HEURISTIC ROUTING ALGORITHM FOR THE REDUCTION OF FWM IN GPON FTTH

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ABSTRACT

Wavelength Division Multiplexing (WDM) is a boon of Light wave Technology as it increases the transmission capacity and enhances the transmission distance by using optical amplification. The capacity of the present system is limited by the noise generated by the amplifiers and interactions due to nonlinearities. According to many literatures, Stimulated Raman Scattering (SRS) and Four Wave Mixing (FWM) are dominant nonlinear effect where the other nonlinear effects like Self Phase Modulation (SFM), Cross Phase Modulation (CFM) and Stimulated Brillouin Scattering (SBS) can be suppressed. My paper focus on simulation and theoretical issues of fiber nonlinearities and impact of FWM on WDM systems and adopted Resource allocation techniques and Heuristic routing algorithm for the reduction of FWM. The Effect of FWM on channels with different values of inter channel spacing, input power, length, effective core area has been analyzed. The blocking probabilities of 14 node Tandem network with random wavelength assignment (WA) and with Heuristic Routing algorithm has been calculated. Simulation results shows that the FWM effect is more dominant at the middle wavelengths compared to end wavelengths and also the FWM noise power is proportional to the power of the channel, length and effective core area i.e., with the increase in any one of the above mentioned parameters, the FWM noise power increases. Blocking probability of the network with Heuristic algorithms shows better performance when compared to random WA techniques. Thus we can reduce the effect of FWM and hence enhance the transmission capacity of the systems by adopting the proposed technique.

Key Words - Wavelength division multiplexing, Fiber nonlinearities, Four-wave mixing, Wavelength assignment.

I. INTRODUCTION

We are moving toward a society which requires that we have access to information at our fingertips *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 and asynchronous transfer mode (ATM) networks do not have the capacity to support the foreseeable bandwidth demands. FTTH deployed with Gigabit Passive Optical Network (GPON) technology seems to be the best solution to alleviate the bandwidth bottleneck in the access network. Fiber optic technology with WDM can also be considered as our savior for meeting our needs because of its potentially limitless capabilities like huge bandwidth [nearly50terabits per second (Tb/s)], low signal attenuation (as low as 0.2 dB/km), low signal distortion, low power requirement, small space requirement, and low cost [2][3].The wavelength division multiplexing has dramatically increased the network capacity. This allows the transport of hundreds of gigabits of data on a single fiber for distances over thousands of kilometers, without the need of optical-to-electrical-to-optical (O-E-O) conversion.

For efficient recovery of received signal, the signal to noise ratio at the receiver must be considerably high. Fiber losses will affect the received power eventually reducing the signal power at the receiver. Hence optical fibers suffer heavy loss and degradation over long distances. To overcome these losses, optical amplifiers were invented which significantly boosted the power in the spans in between the source and receiver.

In long haul transmission, EDFA's (Erbium Doped Fiber Amplifier) are used to compensate the signal attenuation instead of optoelectronic/electro optic conversions and DSF (Dispersion Shifted Fibers) to overcome chromatic dispersion. Booster amplifier, in-line amplifier, Pre- amplifier are mostly preferred for long distance transmission. Singh et al made the comparative study of all the amplifiers and concluded that inline amplifier is most preferable as it requires minimum power for the given probability of error [10].

All these attempts are made to maintain high bit rate however, optical amplifiers introduce amplified spontaneous emission (ASE) noise which is proportional to the amount of optical amplifications they provide and some undesirable nonlinear interactions such as Four Wave Mixing and Stimulated Raman Scattering are created and accumulated as the optical signals propagate along the length of the fiber [5]-[9]. Optical fiber nonlinearities affect the system parameters like Total transmission distance, channel spacing, power per channel and so on [1] [4]. Low loss in optical fibers is still a critical requirement in long distance optical systems to efficiently recover the signal at the receiver.

II. IMPACT OF FIBER NONLINEARITIES ON TRANSMITTED OPTICAL POWER

Refractive Index of the fiber is both intensity and frequency dependent. Nonlinear Kerr effect is dependence of the refractive index of the fiber on the power that is propagating through it. This effect is responsible for the generation of non linear effects like four wave mixing (FWM), stimulated Raman scattering (SRS).

