to 40 Gbps is
still greater than 2.5 Gbps. This may be attributed to the reduction in the SRS effect due to the increase in the pulse walkoff factor at higher data rates as explained in the foregoing section. FWM is the bit rate independent effect and ASE noise/channel also becomes independent of bit rate up to 10 Gbps but increases for data rate of 40 Gbps. Decrease in SRS effect corresponding to the change in data rate from 2.5 Gbps to 10 Gbps results in the more input power for the worst channel (which is always low wavelength channel) and therefore increases the SNR. When the data rate is changed from 10 Gbps to 40 Gbps, decrease in SRS effect is there but there is increase in ASE noise/channel as well hence SNR is decreased.

Figure 4.13 depicts the variation of signal to noise ratio vs. Inter-amplifier separation considering the pulse walk off effect for the different values of data rate, system length of 1000 km, inter-channel separation of 0.8 nm and number of channels to be 32. The optimized value of Inter-amplifier separation is found to be identical for the different data rates, and is 50 km. The SNR increases when the data rate is changed from 2.5 Gbps to 10 Gbps and decreases when data rate is changed from 10 Gbps to 40 Gbps due to above mentioned reasons.

Further, it can also be concluded from the curves of Figure 4.10, 4.11 and 4.12 that increase in system length decreases the SNR. This may be due to the fact that with the increase in the system length, the number of segments increase, which increases the SRS effect, FWM noise and ASE noise as has been indicated by the equations 2.3, 2.4, 2.6 and 2.15. Hence the SNR gets decreased. This trend has further been confirmed by Figure 4.14 which shows the variation in signal to noise ratio vs. system length considering the pulse walk off effect for different values of inter-amplifier separation, number of channels 32 and channel separation 0.8 nm at data rate of 2.5 Gbps.

Another important inference that can be drawn from Figure 4.14 is that SNR comes out to be the maximum for an inter-amplifier separation of 50 km when system length is between 1000 km-3500 km. For system length less than 1000 km, an inter-amplifier separation of 25 km has registered maximum SNR whereas for system length more than 3500 km, an inter-amplifier separation of 75 km has given maximum SNR.
Figure 4.9 Algorithm for optimization of system parameters considering the combined effect of fibre nonlinearities and amplified spontaneous noise taking parameters like Input power, Receiver sensitivity as constant ones and Inter-amplifier separation, Number of channels, System length and Inter-channel separation as varying.
Inter-channel separation=0.8 nm, Number of channels=32, Data rate=2.5 Gbps.

Figure 4.10 Signal to Noise ratio Vs. Inter-amplifier separation (km) for different values of system length (L) in the DWDM transmission system with pulse walk off effect at Data rate of 2.5 Gbps, Input Power/channel=1 mW, Fibre attenuation coefficient=0.205 dB/km, Effective area of the optical fibre=5.3x10^{-7} cm², Dispersion coefficient=3 ps/nm-km, dD/dλ=0.09 ps/nm²-km, Third order nonlinear electrical susceptibility X=6x10^{-14} m³/W and Centre wavelength=1.55 x10^6 m.
Inter-channel separation=0.8 nm, Number of channels=32, Data rate=10 Gbps

Figure 4.11 Signal to Noise ratio Vs. Inter-amplifier separation (km) for different values of system length (L) in the DWDM transmission system with pulse walk off effect at Data rate of 10 Gbps, Input Power/channel=1 mW, Fibre attenuation coefficient=0.205 dB/km, Effective area of the optical fibre=5.3x10^{-7} cm^2, Dispersion coefficient=3 ps/nm-km, dD/dλ=0.09 ps/nm-km, Third order nonlinear electrical susceptibility X=6x10^{-14} m^3/W and Centre wavelength=1.55 x10^{-6} m.
Inter-channel separation=0.8 nm, Number of channels=32, Data rate=40 Gbps