A. Stimulated Raman Scattering (SRS)

SRS is first observed in 1972 and it belongs to inelastic scattering. Optical phonons participate in Raman scattering. The SRS is scattering of a photon by one of the molecules to a lower-frequency photon, while the molecule makes transition to a higher energy vibrational state. Incident light acts as a pump for generating the frequency-shifted radiation called the Stokes wave. The scattered signal has a wavelength longer than incident light due to which longer wavelength channels are amplified by the depleting shorter wavelength channels. As the signal propagates along a long haul fiber, lower wavelength channel gets completely depleted due to SRS resulting in the degradation of SNR. Careful Examination on SRS amplification and depletion power is to be done. The SRS effect in DWDM fiber optic system is examined by many Authors [15]-[19].

Ignoring walk-off effects, Singh and Hudiara [11] have given a model to calculate SRS without any assumptions.

Modified power due to SRS is given by

$$P_m[k] = P_t[k] - P_t[k] \sum_{i=k+1}^{N} D[j,k] + \sum_{j=1}^{k-1} (P_t[j]\, D[j,k]) \quad (1)$$

$$\text{for } k=1,2,3\ldots N$$

$$D[k,i] = 0 \text{ for } i>N$$

$$D[j,k] = 0 \text{ for } k = 1$$

$$D[i,j] = (\lambda_j/\lambda_i)\ P_t[j]\ \{(f_i - f_j)/\ 1.5 \times 10^{13}\} g_{rmax} \{\ L_e(\lambda_j) \times (10^5/b) \times A_e\}$$

$$\text{for } (f_i - f_j) \leq 1.5 \times 10^{13} \text{ Hz and } j>i$$

$$D[i,j] = 0$$

$$\text{for } (f_i - f_j) > 1.5 \times 10^{13} \text{ Hz and } j \leq I \quad (2)$$

In Eq.1, $P_m[k]$ represents the total power transmitted to K_{th} channel, second term gives the total power depleted from the K_{th} channel by amplifying the higher wavelength channels and the third term indicates the total power received by the K_{th} channel from the lower wavelength channels.In Eq.(2), g_{rmax} is the peak Raman gain coefficient (cm/W), λ_j, λ_i are the wavelengths (nm)of jth and ith channels, f_i, f_j are the centre frequencies (Hz) of the i_{th} and j_{th} channels, A_e is the effective core area of optical fiber in cm^2 and the value of b varies from 1 to 2 depending up on the polarization state of the signals at different wavelength channels.

B. Four Wave Mixing (FWM)

Four-wave mixing (FWM) is a major source of nonlinear crosstalk for WDM light wave systems. Consider three waves co propagate along the fiber with the frequencies f_i, f_j, f_k, FWM is the generation of new wave with the frequency $f_{ijk} = f_i + f_j - f_k$ resulting from the interaction of three waves. If the newly generated wavelength falls in the window of original transmitting channel wavelength, it causes cross talk between the channels propagating through fiber resulting in severe degradation of the WDM channels. Probability of this match increases for equally spaced channels [20]-[23].

FWM is one of the major limiting factors in long haul optical communication system which uses low channel spacing or low dispersion fiber as medium. The WDM has concept of propagating the different wavelength channels separated by a particular spacing between each of them in terms of nanometers causes interaction between them weakly. This weak interaction becomes significant in the long range of distance between transmitter and receiver. For a system with in-line amplification, the FWM effect will be more severe [1]. FWM occurs in DWDM systems in which the wavelength channel spacing are very close to each other. This effect is generated by the third order distortion that creates third order harmonics.

The power of the newly generated FWM component at the frequency f_{ijk} [12] [13] with in-line amplification is given by

$$P(f_{ijk}) = k^2 P^3 e^{-aL} [\{(M+1)L_e\}/A_e]^2 \eta_{ijk} (d_{ijk})^2 P \quad (3)$$

$$\text{Where } k = 32\Pi^3 (X/n^2 c\lambda)$$

$$\eta_{ijk} = \{\alpha^2/[\alpha^2 + (\Delta\beta_{ijk})^2]\} \times [1 + \{4e^{-aL}/(1-e^{-aL})\}^2] \sin^2(\Delta\beta_{ijk} L/2) \quad (4)$$

$$\Delta\beta_{ijk} = (2\Pi\lambda^2/c)(|f_i - f_k|\ |f_j - f_k|)\{D + (dD/d\lambda)(\lambda^2/2c)(|f_i - f_k| + |f_j - f_k|)\} \quad (5)$$

where n is refractive index of the fiber, λ is centre wavelength, X is third-order non linear electric susceptibility, P is power injected in the channel, a is fiber attenuation coefficient, M is number of amplifiers, L_e is effective system length, A_e is effective area of fiber, d_{ijk} is degeneracy factor, D is dispersion coefficient, α is total fiber attenuation, L is system length and η_{ijk} is FWM efficiency.

$$L_e = (1-\exp(-\alpha L))/\alpha \quad (6)$$

Two factors strongly influence the magnitude of the FWM products. The first factor is the channel spacing, where the mixing efficiency increases dramatically as the channel spacing becomes closer. Fiber dispersion is the second factor and the mixing efficiency is inversely proportional to the fiber dispersion, being strongest at the zero-dispersion point. In all cases, the FWM efficiency is expressed in dB, and more negative values are better since they indicate a lower mixing efficiency.

C. Amplified Spontaneous Emission (ASE)

WDM system makes use of the optical in-line amplifiers to reduce the fiber loss in long distance transmission. Due to in-line amplifiers, ASE noise is generated and accumulated as the coupled light travels along the fiber. It influences BER (Bit Error Rate) and capacity of the channel [1]

Chraplyvy [14] provided a model for the calculation of ASE

$$P_{ase}=2nsp\,(G-1)\,hfB_oM \quad (7)$$

Where h is Plank's constant (6.63×10^{-34} Js), f is centre frequency, G is gain of amplifier, B_o is equivalent rectangular optical bandwidth in Hz, nsp is population inversion parameter, M is number of amplifiers.

III. CONSIDERATIONS FOR SIMULATING THE EFFECTS OF FWM

A program was written in Matlab to determine the FWM noise power as per the mathematical relations given in (3) with the input power, system length, interamplifier spacing values fixed and by varying the interchannel separation in steps of 0.01×10^{-6}m.

Input power per channel = 3mW,

Fiber attenuation coefficient = 0.205 dB/km,

Number of channels = 4,

System length =1000 km,

Effective area of the optical fiber =5.3×10^{-7} cm^2,

Dispersion coefficient = 3,

Degeneracy factor = 6,

Interamplifier spacing = 100 km.

IV. HEURISTIC ROUTING ALGORITHM

A novel WA technique as shown in Figure1 based on equally spaced channel allocation paradigm wherein wavelengths from either ends of the fiber transmission window are assigned to long lightpaths whereas wavelengths from the middle of the transmission window are assigned to shorter lightpaths. Here a 14 node tandem network has been considered. We calculate the blocking probability of the network by random WA and fixed WA (Resource Allocation).

The wavelength_segment subprogram is used to identify two different sets of wavelengths marked for long and short lightpaths. In this algorithm, outer segment and central segment representing fiber transmission windows reserved for long and short lightpaths respectively are identified such that proportionately equal wavelength resources are ensured for long and short lightpaths where W signifies the total no of wavelengths available in each fiber link.

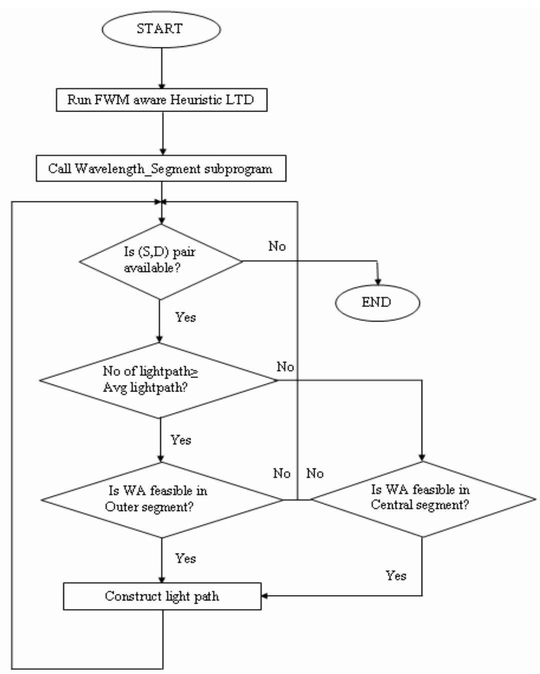

Figure 1. Steps describing Heuristic algorithm and resource allocation

Wavelength_Segment subprogram

Find no of long lightpaths with no of links ≥ Avg lightpaths;