Figure 4.12 Signal to Noise ratio Vs. Inter-amplifier separation (km) for different values of system length (L) in the DWDM transmission system with pulse walk off effect at Data rate of 40 Gbps, Input Power/channel=1 mW, Fibre attenuation coefficient=0.205 dB/km, Effective area of the optical fibre=5.3x10^{-7} \text{cm}^2, Dispersion coefficient=3 \text{ ps/nm-km}, \text{ dD/d\lambda}=0.09 \text{ ps/nm}^2-\text{km}, Third order nonlinear electrical susceptibility X=6x10^{-14} \text{ m}^3/\text{W} and Centre wavelength=1.55 \times 10^{-6} \text{ m}.
Figure 4.13 Signal to Noise ratio Vs. Inter-amplifier separation (km) for different values of data rate in the DWDM transmission system with pulse walk off effect, Input Power/channel=1 mW, Fibre attenuation coefficient=0.205 dB/km, Effective area of the optical fibre=5.3x10^{-7} cm^2, Dispersion coefficient=3 ps/nm-km, dD/d\lambda=0.09 ps/nm^2-km, Third order nonlinear electrical susceptibility \( X=6\times10^{-14} \text{ m}^3/\text{W} \) and Centre wavelength=1.55 x10^{-6} m.
Inter-channel separation=0.8 nm, Number of channels=32, Data rate=2.5 Gbps

Figure 4.14 Signal to Noise ratio Vs. System length (km) in the DWDM transmission system with pulse walk off effect, Input Power/channel=1 mW, Fibre attenuation coefficient=0.205 dB/km, Effective area of the optical fibre=5.3x10^{-7} cm^2, Dispersion coefficient=3 ps/nm-km, dD/d\lambda=0.09 ps/nm²-km, Third order nonlinear electrical susceptibility X=6x10^{-14} m^3/W and Centre wavelength=1.55 x10^{-6} m.
The variation of signal to noise ratio vs. Inter-amplifier separation considering the pulse walk off effect for different values of system length, data rate of 2.5 Gbps, inter-channel separation of 2.4 nm and number of channels to be 32 has been shown in Figure 4.15. The wide channel separation and low data rate have been considered to demonstrate the effect of SRS on the SNR. It can be observed from the figure that when the SRS effect dominates, the amplifier separation of 25 km comes out to be the optimized value for a system length of 1000 km, however for the system length of 2000 km and 3000 km, an amplifier separation of 50 km has been found to be the optimized one.

Figure 4.16 depicts the enhanced SRS effect by ignoring the pulse walk off effect for same values of channel separation, data rate and number of channels as that of Figure 4.15. It can be concluded from the plots that an amplifier separation of 25 km comes out to be the optimized value for the system length of 1000 km and 2000 km, however for the system length of 3000 km, the amplifier separation of 50 km remains to be the optimized one. From Figures 4.15 and 4.16, it can be inferred that the enhanced effect of SRS shifts the optimized value of amplifier separation to the lower side. Although in DWDM systems, the value of channel separation is low and hence SRS is not the dominating factor.

The variation of signal to noise ratio with Inter-amplifier separation considering the pulse walk off effect for different values of inter-channel separation, system length of 1000 km and number of channels to be 32 at data rate of 2.5 Gbps has been described in the Figure 4.17. It is evident from the figure that the optimized value of amplifier separation comes out to be 50 km for all the values of the Inter-channel separation. Another observation that can be made from the plots is that at the Inter-amplifier separation of 25 km, a channel separation of 1.6 nm has given the maximum SNR, whereas at other values of the inter-amplifier separation, a channel separation of 0.4 nm has given the maximum value of the SNR. This may be explained by the dominance of FWM noise over ASE noise at low amplifier separation. To get the minimum value of FWM noise and to achieve maximum SNR, the largest value of channel separation in the given set of inputs proves the most efficient one.

To demonstrate the effect of SRS in the variation of signal to noise ratio with Inter-amplifier separation for different values of inter-channel separation, system length of 1000
km and number of channels to be 32 at data rate of 2.5 Gbps has been considered without pulse walk off effect in Figure 4.18. It is obvious from the figure that the optimized value of amplifier separation comes out to be 50 km up to the Inter-channel separation of 1.2 nm but for 1.6 nm channel separation, an amplifier separation of 25 km gives the maximum SNR. This may be ascribed to the increase in the SRS effect at higher values of channel separation in the absence of pulse walk off effect.

The variation of signal to noise ratio vs. Inter-amplifier separation considering the pulse walk off effect for different values of number of channels for system length of 1000 km and inter-channel separation of 0.8 nm has been compiled in Figure 4.19. The optimized value of Inter-amplifier separation has been found to be 50 km for number of channels 16, 32 and 64. However for the system of 128 channels, the optimized value has shifted to 75 km. The signal to noise ratio has shown decrease with the increase in the number of channels. This may be due to increase in the SRS effect with the number of channels. Although the SRS effect becomes independent of the number of channels at the higher values of the later, it is increasing with the increase in the channel count up to 120 at 0.8 nm channel spacing.

The variation of signal to noise ratio with Inter-channel separation considering the pulse walk off effect for different values of inter-amplifier separation has been shown in Figure 4.20 for a data rate of 2.5 Gbps, system length of 2000 km and number of channels to be 32. It can be observed that the optimized value for the Inter-channel separation is 0.8 nm for inter-amplifier separation of 25 km, 50 km and 75 km and 0.4 nm for inter-amplifier separation of 100 km. As discussed in the chapter 3, the channel separation has conflicting effects on the SRS, ASE and FWM. An increase in the channel separation leads to the increase in the SRS effect and the ASE noise but decrease in the FWM noise. Hence 0.8 nm was the expected value of the channel separation that could minimize the noise and maximise the SNR. The optimized channel separation of 0.4 nm for the inter-amplifier separation of 100 km may be explained by the domination of FWM noise over ASE noise at low channel separation. As FWM noise dominates over ASE noise at low channel separation, higher value of amplifier separation is required to reduce the total noise and to maximize the SNR.
Inter-channel separation=2.4 nm, Number of channels=32, Data rate=2.5 Gbps

Figure 4.15 Signal to Noise ratio Vs. Inter-amplifier separation (km) for different values of system length (L) in the DWDM transmission system with pulse walk off effect at Channel separation of 2.4 nm, Input Power/channel=1 mW, Fibre attenuation coefficient=0.205 dB/km, Effective area of the optical fibre=5.3x10^-7 cm^2, Dispersion coefficient=3 ps/nm-km, dD/dλ=0.09 ps/nm^2-km, Third order nonlinear electrical susceptibility X=6x10^{-14} m^3/W and Centre wavelength=1.55 x10^6 m.
Inter-channel separation=2.4 nm, Number of channels=32, Data rate=2.5 Gbps

Figure 4.16 Signal to Noise ratio Vs. Inter-amplifier separation (km) for different values of system length (L) in the DWDM transmission system without pulse walk off effect at Channel separation of 2.4 nm, Input Power/channel=1 mW, Fibre attenuation coefficient=0.205 dB/km, Effective area of the optical fibre=5.3x10^{-7} cm^2, Dispersion coefficient=3 ps/nm-km, dD/dλ=0.09 ps/nm²-km, Third order nonlinear electrical susceptibility X=6x10^{-14} m³/W and Centre wavelength=1.55 x10^{-6} m.
System length=1000 km, Number of channels=32, Data rate=2.5 Gbps

Figure 4.17 Signal to Noise ratio Vs. Inter-amplifier separation (km) for different values of Inter-channel separation (ICSEP) in the DWDM transmission system with pulse walk off effect at Data rate of 2.5 Gbps, Input Power/channel=1 mW, Fibre attenuation coefficient=0.205 dB/km, Effective area of the optical fibre=5.3x10^{-7} cm^2, Dispersion coefficient=3 ps/nm-km, dD/d\lambda=0.09 ps/nm^2-km, Third order nonlinear electrical susceptibility X=6x10^{-14} m^3/W and Centre wavelength=1.55 x10^{-6} m.
Figure 4.18 Signal to Noise ratio Vs. Inter-amplifier separation (km) for different values of Inter-channel separation (ICSEP) in the DWDM transmission system without pulse walk off effect at Data rate of 2.5 Gbps, Input Power/channel=1 mW, Fibre attenuation coefficient=0.205 dB/km, Effective area of the optical fibre=5.3x10^{-7} cm^2, Dispersion coefficient=3 ps/nm-km, dD/dλ=0.09 ps/nm²-km, Third order nonlinear electrical susceptibility X=6x10^{-14} m^3/W and Centre wavelength=1.55 x10^{-6} m.
Inter-channel separation=0.8 nm, System length=1000 km, Data rate=2.5 Gbps

Figure 4.19 Signal to Noise ratio Vs. Inter-amplifier separation (km) for different values of number of channels (N) in the DWDM transmission system with pulse walk off effect, Input Power/channel=1 mW, Fibre attenuation coefficient=0.205 dB/km, Effective area of the optical fibre=$5.3\times10^{-7}\text{cm}^2$, Dispersion coefficient=3 ps/nm-km, dD/d\(\lambda\)=0.09 ps/nm\(^2\)-km, Third order nonlinear electrical susceptibility $X=6\times10^{-14}$ m\(^3\)/W and Centre wavelength=$1.55\times10^{-6}$ m.
System length=2000 km, Number of channels=32, Data rate=2.5 Gbps