Ratio = (No of long lightpaths)/ (Total no of lightpaths);

Threshold = (int) ceil (W*ratio);

If

Threshold = = odd

then

Outer_segment = (Threshold+1)/2;

Else

Outer_segment = (Threshold)/2;

end

Central_segment = W-2* Outer_segment;

The ratio of no of longer lightpaths and total no of lightpaths are estimated and bandwidth partitioning in to Outer _segment and Central_segment is made in accordance with the ratio. Threshold determines total no of lightpaths in two Outer_segments. After partition, the most suitable source-destination pair is established satisfying wavelength continuity constraints.

If the lightpath route is found to have fiber links more than the avg lightpath, it is identified as longer lightpath and assigned wavelength from Outer_segment in a random manner else it is a shortest lightpath and assigned wavelength from Central_segment. When source-destination pair is not available then the algorithm ends. First by random WA technique the blocking probability of 14 node tandem network has been calculated.

V. RESULTS AND DISCUSSION

The simulation results of the program are presented in graphical form. Fig.2 shows the variation of FWM noise power Vs wavelength. The FWM noise power at 1.5 x 10^{-6} m with a channel spacing of 0.01 x 10^{-6} m is -51.1dBm and with 0.04 x 10^{-6} m is -55.5 dBm. It is proven from the figure that the FWM noise power is more severe in the middle wavelengths when compared to end wavelengths (High and Low) and by putting the maximum spacing between the channels, causes low interaction between them and results in low FWM noise power.

Fig 3, Fig 4, Fig 5 and Fig 6 depicts the variation of FWM noise power in dBm Vs length (L) in km for different values of channel input power (1mw, 10mw, 20mw, 30mw) and interchannel spacing (0.01 x 10^{-6}m, 0.02 x 10^{-6}m, 0.03x 10^{-6}m, 0.04 x 10^{-6}m). As shown in Fig 2, when we launch more power through the fiber, the system gets affected by FWM noise power.

Another important relation from above result was the dependency of the FWM power with the system propagating length. The FWM power at 10Km for input channel power of 1mW was around -41dBm and the corresponding FWM power at the system length of 100Km was around -37dBm which is equal to the FWM power produced at 11Km at channel input power of 30mW. For better system performance we have to choose the correct value of input channel power and the regenerator distance.

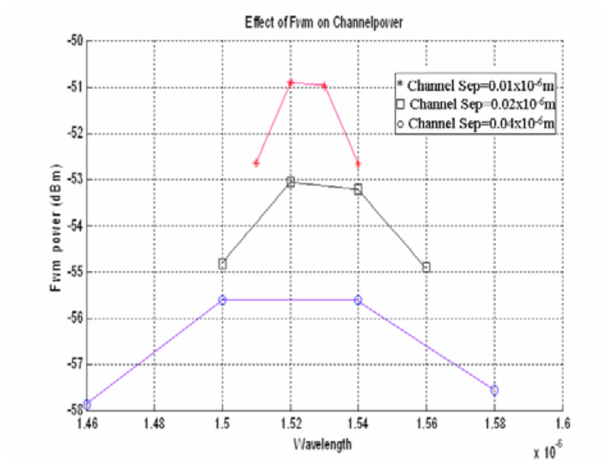

Figure 2. FWM Noise Power Vs Wavelength

For different values of interchannel spacing (10nm, 20nm and 40nm) in WDM transmission system with Fiber attenuation coefficient = 0.205 dB/km, Effective area of the optical fiber =5.3x10^{-7} cm^2, Dispersion coefficient = 3, Degeneracy factor = 6.