Figure 4.20 Signal to Noise ratio Vs. Inter-channel separation (km) for different values of Inter-amplifier separation (IASEP) in the DWDM transmission system with pulse walk off effect at Data rate of 2.5 Gbps, Input Power/channel=1 mW, Fibre attenuation coefficient=0.205 dB/km, Effective area of the optical fibre=5.3x10^{-7} \text{cm}^2, Dispersion coefficient=3 \text{ ps/nm-km}, \frac{dD}{d\lambda}=0.09 \text{ ps/nm}^{-2}\text{-km}, Third order nonlinear electrical susceptibility $X=6\times10^{-14} \text{ m}^3/\text{W}$ and Centre wavelength=1.55 $\times 10^{-6}$ m.
The same optimized value of Inter-channel separation has been reported by the systems with a system length of 2000 km, number of channels to be 32 and for data rate of 10 Gbps (Figure 4.21); a system length of 2000 km, number of channels to be 32 and for data rate of 40 Gbps (Figure 4.22) although the value of the SNR corresponding to the optimized value has been found changing with increasing data rates. This may be attributed to the pulse walk off effect which reduces the impact of SRS effect as explained in the case of the Inter-amplifier separation. This trend of change in the SNR with data rate has been established by the Figure 4.23 which shows the variation in signal to noise ratio vs. Inter-channel separation for different data rates, inter-amplifier separation of 25 km, number of channels 32 and system length of 2000 km.

Figure 4.24 describes the variation of signal to noise ratio with Inter-channel separation considering the pulse walk off effect for different values of system length, inter-amplifier separation of 50 km and number of channels 32 at data rate of 2.5 Gbps. It can be seen from the figure that the optimized value of channel separation comes out to be 0.8 nm for different values of system length. However, the SNR decreases with the increase in the system length as found in Figure 4.9 and Figure 4.10 for the same reasons. The trends of getting same optimized value of channel separation in spite of changing system length and decrease in SNR with increase in system length have been verified for different data rates in Figure 4.25 (data rate of 10 Gbps) and Figure 4.26 (data rate of 40 Gbps). Further change in SNR with the increase in data rates as originated in Figure 4.13 and established in Figure 4.23 has been verified by comparing Figures 4.24, 4.25 and 4.26.

The variation of signal to noise ratio vs. Inter-channel separation considering the pulse walk off effect for the different values of number of channels, inter-amplifier separation of 50 km and system length of 1000 km at data rate of 2.5 Gbps has been reported in Figure 4.27. It can be inferred from the figure that the optimized channel separation is 0.8 nm for 16, 32 and 64 channels, but 1.6 nm for 128 channels. Moreover, with the increase in the number of channels, the SNR has decreased as can be observed in Figure 4.19.
4.5 CONCLUSION

It can be concluded from the combined study of the FWM and ASE that ASE noise power/channel is constant for all the channels, whereas the FWM noise power/channel is more for the central channels and less for the channels at the ends. At high value of channel separation, ASE noise power dominates the total system noise whereas at low values of channel separation, FWM noise power contributes more to the total system noise. Further, it was observed that the gravity of SRS effect decreases by considering pulse walk off effect in the analysis. Moreover, optimization of inter-amplifier separation and inter-channel separation has been done at different data rates considering the SNR as the deciding factor. It can be inferred from the analysis done above that an inter-amplifier separation of 50 km comes out to be the optimized value in most of the cases. However for the system with 128 channels, the optimized value has shifted to 75 km. The SNR has also shown decrease with the increase in the number of channels. An inter-channel separation of 0.8 nm has been identified as the optimized value in most of the cases, although for 128 channels it comes out to be 1.6 nm.
System length=2000 km, Number of channels=32, Data rate=10 Gbps

Figure 4.21 Signal to Noise ratio Vs. Inter-channel separation (km) for different values of Inter-amplifier separation (IASEP) in the DWDM transmission system with pulse walk off effect at Data rate of 10 Gbps, Input Power/channel=1 mW, Fibre attenuation coefficient=0.205 dB/km, Effective area of the optical fibre=5.3x10^{-7} cm^2, Dispersion coefficient=3 ps/nm-km, dD/dz=0.09 ps/nm^2-km, Third order nonlinear electrical susceptibility X=6x10^{-14} m^3/W and Centre wavelength=1.55 x10^{-6} m.
System length=2000 km, Number of channels=32, Data rate=40 Gbps