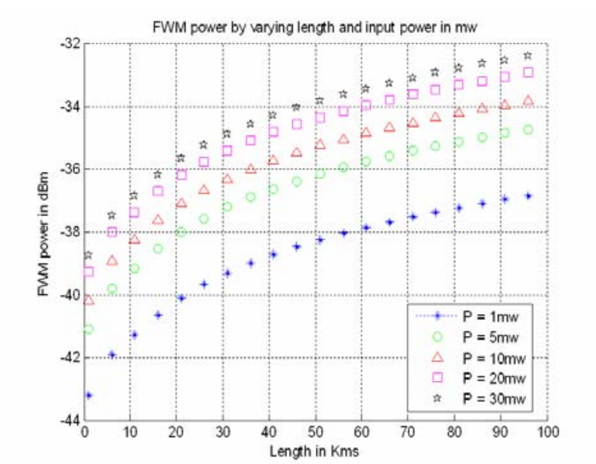

Figure 3. FWM Noise Power in dBm Vs Length in Kms

For different values of input power (1mw, 5mw, 10mw, 20mw, 30mw) with an interchannel spacing of 0.01 x 10^{-6}m in WDM transmission system with Fiber attenuation coefficient = 0.205 dB/km, Effective area of the optical fiber =5.3x10^{-7} cm^2, Dispersion coefficient = 3, Degeneracy factor = 6.

On comparing Fig.3 and Fig.4, the FWM power at a length of 10Km for input channel power of 1mW with an interchannel spacing of 0.01 x 10^{-6}m was around -41dBm whereas the FWM power with same length and same input channel power with an interchannel spacing of 0.02 x 10^{-6}m is around-40dBm. The increase in interchannel spacing can control the effect of FWM.

According to the simulation results shown in Fig.3, Fig.4, Fig.5 and Fig.6, FWM power increases with the increasing system length and input injected channel power assuming all channels were transmitted in the same power and decreases with increase in channel spacing between the channels.

Fig.7 illustrates the FWM noise/crosstalk power variation for different values of system length. The FWM power variation was from -31dBm to -28.3dBm for

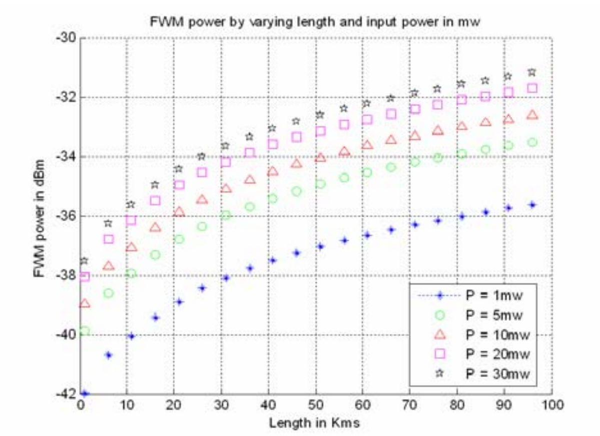

Figure 4. FWM Noise Power in dBm Vs Length in Kms

For different values of input power (1mw, 5mw, 10mw, 20mw, 30mw) with an interchannel spacing of 0.02 x 10^{-6}m in WDM transmission system with Fiber attenuation coefficient = 0.205 dB/km, Effective area of the optical fiber =5.3x10^{-7} cm^2, Dispersion coefficient = 3, Degeneracy factor = 6.

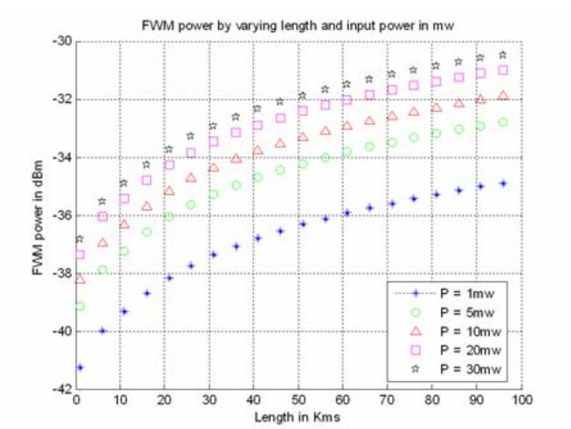

Figure 5. FWM Noise Power in dBm Vs Length in Kms

For different values of input power (1mw, 5mw, 10mw, 20mw, 30mw) with an interchannel spacing of 0.03 x 10^{-6}m in WDM transmission system with Fiber attenuation coefficient = 0.205 dB/km, Effective area of the optical fiber =5.3x10^{-7} cm^2, Dispersion coefficient = 3, Degeneracy factor = 6.

L=5Km and from-29dBm to -27dBm for L=20Km.This figure shows the dependency of FWM on input power and length. Therefore FWM noise power is proportional to input power and Length.

Fig.8 shows the FWM noise power variation for different values of Effective core area. The interaction between the channels will be more when the channel spacing is low which increases the FWM noise power. For A_{eff} = 50µm, the FWM power was high which varies between -35.2dBm to -32.5dBm and for A_{eff} = 140µm the FWM power was low compared to all others. The decision of spacing between the channels was decided by considering the available channel capacity, bandwidth and number of channels that we want to propagate through the same fiber.

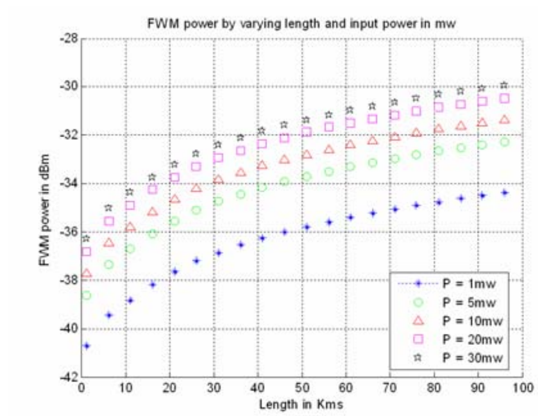

Figure 6. FWM Noise Power in dBm Vs Length in Kms

For different values of input power (1mw, 5mw, 10mw, 20mw, 30mw) with an interchannel spacing of 0.04 x 10^{-6}m in WDM transmission system with Fiber attenuation coefficient = 0.205 dB/km, Effective area of the optical fiber =5.3x10^{-7} cm^2, Dispersion coefficient = 3, Degeneracy factor = 6.

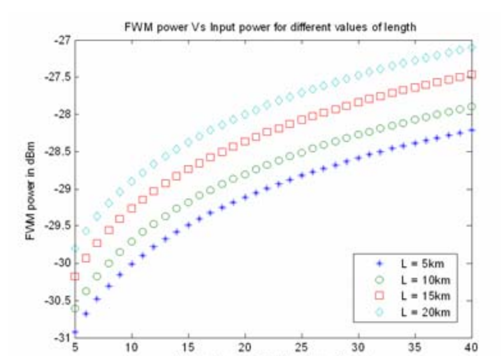

Figure 7. FWM Noise Power in dBm Vs Injected power in mW

For different values of Length (5Km, 10Km, 15Km, 20Km) in WDM transmission system with Fiber attenuation coefficient = 0.205 dB/km, Effective area of the optical fiber $=5.3\text{x}10^{-7}$ cm^2, Dispersion coefficient = 3, Degeneracy factor = 6.

From the figures 1-8, we infer that even in coarse DWDM systems with larger spacing of channels, the transmission capacity of the system is affected by FWM noise due to its dependency on system parameters.

Fig.9 and Fig.10 represents the blocking probability of 14 node (N) Tandem network with number of channels/available lightpaths C=15 and 25 respectively with random WA. On comparing both figures, as the no of channel increases the blocking probabilities reduces in case of random WA but the signal carried by the network is severely affected by FWM noise power and hence the SNR decreases.

In the second case, by applying Heuristic routing algorithm and WA, blocking probability of same network has been calculated. Fig 11A and Fig 11B represents the blocking probability of 14 node (N) Tandem network with number of channels/available lightpaths C=15 for longer

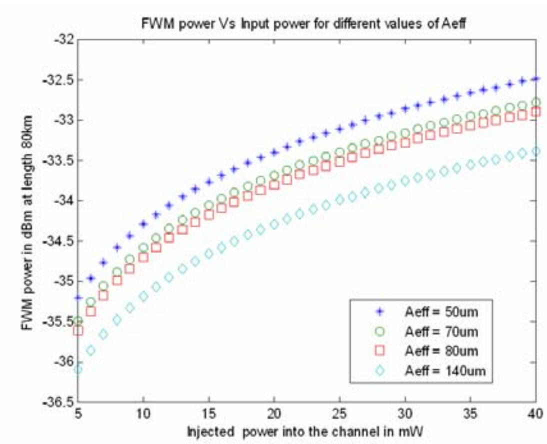

Figure 8. FWM Noise Power in dBm Vs Injected power in mW

For different values of Effective core area (50µm, 70µm, 80µm, 140µm) in WDM transmission system with Fiber attenuation coefficient = 0.205 dB/km, Effective area of the optical fiber $=5.3\text{x}10^{-7}$ cm^2, Dispersion coefficient = 3, Degeneracy factor = 6.