![Signal to Noise ratio Vs. Inter-channel separation (km) for different values of Inter-amplifier separation (IASEP) in the DWDM transmission system with pulse walk off effect at Data rate of 40 Gbps, Input Power/channel=1 mW, Fibre attenuation coefficient=0.205 dB/km, Effective area of the optical fibre=5.3x10^{-7} cm^2, Dispersion coefficient=3 ps/nm-km, dD/d\lambda=0.09 ps/nm^2-km, Third order nonlinear electrical susceptibility X=6x10^{-14} m^3/W and Centre wavelength=1.55 x10^{-6} m.](image-url)
System length=2000 km, Number of channels=32, Inter-amplifier separation=25 km

Figure 4.23 Signal to Noise ratio Vs. Inter-channel separation (km) for different values of data rate in the DWDM transmission system with pulse walk off effect, Input Power/channel=1 mW, Fibre attenuation coefficient=0.205 dB/km, Effective area of the optical fibre=5.3x10^{-7} cm^2, Dispersion coefficient=3 ps/nm-km, dD/dλ=0.09 ps/nm^2-km, Third order nonlinear electrical susceptibility X=6x10^{-14} m^3/W and Centre wavelength=1.55 x10^{-6} m.
Inter-amplifier separation=50 km, Number of channels=32, Data rate=2.5 Gbps

Figure 4.24 Signal to Noise ratio Vs. Inter-channel separation (km) for different values of system length (L) in the DWDM transmission system with pulse walk off effect at Data rate of 2.5 Gbps, Input Power/channel=1 mW, Fibre attenuation coefficient=0.205 dB/km, Effective area of the optical fibre=5.3x10^{-7} cm^2, Dispersion coefficient=3 ps/nm-km, dD/dλ=0.09 ps/nm^2-km, Third order nonlinear electrical susceptibility X=6x10^{-14} m^3/W and Centre wavelength=1.55 x10^{-6} m.
Inter-amplifier separation=50 km, Number of channels=32, Data rate=10 Gbps

![Signal to Noise ratio Vs. Inter-channel separation (km) for different values of system length (L) in the DWDM transmission system with pulse walk off effect at Data rate of 10 Gbps, Input Power/channel=1 mW, Fibre attenuation coefficient=0.205 dB/km, Effective area of the optical fibre=5.3x10^{-7} cm^2, Dispersion coefficient=3 ps/nm-km, dD/dλ=0.09 ps/nm^2-km, Third order nonlinear electrical susceptibility X=6x10^{-14} m^3/W and Centre wavelength=1.55 x10^{-6} m.](image)

Figure 4.25 Signal to Noise ratio Vs. Inter-channel separation (km) for different values of system length (L) in the DWDM transmission system with pulse walk off effect at Data rate of 10 Gbps, Input Power/channel=1 mW, Fibre attenuation coefficient=0.205 dB/km, Effective area of the optical fibre=5.3x10^{-7} cm^2, Dispersion coefficient=3 ps/nm-km, dD/dλ=0.09 ps/nm^2-km, Third order nonlinear electrical susceptibility X=6x10^{-14} m^3/W and Centre wavelength=1.55 x10^{-6} m.
Inter-amplifier separation=50 km, Number of channels=32, Data rate=40 Gbps

![Graph showing signal to noise ratio vs. inter-channel separation for different system lengths](image)

Figure 4.26 Signal to Noise ratio Vs. Inter-channel separation (km) for different values of system length (L) in the DWDM transmission system with pulse walk off effect at Data rate of 40 Gbps, Input Power/channel=1 mW, Fibre attenuation coefficient=0.205 dB/km, Effective area of the optical fibre=5.3x10^{-7} cm^2, Dispersion coefficient=3 ps/nm-km, dD/dλ=0.09 ps/nm^2-km, Third order nonlinear electrical susceptibility X=6x10^{-14} m^3/W and Centre wavelength=1.55 x10^{-6} m.
Inter-amplifier separation=50 km, System length=1000 km, Data rate=2.5 Gbps

Figure 4.27 Signal to Noise ratio Vs. Inter-channel separation (km) for different values of Number of channels (N) in the DWDM transmission system with pulse walk off effect, Input Power/channel=1 mW, Fibre attenuation coefficient=0.205 dB/km, Effective area of the optical fibre=5.3x10^{-7} cm^2, Dispersion coefficient=3 ps/nm-km, dD/dλ=0.09 ps/nm^2-km, Third order nonlinear electrical susceptibility X=6x10^{-14} m^3/W and Centre wavelength=1.55 x10^{-6} m.