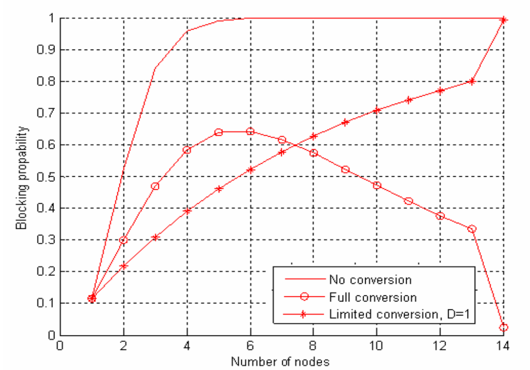

Figure 9. Blocking Probability Vs No of Nodes for C=15 And N=14

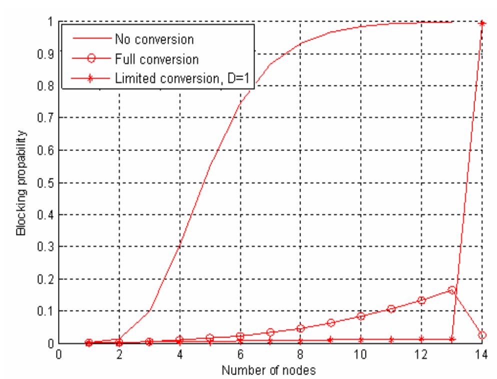

Figure 10. Blocking Probability Vs No of Nodes for C=25 And N=14

lightpaths and shorter lightpaths respectively. In both the figure the blocking probability is almost same for No, full and limited wavelength conversion, which means that both long and short lightpaths are transmitted with minimum FWM noise power and with minimum blocking probability. Here for limited wavelength conversion the maximum degree of 1 is taken.

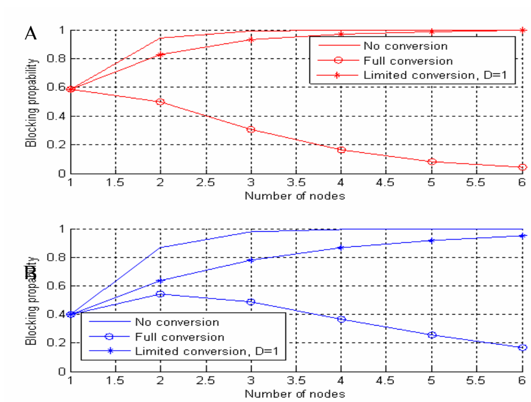

Figure 11. Blocking Probability Vs No Of Nodes For C=15 Using Heuristic Routing Algorithm A. Long Lightpaths B. Shorter Lightpaths.

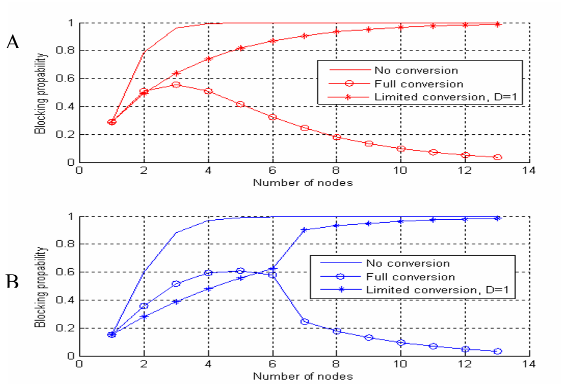

Figure 12. Blocking Probability Vs No Of Nodes For C=25 Using Heuristic Routing Algorithm A. Long Lightpaths B. Shorter Lightpaths.

Fig 12A and Fig 12B represents the blocking probability of 14 node (N) Tandem network with number of channels/available lightpaths C=25 for longer lightpaths and shorter lightpaths respectively. Blocking probability slightly increases as we increase the number of channels from 15 to 25, but as the no of nodes increases from 8, the blocking probability of C=15 becomes almost equal to C=25.

From the simulation results it is clear that even though the blocking probability of random WA is comparable to FWM aware WA, the FWM noise power is severe in all the available channels. By the proposed techniques, better blocking probability can be achieved with the reduction in FWM noise power which enhances the transmission capacity of the network.

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